Food and Agriculture Organization of the United Nations

FAO FISHERIES AND AQUACULTURE PROCEEDINGS

73

ISSN 2070-6103

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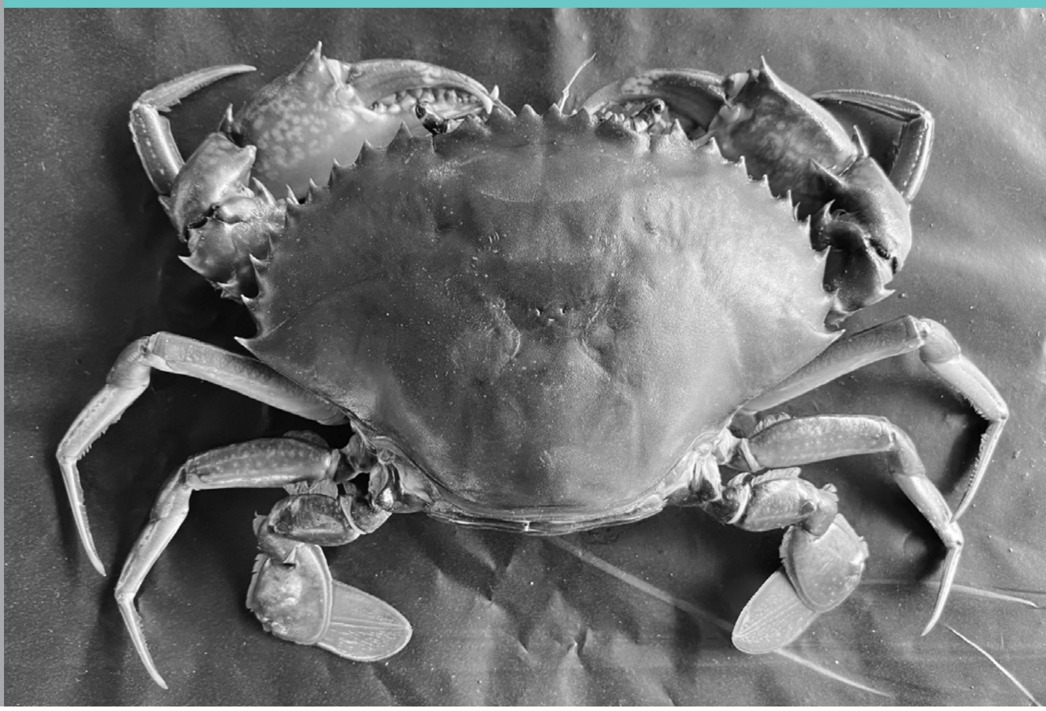

Cover photo:
Dorsal view of an adult mud crab Scylla paramamosain specimen from southern Thailand. ©N. Chema.

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Required citation:

Lovatelli, A., Shelley, C., Tobias-Quinitio, E., Waiho, K. & Chan, D., eds. 2025. *Status, technological innovations, and industry development needs of mud crab (*Scylla *spp.) aquaculture – FAO Expert Workshop, 27–30 November 2023, Singapore*. FAO Fisheries and Aquaculture Proceedings, No. 73. Rome, FAO. https://doi.org/10.4060/cd3976en

ISSN 2070-6103 [Print]

ISSN 2707-5532 [Online]

ISBN 978-92-5-139558-5

Preparation of this document

This document contains the proceedings of the technical workshop entitled "Status, technological innovations, and industry development needs of mud crab (*Scylla* spp.) aquaculture" held from 27 to 30 November 2023, in Singapore, and organized by the Fisheries and Aquaculture Division of the Food and Agriculture Organization of the United Nations (FAO) in collaboration with the Aquaculture Innovation Centre (AIC), Temasek Polytechnic.

The workshop was a direct result of the growing interest by FAO Members engaged at different levels in mud crab aquaculture and the desire to exchange innovative hatchery production and farming solutions that would improve the overall production outputs. The sustainable expansion and technically advanced production of this valuable crustacean would support existing farming activities, contribute to the production of aquatic food, secure revenues for rural coastal communities, as well as generate new employment opportunities.

This document provides a summary of the workshop, highlighting key opportunities and challenges in the development of mud crab aquaculture, along with a series of follow-up actions and recommendations to support growth in the sector. It also includes a brief global overview of the status of mud crab aquaculture development as well as reviews detailing the development status in major producing countries. Additionally, the document features technical reports on advancements in hatchery-produced seedstock, farming systems for both soft-shell and hard-shell crabs, value chains, marketing, and topics related to management, conservation, transportation, and the future quality and handling standards of the industry. These reviews offer valuable insights into recent experiences and ongoing activities within the field of mud crab aquaculture.

The exchange of information and innovative farming and handling practices during the workshop will be captured in the second edition of the FAO Mud Crab Aquaculture Manual, due out in early 2026, reflecting the spirit of collaboration and information sharing.

The proceeding of the workshop is intended for national authorities, including government bodies and research institutions, as well as academia and private sector stakeholders, aiming to foster engagement and collaboration in promoting and supporting the further expansion of this aquaculture subsector through a comprehensive review of its key challenges and opportunities.

This document was prepared under the supervision of Alessandro Lovatelli, Aquaculture Officer, Technology and Production Team (NFIAT), FAO Fisheries and Aquaculture Division.

Abstract

The FAO Expert Workshop on Mud Crab Aquaculture, held in Singapore, brought together leading experts to address critical challenges and emerging opportunities in the sustainable farming of *Scylla* spp. mud crabs. Driven by escalating demand for both hard-shell and soft-shell mud crabs, the sector faces constraints such as overfishing, habitat degradation, reliance on wild seedstock, and unsustainable farming practices. The workshop provided a collaborative platform to evaluate the current state of the industry, identify technological innovations, and set a course for advancing sustainability and resilience in mud crab aquaculture.

Central to the discussions was the transition from capture-based to hatchery-based production systems to secure consistent and high-quality seedstock. Experts highlighted the importance of domestication and selective breeding to enhance aquaculture yields. The development of formulated feeds, reducing reliance on wild-sourced feed, and the integration of advanced technologies such as probiotics and recirculating aquaculture systems (RAS) were identified as critical pathways to address water quality, biosecurity, and production efficiency challenges.

Innovative farming system approaches were presented, including sustainable polyculture systems and the adoption of cellular farming techniques to mitigate cannibalism and improve survival rates. The potential of the soft-shell crab sector for value addition through enhanced post-harvest practices, packaging, and processing was also discussed, though key bottlenecks such as limited seedstock availability, forced moulting practices, and inconsistent farming standards need to be adequately addressed.

Broader ecological concerns, such as the overexploitation of wild populations and the degradation of mangrove habitats were highlighted. Experts advocated strengthened fishery management, habitat restoration, and policy interventions to mitigate these issues. Additionally, the role of advanced technologies such as IoT-enabled systems, digital training tools, and automation was underscored as transformative for achieving scalability and operational efficiency in mud crab farming.

Aligned with FAO's Blue Transformation initiative, the workshop outlined a comprehensive strategy to promote sustainable development in the mud crab aquaculture sector. Key recommendations included establishing broodstock banks, deploying cost-effective disease screening, enhancing international collaboration, and scaling capacity-building programmes to share knowledge and technologies across diverse aquaculture contexts. By fostering innovation, improving productivity, and addressing environmental challenges, the outcomes of the workshop aim to strengthen global food security, enhance aquaculture value chains, and sustain the livelihoods of communities dependent on mud crab production.

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Acknowledgements

Numerous individuals contributed to the successful organization and implementation of the mud crab aquaculture workshop in Singapore, which resulted in the present publication. All of them are gratefully acknowledged for their efforts and contributions during the preparatory phase and at the workshop itself.

Special thanks are due to the Aquaculture Innovation Centre (AIC) and its staff for the logistical support; in particular, Lee Chee Wee, AIC Director, for his opening and closing speeches at the workshop and for his hospitality, Diana Chan for her kind and competent assistance in the preparation of the workshop, and Susila Krishnasamy for her support with administrative matters. They all played a key role in ensuring the professional organization of the event while also contributing to the pleasant atmosphere during the breaks.

A special thank you is extended to the members of the Organizing Committee – Emilia Tobias-Quinitio, Diana Chan, Colin Shelley, and Khor Waiho – for their committed support throughout the planning and implementation phases of the workshop. Their technical expertise and editorial guidance have been invaluable to the experts who submitted country status reports and technical papers.

Thanks are also due to Xiaowei Zhou, Ng Bak Kuang, Ang Phuay Fern, Kevin Fitzsimmons, Michael Akester, U Khin Maung Soe, Shri Dodda Venkata Swamy, Fe Dolores P. Estepa, Juliette Virgula, Sue Poole, and many others, for their valuable contributions and expert insights on the mud crab industry.

Finally, FAO would like to express sincere gratitude to all the experts who attended the workshop, as well as to their respective institutions and companies, for preparing and presenting the papers. Their willingness to share valuable technical insights and innovative experiences will undoubtedly contribute to enhancing the overall production performance of this aquaculture subsector.

Teri Neer (FAO, Rome) is warmly acknowledged for her invaluable assistance with internal administrative matters, which facilitated an efficient and transparent collaboration with AIC. The graphic layout of the proceedings was expertly prepared by José Luis Castilla Civit.

The organization of the workshop and the preparation of this document were possible thanks to funds provided by the FAO Regular Programme.

Abbreviations

AI	artificial intelligence
AIC	Aquaculture Innovation Centre (Singapore)
AILMCGS	Australian Industry Live Mud Crab Grading Scheme
AO	Administrative Order
ASEAN	Association of Southeast Asian Nations
AWMCF	Arnhem West Mud Crab Fishery (Australia)
BAFS	Bureau of Agriculture and Fisheries Standards (Philippines)
BDT	Bangladeshi taka
BFAR	Bureau of Fisheries and Aquatic Resources (Philippines)
BFRI	Bangladesh Fisheries Research Institute
BSFL	black soldier fly larvae
BT	Blue transformation Initiative (FAO)
BW	body weight
C1, C2, etc.	crablet stage
CFU	colony forming unit
CO_2	carbon dioxide
COFI	Committee on Fisheries (FAO)
COVID	Coronavirus disease
CPUE	catch per unit effort
CUC	commercially unsuitable crab
CW	carapace width
CYN	Chinese yuan renminbi
DA	Department of Agriculture
DAF	Department of Agriculture and Fisheries
DAFF	Department of Agriculture, Fisheries and Forestry
DENR	Department of Environment and Natural Resources (Philippines)
DHA	docosahexaenoic acid
DNA	deoxyribonucleic acid
DO	dissolved oxygen
DOF	Department of Fisheries
DOST	Department of Science and Technology
EDTA	Ethylenediaminetetraacetic acid
EFA	essential fatty acids
EGF	Estuary General Fishery (Australia)
EPA	eicosapentaenoic acid
EU	European Union
FAO UN	Food and Agriculture Organization of the United Nations
FAO	Fisheries Administrative Order (Philippines)

FCR	feed conversion ratio
FM	fishmeal
FRA	Fisheries Research and Education Agency (Japan)
GAqP	good aquaculture practices
GI	geographical indication
GoC	Gulf of Carpentaria (Australia)
GS	genomic selection
GWAS	genome wide association studies
HACCP	hazard analysis and critical control points
HDPE	high density polyethylene
HiFi	high fidelity
hp	horsepower
HPI	hours post-injection
HS	harmonized system code
HUFA	highly unsaturated fatty acids
ICW	internal carapace width
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer (French Research Institute for Exploitation of the Sea)
INR	Indian Rupee
IoT	Internet of Things
ITCAL	interim total commercial access level
JMU	Jimei University (China)
KCMF	Kimberley Crab Managed Fishery (Australia)
KKP	Ministry of Maritime Affairs and Fisheries (Indonesia)
LG	linkage groups
LSI	larval stage index
LTP	local transport permit
MAPK	mitogen-activated protein kinase
MCLC	Mud Crab Learning Centre (Thailand)
MCRV	mud crab reovirus
MMK	Myanmar kyats
MNR	Ministry of Natural Resources (Philippines)
MOI	megalopa occurrence index
MPEDA	Marine Products Export Development Authority (India)
MPN	most probable number
MSC	Marine Stewardship Council
MYR	Malaysian ringgit
MYSAP	Myanmar Sustainable Aquaculture Programme
NGF	Nowabenki Gonomukhi Foundation (Bangladesh)
NGO	non-governmental organization
NIRS	near infrared spectroscopy
NRMP	national residues monitoring plan
NSW	New South Wales (Australia)

NT	Northen Territory (Australia)
OECD	Organization for Economic Cooperation and Development
OTC	oxytetracycline
OXO	oxolinic acid
PCAARRD	Philippine Council for Agriculture, Aquatic and Natural Resources, Research and Development
PCR	Polymerase Chain Reaction
PD	Presidential Decree
PER	protein efficiency ratio
PNS	Philippine National Standard
PSU	Prince of Songkhla University (Thailand)
PVC	polyvinyl chloride
Qld	Queensland (Australia)
QTL	quantitative trait locus
R&D	research and development
RAS	recirculating aquaculture system
RGCA	Rajiv Gandhi Centre for Aquaculture (India)
RI	refractive index
S&T	science and technology
SAFS	Status of Australian Fish Stocks
SDR	sex-determining region
SEAFDEC/AQD	Southeast Asian Fisheries Development Center/Aquaculture Department
SGR	specific growth rate
SNP	single nucleotide polymorphism
SPC	sodium percarbonate/soy protein concentrate
SRF	Sundarbans Reserve Forest (Bangladesh)
SSC	soft-shell crab
TAC	total allowable catch
TAS	Thai Agricultural Standards Committee
TEPS	threatened, endangered and protected species
THB	Thai baht
TWG	technical working group
UNDP	United Nations Development Programme
USD	United States dollar
USFDA	United States Food and Drug Administration
UV	ultraviolet light
VASEP	Viet Nam Association of Seafood Exporters and Producers
VFI	voluntary feed intake
WA	Western Australia
WGoCMCF	Western Gulf of Carpentaria Mud Crab Fishery (Australia)
WPP	Fisheries Management Area (Indonesia)
WSSV	white spot syndrome virus

WTO	Wildlife Trade Operation
XX	female
XY	male
Z1, **Z2**, etc.	Zoea larval stage
ZW	heterogametic
ZZ	homogametic

>	greater than
<	less than
≥	greater than or equal to
cM	centimorgan
nm	nanometre
cm	centimetre
m	metre
mM	millimolar
mmol	millimole
mg	milligram
g	gram
kg	kilogram
t	tonne
ml	millilitre
L	litre
m^2	square metre
ha	hectare
ppt	parts per thousand
ppm	parts per million
°C	degree Celsius
%	percent
psu	practical salinity unit

Workshop summary and key recommendations

BACKGROUND

An expert workshop on mud crab aquaculture, organized by the Food and Agriculture Organization of the United Nations (FAO) in collaboration with the Aquaculture Innovation Centre (AIC), was held in Singapore from 27 to 30 November 2023. The main objective of this technical event was to assess the current progress and development, as well as to identify persisting bottlenecks, future challenges and priority needs of the sector and identify key pathways for sustainable mud crab aquaculture production at a global level. The workshop was divided into four main sessions: a glimpse of the current global status of mud crab aquaculture; the advancement of mud crab hatchery, larviculture and nursery production; the development of current value chains, marketing and farming systems; and a final session on topics related to management, conservation, transportation and future industry needs.

The experts agreed that there is a strong and increasing global market demand for mud crabs, both in hard-shell and soft-shell forms. Soft-shell crabs are seeing a rise in demand, in particular, as a result of the value-adding opportunities they provide. Key advances include a shift towards the use of formulated feeds to reduce a dependence on unsustainable wild fishery feed resources and the improvement of hatchery production methods, including the adoption of probiotics and the integration of advanced water quality management technologies. The industry's future will also be strengthened by the development of selective breeding and genetic improvement programmes.

At present, most mud crab farming employs extensive production systems. However, research and trials on intensive farming systems, including strategies to minimize cannibalism, are gaining attention, incorporating cellular systems (individualized compartment) to reduce cannibalism. Many processes across the entire mud crab aquaculture system, ranging from broodstock culture to juvenile production, still require optimization. Close collaboration and knowledge exchange among stakeholders is required to propel these advancements forward.

Although mud crab aquaculture is a relatively small sector in the global aquaculture industry, it has promising growth potential based on several decades of industry development, a solid technological foundation and strong global demand. The decline of shrimp aquaculture industry in many countries has opened opportunities for alternative aquaculture options, with mud crab farming gaining increasing attention. This sector merits consideration of private sector investment to meet market demand. In addition, mud crab aquaculture and its associated product value chains support the livelihoods of local communities in mud crab producing countries. Thus, future development of the mud crab aquaculture sector can contribute to livelihood improvement and economic growth in many developing countries.

To build on the momentum generated by the workshop, the experts agreed on the importance of further dissemination of information through digital channels, targeted events and meetings to engage the broader aquaculture community.

INTERNATIONAL MUD CRAB INDUSTRY STATUS

The most recent FAO production figures showed that whilst China dominates global production of mud crabs with over half the total annual production of 296 000 t, Viet Nam has demonstrated the strongest growth over the past decade, increasing its production by over 650 percent, to about 81 000 t/year. Most mud crab producing countries farmed the most abundant mud crab species in their localities. The main species produced in China and Viet Nam is the green mud crab, *Scylla paramamosain*, which also contributes to Indonesian farming. In the Philippines and India the giant mud crab, *Scylla serrata*, is the most common species farmed, whilst the orange mud crab, *Scylla olivacea*, is cultured by countries including Thailand, Myanmar, Bangladesh and Indonesia. However, globally, all mud crabs of the genus *Scylla* are generally regarded as one type of crab, with no specific preference for individual species in most markets.

Mud crab farming now incorporates intensive (individual compartments), semi-intensive and extensive systems, polyculture and crab fattening of both hard-shell and soft-shell crabs. The choice of system selection depends on several factors, including space, resource availability, technical feasibility, and availability of financial resource. In some countries with more advanced mud crab culture technologies, such as China and Viet Nam, the growth of the sector has led to significant segmentation of the industry, with individuals or companies specializing in the sale of live feeds, broodstock, larvae and/or crablets, juveniles and farming.

Identified global key issues include:

- Continued dependence on wild seedstock for farming.
- Use of unsustainable feed sources such as trash fish.
- Insufficient hatchery production of quality seedstock.
- Inadequate aquatic health management of mud crabs.
- Domestication and genetic improvement of mud crab broodstock.

The reliance on capture-based stock for farming, coupled with overfishing, has resulted in significant reduction in catch per unit effort, decrease in the size of wild broodstock, and increase in the costs of wild stock for farming in many countries. This highlights the urgent need for more investment and transfer of technology to establish more mud crab hatcheries. Having the capability to produce sufficient high quality seedstock would not only reduce wild stock reliance but could also contribute toward sustainable fishery management through targeted restocking of wild populations. Transition from a capture-based to hatchery-based industry is critical to underpin the long-term sustainability of the industry and wild mud crab populations.

DOMESTICATION AND SELECTIVE BREEDING OF MUD CRABS

The workshop recognised that broodstock quality, desired species to culture, desirable traits, and stock genetic diversity are essential criteria in the development of mud crab selective breeding programme. Preliminary domestication of *S. serrata,* with a special focus on growth and disease resistance, was successfully conducted by Southeast Asian Fisheries Development Center/Aquaculture Department (SEAFDEC/AQD). Preliminary findings indicated that stronger and healthier mud crabs could be produced. Whilst genome editing technologies could potentially be used for future trait enhancement, subject to consumer acceptance, trait selection through traditional selective breeding is certainly possible.

Currently, two kinds of whole genome maps and four kinds of genetic linkage maps of *S. paramamosain* are publicly available. Meanwhile a 40 K liquid SNP array was developed for breeding based on whole genome resequencing data. In addition, an artificial inter-specific hybridization technique has been developed between *S. paramamosain* and *S. serrata* and two kinds of hybrid offsprings produced. This work will serve as important baseline information for the development of various genetic selection and improvement programmes for the mud crab aquaculture industry.

MUD CRAB BROODSTOCK

Mud crab broodstock husbandry practices and culture systems are well established and standardised in some countries such as China, Viet Nam, Philippines and Thailand.

The most significant issue with mud crab broodstock in many countries is the inconsistent availability of good quality broodstock for hatcheries, which is exacerbated by the uncertainty of female insemination and seasonal availability of broodstock in some regions. The lack of good quality broodstock in some countries has led to some limited translocation of mud crabs between countries. One option under consideration is the need for 'broodstock banks' to be developed to underpin future hatchery production.

Another commonly agreed issue faced by broodstock hatcheries is their reliance on wild caught aquatic organisms such as trash fish, bivalves, molluscs and polychaetes as food sources. Thus, the development of a formulated diet to potentially improve broodstock performance is needed to ensure nutrient consistency and improve biosecurity.

An important element related to biosecurity identified at the workshop was the need for screening of broodstock and food sources for viral and bacterial pathogens as has been conducted in the Philippines and India. However, owing to the high cost of screening, the use of common disinfection techniques and resulting uncertain health status of stock remains common for the majority of hatcheries. The development of a low-cost pathogen detection system for broodstock is recommended.

Domestication and genetic improvement of mud crab stocks are essential for the future growth of the mud crab industry based on consistent, reliable hatchery production. This has a key role in shifting from an industry dependent on capture-based stock to a more sustainable hatchery-based one. The domestication and genetic improvement of mud crabs are anticipated to yield significant production gains, akin to the remarkable advancements achieved in shrimp farming with the genetic enhancement of species like *Penaeus monodon* and *Penaeus vannamei*.

MUD CRAB HATCHERY AND NURSERY PRODUCTION

Mud crab hatchery technology has evolved significantly over the last 20 years, using feeds and systems adapted from those developed for shrimp culture. However, the average larval survival remains inconsistent and low in all countries compared to that of shrimp hatcheries. Nonetheless, the fecundity of female mud crabs, which varies from 1.5 to over 6 million larvae per broodstock, has enabled the commercial-scale production of megalopa and crablets.

Two notable trends in mud crab larviculture is the replacement of antibiotics with probiotics and a greater importance being given to water quality. Recirculating aquaculture system (RAS) and water sterilisation techniques including UV and ozone are being increasingly adopted by industry players to better manage water quality during this delicate stage of mud crab farming. Nature-based RAS hatcheries utilising seaweeds and other organisms to maintain and remediate water have also been used, which can also provide secondary crops for farmers.

In mud crab nurseries, an improved understanding of the moulting cycle and nutritional requirements of mud crabs should lead to the development of improved, crab-specific diets in the near future, replacing shrimp feeds and low value fisheries products.

Discussions held at the workshop reflected the wide variety of approaches to mud crab larviculture in terms of stocking densities, feeds, feeding management and water quality management. Tanks, ponds and net cages ("hapa") are all used in the nursery phase. The megalopa-to-crablet transition remains the most significant challenge for many operations, whereby low survival is often observed if not managed properly. As larvae move from the zoea to megalopa and crab stages in nurseries, significant more surface area is required as both megalopa and initial crab stages are kept at relatively low densities, compared to zoea.

Notable constraints to the economic performance of the hatchery and nursery sectors include:

- Aquatic disease management (viruses, bacteria, fungi and protozoans) in eggs and larvae.
- Lack of suitable formulated feeds.
- Inconsistent crablet survival.
- Cannibalism.
- Lack of quality standards for crablets.
- Absence of automated counting systems for megalopa and crablets.

FARMING SYSTEMS

The current status of farming systems being used to produce hard-shell mud crabs include extensive earthen brackish water ponds (polyculture or monoculture systems), fattening in boxes or cellular/compartmental systems, aqua-silviculture and crab-rice farming. Species that are often being co-cultured with mud crabs include various fish species (omnivores or herbivores), shrimps, seaweeds and molluscs. Although co-culturing other species with mud crabs can diversify production outputs and potentially increases profitability, it can also add significant biosecurity and health risks.

For soft-shell crabs, floating box systems within ponds, where juvenile crabs are being cultured until their next moult and then harvested, remains the most productive and economically viable technology in most mud crab producing countries. Facilities utilizing cellular closed systems with recirculating aquaculture systems (RAS), where crabs are housed individually in "condominium" or "vertical" structures, offer an alternative approach that allows for better control of environmental parameters, though at a higher operational cost.

Critical issues in farming include:

- Control of cannibalism and relatively low survival rate.
- Disease management.
- Quality and quantity of seedstock.
- Formulated feed development.
- Inter-moult duration and growth.
- Mortalities in soft-shell crab farming.
- Adaptation to changing climatic conditions e.g. heavy rainfall leading to reduced salinity and alkalinity.
- Effective harvesting technique.

As sourcing wild crab seedstock for soft-shell production is still dominant, overfishing is continuing to result in significant increase in unit costs; transitioning to hatchery-based production is the only long-term solution for growth and sustainability, combined with responsible wild fishery management and practical fisheries enforcement.

A relatively new innovation in soft-shell crab production is the use of claw or cheliped "restraints" applied on pre-moult crabs at high densities in communal systems to prevent intra-specific aggression, damage and mortalities, negating the need for cellular systems in some instances.

PRODUCT HANDLING, VALUE CHAINS AND POST-HARVEST PROCESSES

Hard-shell mud crabs

Quality grading of live hard-shell mud crabs is based on several criteria, including body size and weight, meat fullness, appendage completeness and activity. Various national guidelines for mud crabs have been developed for countries such as Philippines and Thailand to underpin marketability, global competitiveness and customer satisfaction.

Post-harvest losses for live mud crabs are also an issue. Such losses can be from poor storage and packing, and inappropriate transportation and logistics processes during the transport of live mud crabs from farms to wholesale or retail markets. Research and development in Australia examined the live mud crab value chain from a physiological perspective resulting in significant improvements in post-harvest management. To date this post-harvest technology has yet to be disseminated internationally. In Viet Nam, practical measures to reduce dehydration of crab stock have also been developed to reduce post-harvest loss.

Whilst hard-shell mud crabs of all sizes (100 g and above) are traded live, the larger sized crabs (≥ 700 g) and females at the final stage of ovarian maturation (full of eggs internally) fetch premium prices. Generally, the larger the crab and the higher the grade, the higher the price/kg. In some markets, such as Singapore, value added services such as slaughtering, segmenting and separation of claws, legs and body to minimise chef's preparation time can improve wholesaler income.

With increased overfishing, it is becoming more difficult to access large mud crabs for the live trade, constraining the growth of the industry. The market demand (for perceived better meat quality) of wild-caught crabs is higher compared to farmed crabs in some markets. Although the demand has increased, wild-caught supply has plateaued. In some countries regulations can influence prices. For example, Indonesia prohibits the sale of female crabs and Papua New Guinea has had a 6-month closed season on mud crabs.

Soft-shell crabs

Anecdotal information from experts at the workshop points to significant wastage and losses in mud crab value chains from harvest to consumer. Losses are particularly high in the soft-shell crab production sector due to unoptimized culture conditions, poor storage and transportation of wild caught seedstock, improper packing, physical damage from sorting and on-farm losses from poor husbandry practices. In contrast, post-harvest processing of soft-shell crabs require high standards as the product has to be prepared to meet international food safety standards.

Soft-shell mud crabs have significantly more value-adding opportunities than hard-shell counterparts. Whole Round and Whole Cleaned are the two major processed types of soft-shell mud crabs, with size grades standardised, based on those developed for soft-shell crabs in the United States of America. Their popularity has been largely driven by the global growth of Japanese restaurants, other Asian cuisines and fast food sectors. The sector will in the future benefit from economies-of-scale, improved consumer awareness and development of more value-added products incorporating soft-shell mud crab.

Soft-shell crab processing for international markets typically includes the development and ongoing audit of HACCP for cold chain management, food safety and soft-shell crab cleaning and preparation.

The soft-shell crab value chain is often segmented with specialisation in either fishing, trading, farming or processing. A soft-shell processing plant, designed to process large quantities of raw material is expensive to build and operate. For this reason, it is common for many small-scale soft-shell crab farmers to supply each processing plant, rather than process themselves.

An important issue in soft-shell crab farming is the forced moulting of mud crabs, used in some countries, to hasten the moulting process. This results in “balloon crabs”; crabs with little meat and significant physical deformities, which are of lower quality compared to those crabs that moult naturally, and fetch a lower market price compared to natural moults.

Another major concern in the soft-shell crab industry is the sustainable supply of juvenile crabs to be used for soft-shell crab production. Currently, most soft-shell crab production farms source wild mud crab juveniles that are still available, especially in Southeast Asian countries. There is an urgent need for mud crab producing countries to set forth sustainable fishery management measures and focus on large-scale production of mud crabs to cater for the high demand needed in the soft-shell crab industry.

FISHERY MANAGEMENT

In most mud crab producing countries, overfishing of mud crabs, at varying degrees, are apparent. However, Australia has demonstrated that it is possible to sustainably manage wild mud crab populations. Its management regime reflects the country's unique industry structure, involving few fishers and strong regulatory and enforcement capabilities. It is considered possible to adapt Australia's management approach to help improve fishery management in other countries, if there are adequate resources and the necessary political will. Many other countries, e.g. Indonesia and Philippines, have fisheries regulations limiting mud crab catches based on size and sex which contribute to better fisheries management, but generally and globally more needs to be done in this area to effectively manage and conserve wild *Scylla* populations.

The decline of wild mud crab populations, particularly *S. olivacea* has also been exacerbated by the destruction of mangrove habitats in a number of countries. Mangroves serve as critical breeding, nursery, and feeding grounds for mud crabs. The loss of these vital ecosystems has far-reaching socio-economic consequences.

FUTURE INDUSTRY NEEDS

The needs of the mud crab aquaculture sector identified during the workshop varied significantly between countries, between species and the hard- and soft-shell sectors. Additionally, their perceived importance will vary relative to each stakeholders' role in the mud crab value chain and their principal occupation (e.g. farmer, trader, processor, researcher or government).

Overall, there was strong consensus to work towards a sustainable, hatchery-based mud crab farming sector, incorporating domestication, formulated feeds and reliable technology to produce high quality crab products to meet the increasing market demand. Global needs and recommendations generated by the workshop are listed below.

International

- Shift from a capture-based to a hatchery-based aquaculture sector.
- Replace low value fish and other unsustainable fresh feeds with formulated diets.
- Increase hatchery and nursery production to meet the growing demand for seedstock.
- Domesticate and genetically improve mud crab broodstock.
- Implement sustainable management practices for mud crab fisheries.

Broodstock

- Ensure an adequate supply of broodstock to meet short- and medium-term hatchery demands before fully relying on domesticated stock.
- Domesticate and genetically improve mud crab broodstock.
- Improve husbandry and nutrition of broodstock to maximise reproductive performance.

Mud crab hatchery and nursery production

- Improve aquatic health management in hatchery and nursery operations.
- Develop improved hatchery and nursery systems to increase survival rates, reduce

production costs and produce high quality seedstock.
- Incorporate enhanced monitoring and control of hatchery and nursery systems into management systems.
- Make use of advanced water management treatments and probiotics to reduce the dependence on prophylactic use of antibiotics.
- Utilise an improved understanding of the microbiome of mud crab larval and nursery systems to improve larval rearing protocols, feeds and feeding regimens.

Farming systems

- Improve extensive and semi-intensive pond-based systems through adoption of standard operational procedures and best aquaculture practices.
- Develop improved cellular systems for both soft-shell and hard-shell farming of mud crabs to reduce losses from cannibalism.
- Utilise best practices on biosecurity, improve health screening and increase aquatic health surveillance to reduce losses to common crustacean diseases.
- Formulate suitable mud crab diets to improve the physical nature of feeds to enhance growth and immunity, improve disease resistance and reduce wastes.
- Develop more efficient reduction of intra-specific aggression and cannibalism in communal farming systems.

Product handling and marketing

- Disseminate best practice on mud crab packaging and transportation techniques to support reduced waste, unnecessary stock loss and improved profits.
- Develop high quality standards for mud crab products to further improve value chain efficiency and international trade similar to other seafood commodities.
- Discourage forced moulting as this produces an inferior quality product.

Fishery management

- Regularly assess wild mud crab populations to address widespread overfishing concerns.
- Determine cost-effective mud crab fishery management plans. Such plans will only be effective with strong community, industry and other stakeholder consultation and government support.

Training

- Determine training needs as there are significant differences in mud crab aquaculture development between countries.
- Develop information, education and communication (IEC) materials to enable mud crab farming technology to be shared at scale via digital transmission.
- Support international collaboration in technology transfer and knowledge sharing.

GENERAL CROSS SECTOR RECOMMENDATIONS

The establishment of aquatic health surveillance programmes and better management practices to mitigate significant diseases need to be developed. The development of disease screening platforms and molecular kits to monitor key viral and bacterial diseases are required, that include mud crab specific diseases, as well as generic crustacean ones.

In comparison to major aquaculture commodities, such as shrimp or salmon, there is still a paucity of research and information on mud crab aquaculture. To support the industrialisation of mud crab farming, there is need for ongoing research and development in areas including, but not limited to:

- Genetics, genomics, immunogenetics and nutrigenomics.
- Nutrition and feed development, proteomics.

- Water quality treatment and management.
- Aquatic health management.
- Reduction of aggression and cannibalism.
- Immune system enhancement.
- Improved control of moulting.
- Microbiome analysis and microbial management.
- Moult death syndrome mitigation.
- RAS engineering.
- Automation of farm management systems including the incorporation of advanced sensors, internet of things, machine learning, deep learning, robotic systems and artificial intelligence.

COUNTRY STATUS AND TECHNICAL PAPERS

Global overview of the mud crab production sector

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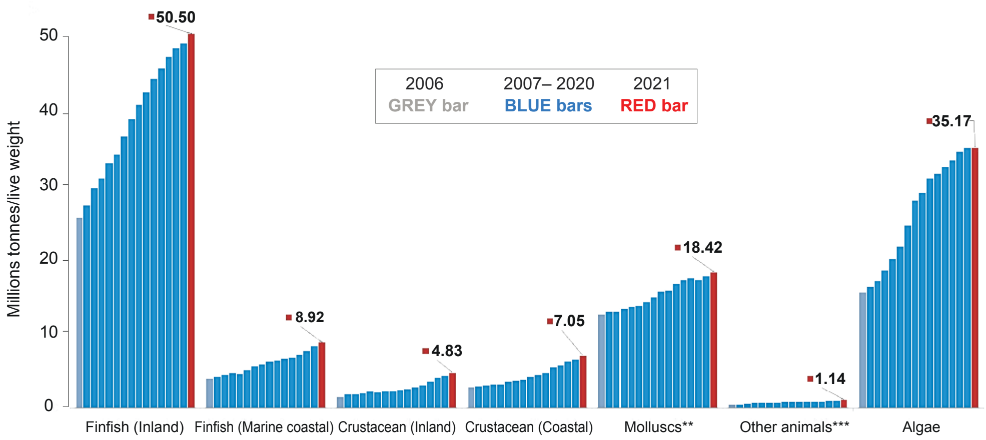
ABSTRACT

Whilst a significant dataset is available on mud crab aquaculture production, the level of information it provides is limited. At present there is no differentiation in the dataset between the four species of mud crab, *Scylla serrata*, *Scylla paramamosain*, *Scylla olivacea* and *Scylla tranquebarica*. The vast majority of farmed mud crab production is still capture-based, where wild seedstock of various sizes are harvested and subsequently cultured for either hard-shell or soft-shell production. The contribution from hatchery-based production to the overall production volume is uncertain. However, other papers from this workshop will shed some light on that matter. Similarly, based on industry experience, there is also uncertainty regarding the volume of farmed or wild-caught crab products. This paper reviews official FAO statistics and combines personal industry experiences and other information sources to provide an overview of production. It is acknowledged that the statistics and observations presented herein have significant limitations and inherent inaccuracies.

GLOBAL PRODUCTION OF MUD CRABS

In a global context, mud crab aquaculture production of approximately 300 000 tonnes per annum in 2021 represents around 4.25 percent of the total 7 million tonnes of coastal crustaceans produced annually (Figure 1). This places mud crab aquaculture as a relatively small sector compared to freshwater fish and seaweeds, which have production volumes of 50.5 million and 35.1 million tonnes, respectively.

FIGURE 1
World aquaculture production by species groups 2006–2021



* Includes aquatic turtles, frogs, sea cucumbers, sea squirts and edible jellyfish, etc.
** Mostly marine molluscs, such as oysters, mussels, clams and scallops, etc. and small quantity of freshwater clams and snails.
*** Includes small quantity of tropical spiny lobsters and negligible quantity of marine shrimps grown in cages in the sea.

Source: FAO. 2024. Fishery and Aquaculture Statistics – Yearbook 2021. FAO Yearbook of Fishery and Aquaculture Statistics. Rome. https://doi.org/10.4060/cc9523en

Among the top eight producers of mud crabs, only those exceeding 3 000 tonnes per year are notable, with production from other countries totalling less than 0.1 percent of total global production. China and Viet Nam are the largest producers of mud crabs, accounting for 51 and 28 percent respectively of the global annual production of 296 848 tonnes in 2021 (Table 1). Viet Nam has shown rapid growth in mud crab aquaculture production, with a nearly 650 percent increase in production since 2010. This increase can be largely attributed to the rapid rise in hatchery production, where estimates of the number of crablet-producing hatcheries in Viet Nam varies from 400–700, seasonally. Whilst hatchery production of mud crabs is practised in China, the Philippines, Indonesia, Bangladesh and India to varying degrees, Viet Nam is the only country where more crablets are produced from hatcheries (80 percent) than harvested from the wild (20 percent).

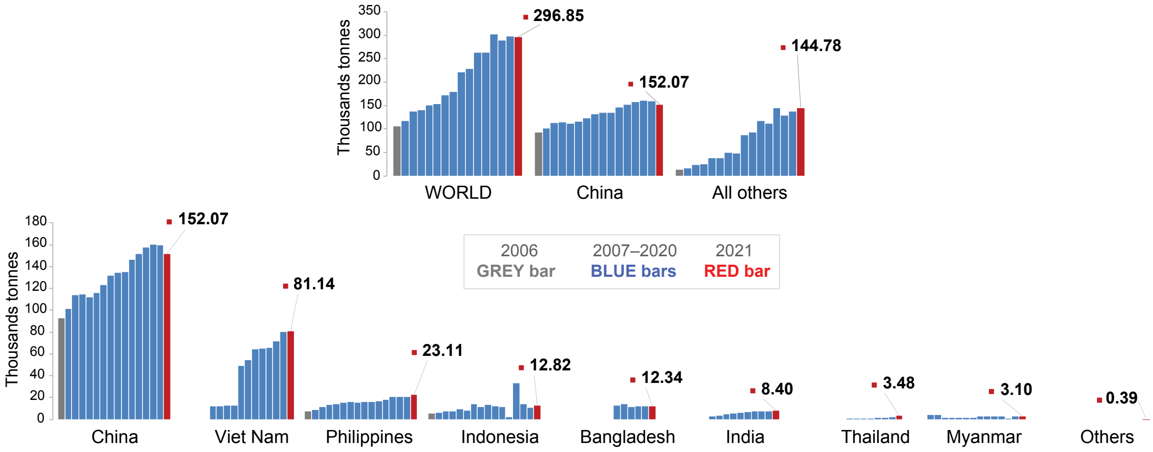
TABLE 1
World aquaculture production quantity of mud crabs by producing country and territory (t)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
China	112 408	115 772	123 599	132 149	134 507	135 094	146 189	151 976	157 712	160 616	159 433	152 065
Viet Nam	12 500	12 500	13 000	13 000	49 140	54 588	64 633	65 463	66 000	71 757	80 162	81 144
Philippines	14 438	15 731	16 360	15 794	16 160	16 199	16 860	18 100	20 770	20 772	20 766	23 113
Indonesia	9 557	8 153	14 164	11 898	13 594	12 546	11 407	2 704	33 807	14 208	10 767	12 823
Bangladesh	...	...	...	...	...	...	13 160	14 421	11 787	12 084	12 562	12 337
India***	...	...	3 000	4 000	5 000	6 000	6 500	7 000	7 500	7 600	7 900	8 400
Thailand	45	600	700	700	800	800	1 000	1 100	1 773	1 561	2 556	3 479
Myanmar	1 500	1 500	1 933	1 950	2 000	2 836	3 151	3 038	2 883	842	2 973	3 096
Malaysia	8	20	42	14	36	61	14	96	15	234	210	206
Cambodia	20	20	40	40	50	50	68	70	80	90	120	100
Singapore	...	7	42	314	137	101	45	35	43	27	19	36
Taiwan Province of China	225	165	122	89	26	32	21	7	6	6	12	27
Fiji***	...	...	...	...	7	7	7	10	10	10	10	10
Sri Lanka	18	20	2	1	2	12	155	51	69	60	22	7
United Republic of Tanzania	5	0	...	0	0	0	2	2	1	0	...	1
Brunei Darussalam	3	5	5	...	...	...	...	...	1	...	1	1
Timor-Leste***	...	...	...	...	...	...	1	1	1	1	1	1
Mauritius	1	1	1	1	1	1	1	1	1	1	1	1
Papua New Guinea	18	0	4	4	4	4	4	0	0	0	1	1
Madagascar***	5	5	5	5	5	5	...	...	...	...	...	...
Samoa	0	0	0	0	...	...	...	0	0	0	...	...
Australia	...	...	...	...	...	...	...	...	...	...	...	...
WORLD	**150 751**	**154 499**	**173 019**	**179 959**	**221 468**	**228 335**	**263 219**	**264 075**	**272 459**	**416 841**	**297 516**	**296 848**

The resilience of mud crab aquaculture production in 2020 (Figure 2) despite dramatic reduction of seafood consumption in most countries during the peak of the COVID-19 pandemic is noteworthy. This phenomenon prompts speculation on whether it underscores the robust demand for the product or highlights potential inaccuracies in the dataset.

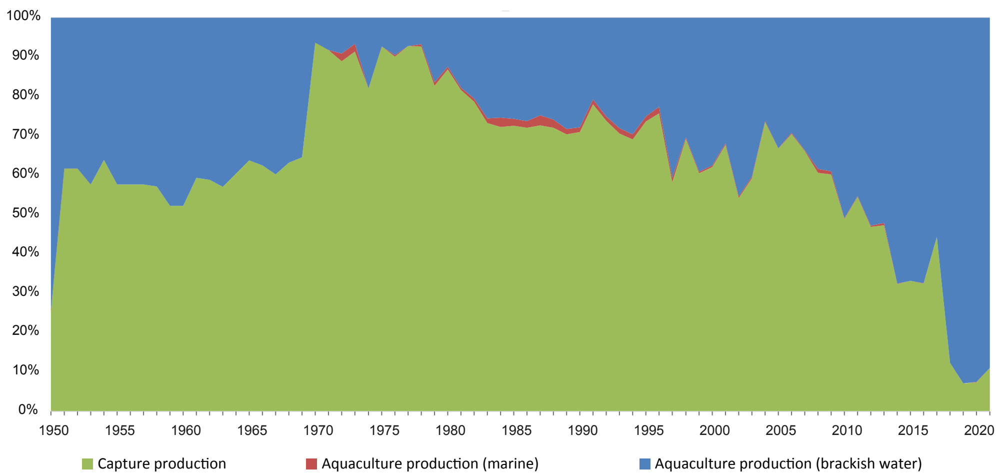
Over the last 70 years, the proportion of farmed mud crabs has increased dramatically compared to wild harvest, with only just over 10 percent coming from the wild in 2021 compared to the 1970s when that figure was 90 percent (Figure 3). Whilst limited numbers of mud crabs are produced in seawater, most are from brackish water operations.

FIGURE 2
World production of farmed mud crabs by major producing countries 2006–2021
(tonnes live weight)



Source: FAO. 2024. Fishery and Aquaculture Statistics –Yearbook 2021. FAO Yearbook of Fishery and Aquaculture Statistics. Rome. https://doi.org/10.4060/cc9523en

FIGURE 3
***Scylla* spp. share of world production by production source, 1950–2021**

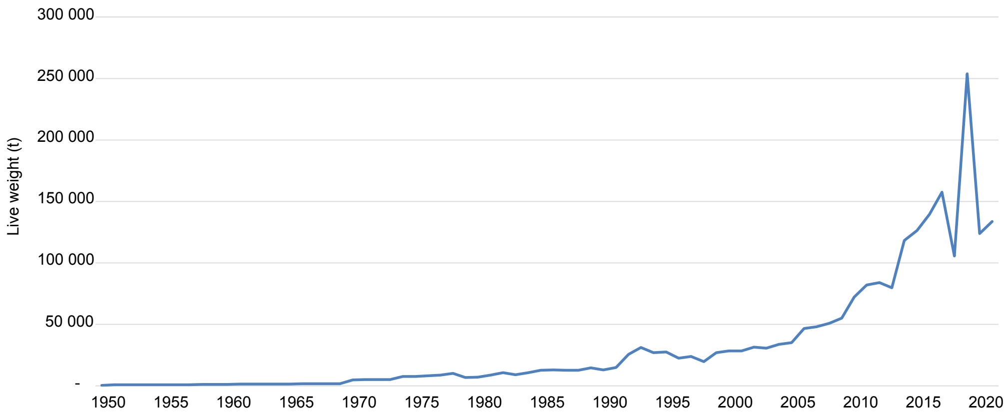


Source: FAO. 2024. Fishery and Aquaculture Statistics –Yearbook 2021. FAO Yearbook of Fishery and Aquaculture Statistics. Rome. https://doi.org/10.4060/cc9523en

Although production is now dominated by farmed produce, the main source of seed is still capture-based, from wild fishery stocks. This indicates the growing pressure on mud crab fisheries in most countries, which are now considered unsustainable.

Over the last 70 years, *Scylla* spp. production has demonstrated significant exponential growth (Figure 4). This surge in production is largely attributed to China, which is also the largest market for live mud crabs. The growth in production aligns with the expansion of China's middle class and their increasing ability to afford higher-priced seafood products, thereby driving demand. If this trend in production is to continue, it is highly unlikely that capture-based seed-stock will be able to sustain it. To fulfill the market demand for mud crabs, increased hatchery production will be required.

FIGURE 4
Scylla spp. global production over time, 1950–2021



Source: FAO. 2024. Fishery and Aquaculture Statistics –Yearbook 2021. FAO Yearbook of Fishery and Aquaculture Statistics. Rome. https://doi.org/10.4060/cc9523en

Overview by species

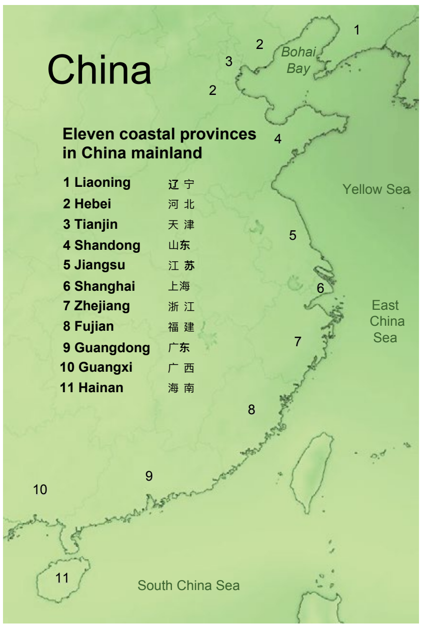
Of the four species of mud crabs, production is dominated by *S. paramamosain*, the only species farmed in both China and Viet Nam. *S. serrata* is the most common species in the Philippines and India, whilst *S. olivacea* dominates the production in Thailand, Myanmar and Bangladesh. All four species contribute to Indonesia's production.

When looking at soft-shell mud crab farming only, then *S. olivacea* accounts for the most farmed production (Myanmar, Bangladesh and Thailand), followed by *S. paramamosain* (Viet Nam) and *S. serrata* (Philippines, Indonesia).

Country production notes

China produces mud crabs in seven of its 11 coastal provinces, with Guangdong being the largest – averaging around 60 000 tonnes per annum for the last four years (Figure 5). Two other provinces, Hainan and Guangxi, reported an annual production

FIGURE 5
Production of farmed green mud crab in coastal provinces in China



Mud crab

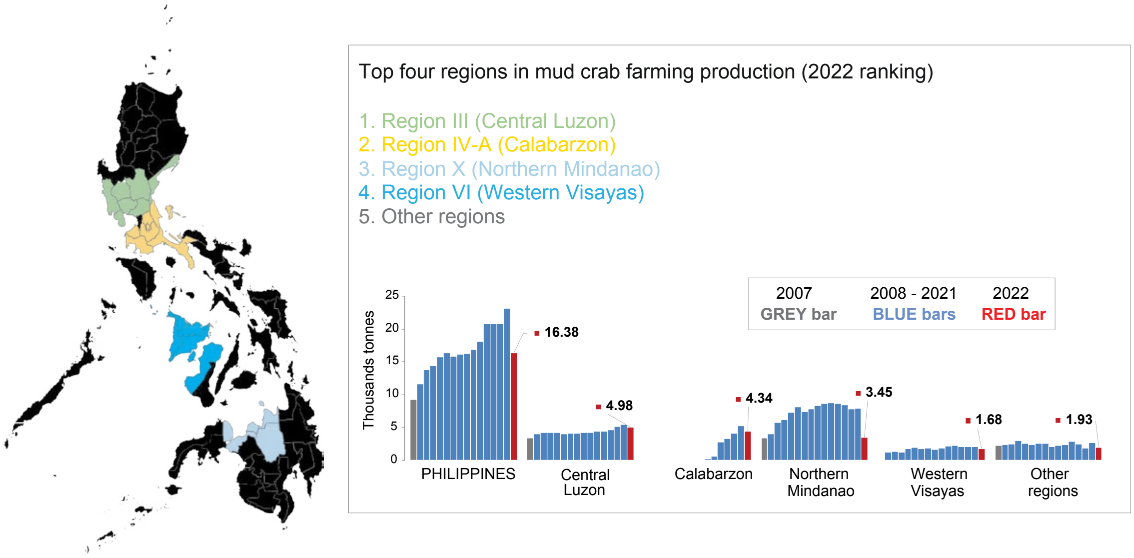
Production of farmed green mud crab in coastal provinces in China Unit: tonnes (in live weight)

		2015	2016	2017	2018	2019	2020	2021
Liaoning	辽宁	…	…	…	…	…	…	…
Hebei	河北	…	…	…	…	…	…	…
Tianjin	天津	…	…	…	…	…	…	…
Shandong	山东	…	…	…	…	220	555	675
Jiangsu	江苏	1 968	1 990	1 972	2 047	1 887	1 987	1 800
Shanghai	上海	…	…	…	…	…	…	…
Zhejiang	浙江	26 563	26 549	26 083	25 358	26 272	26 090	27 595
Fujian	福建	32 335	35 093	35 109	36 320	36 305	37 497	38 898
Guangdong	广东	47 421	51 664	55 036	60 691	65 107	62 390	59 228
Guangxi	广西	16 730	17 394	19 298	19 521	18 048	18 390	11 871
Hainan	海南	16 023	16 287	14 478	13 775	12 777	12 524	11 998
TOTAL		**141 040**	**148 977**	**151 976**	**157 712**	**160 616**	**159 433**	**152 065**

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Fisheries Administration, Ministry of Agriculture and Rural Affairs, China.

FIGURE 6
Philippines: Top four regions in mud crab farming production (2022 ranking)



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Philippines Statistical Authority. Aquaculture: Volume of production by species, region and province, 2022. Fisheries Statistics Division.

of over 10 000 tonnes, whilst the annual mud crab production in Zhejiang and Fujian was well over 20 000 tonnes.

The mud crab industry in the Philippines has shown steady growth until 2022, when the sector was badly affected by floods, with all key production regions reporting lower than normal production (Figure 6). Government legislation has attempted to limit capture-based production and encourage hatchery-based farming; however, hatchery development has been relatively slow compared to Viet Nam.

Myanmar, known for its top quality soft-shell crabs, was badly affected by the COVID-19 pandemic, which impacted on demand, sales and production (Table 2). It is anticipated that this was a temporal anomaly, and that production will reach its pre-COVID-19 levels in the near future (Anon, 2020). However, trading conditions in the

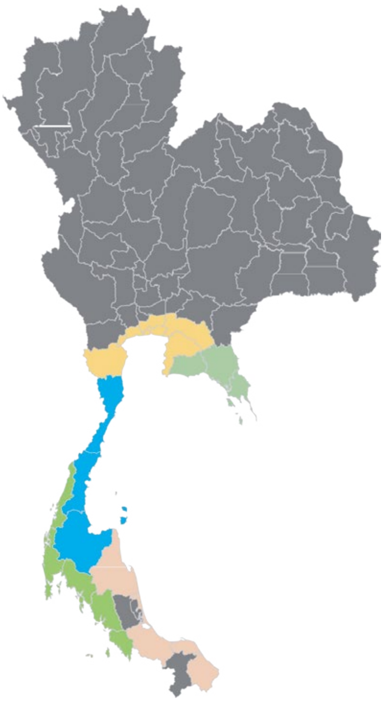
TABLE 2
Myanmar: Annual export of fisheries production, including mud crabs

Rank	Species	2019–2020		Rank	Species	2020–2021		Rank	Species	2021 Oct to 2022 March	
		Quantity	Value			Quantity	Value			Quantity	Value
1	Rohu	58 838	61	1	Ribbon fish	32 449	55	1	Fishmeal	39 314	40
2	Fishmeal	58 694	56	2	Fishmeal	53 061	53	2	Rohu	24 732	30
3	Squid	32 754	56	3	Rohu	43 990	46	3	Live mud crab	5 711	29
4	Ribbon fish	30 478	55	4	Live mud crab	10 762	46	4	Squid	9 793	23
5	Hilsa	13 769	39	5	Live eel	9 305	37	5	Hilsa	5 247	22
6	Soft-shell crab	2 745	32	6	Hilsa	10 600	32	6	Big eye croaker	14 804	16
7	Live mud crab	9 621	30	7	Soft-shell crab	3 096	32	7	Soft-shell crab	1 570	16
8	Trash fish	78 055	26	8	Big eye croker	20 974	28	8	Ribbon fish	13 633	15
9	Live eel	6 991	24	9	Squid	16 513	28	9	Platu/Indian mackerel/Short body mackerel	16 774	13
10	White/Silver po	4 406	23	10	Black pomfret	9 659	21	10	Live eel	3 062	12

Note: Soft-shell crabs are most likely of farm origin. Live mud crabs are of both capture and aquaculture origin.

Source: Fishery Statistics. Annual yearbooks. Ministry of Agriculture, Livestock and Irrigation, Department of Fisheries, Republic of the Union of Myanmar.

FIGURE 7
Thailand: Quantity and value of sea crabs farms by provinces, 2021



Units: tonnes/thousand bhat

Quantity	*Scylla*		*Portunus*		TOTAL	
	Value	Quantity	Value	Quantity	Value	Quantity
COASTAL ZONE 1	**60**	**19 345**	**-**	**-**	**60**	**19 345**
Trat	29	10 078	-	-	29	10 078
Chantaburi	28	8 147	-	-	28	8 147
Rayong	3	1 120	-	-	3	1 120
COASTAL ZONE 2	**574**	**182 095**	**3**	**607**	**577**	**182 702**
Chon Buri	-	-	-	-	-	-
Chachoengsao	7	3 098	-	-	7	3 098
Samut Prakhan	98	34 728	-	-	98	34 728
Bangkok	7	2 330	-	-	7	2 330
Samut Sakhon	357	100 000	0	68	357	100 068
Samut Songkhram	97	39 359	2	539	99	39 898
Phetchaburi	8	2 581	-	-	8	2 581
COASTAL ZONE 3	**114**	**37 324**	**0**	**107**	**114**	**37 431**
Prachuap Khiri Khan	22	8 163	0	107	22	8 270
Chumphon	7	2 272	-	-	7	2 272
Surat Thani	85	26 889	-	-	85	26 889
COASTAL ZONE 4	**1 779**	**574 341**	**0**	**67**	**1 779**	**574 408**
Nakhon si Thammarat	1 752	565 064	0	67	1 752	565 130
Songkhla	22	7 410	-	-	22	7 410
Pattani	5	1 868	-	-	5	1 868
Narathiwat	-	-	-	-	-	-
COASTAL ZONE 5	**952**	**241 668**	**-**	**-**	**952**	**241 668**
Ranong	848	211 989	-	-	848	211 989
Phangnga	17	4 996	-	-	17	4 996
Phuket	-	-	-	-	-	-
Krabi	19	4 276	-	-	19	4 276
Trang	13	4 097	-	-	13	4 097
Satun	56	16 310	-	-	56	16 310
Total	3 479	1 054 773	3	781	3 482	1 055 554

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: DoF. 2022. Fishery statistics of Thailand 2020. Report No. 4/2022. Bangkok, Department of Fisheries, Ministry of Agriculture and Cooperatives.

country, currently under a military regime, will likely impact the sector's performance in the short to medium term.

In Thailand, over 2 700 tonnes of the country's annual production are from its two most southern zones, 4 and 5 (Figure 7). Having once led the production of soft-shell crabs, Thailand suffered from overfishing of its wild stocks and in recent years has become dependent on imported live crabs from Myanmar to stock its farms. However, in the last few years Thailand has reported steady growth (see Figure 3), and hatchery production is now adding noticeably to the industry's development.

Mud crab production is the smallest form of coastal pond aquaculture in Bangladesh, representing just over 4 percent of the total, with over 13 000 tonnes produced in 2022 (Table 3). However, the collection of mud crab for both farming and direct export has resulted in significant overfishing in the country, with key indicators – including catch

TABLE 3
Bangladesh: Production of coastal pond aquaculture by species

Species	2020		2021		2022	
	Production	Share (%)	Production	Share (%)	Production	Share (%)
Rohu Shrimps/prawns*	127 601	45.14	131 509	45.24	137 021	45.54
Finfish**	142 513	50.42	146 908	50.52	150 476	50.01
Mud crabs	12 562	4.44	12 337	4.24	13 397	4.45
Total	282 676	100	290 754	100	300 894	100

Note: *Include both marine shrimps and freshwater prawn; **Mostly freshwater fish species.

Source: DoF. 2022. Yearbook of Fisheries Statistics of Bangladesh, 2021–22, Volume 39. Dhaka, Fisheries Resources Survey System, Department of Fisheries, Ministry of Fisheries and Livestock.

per unit effort and the average size of crabs collected – all showing significant decreases in recent years.

GLOBAL ISSUES IN MUD CRAB FARMING

The strong market demand for live mud crabs of all sizes, particularly from China has put significant pressure on mud crab fisheries globally. Mud crabs are widely distributed from the east coast of Africa, through Asia to the mid-Pacific, and from South Africa and Australia in the south to China and southern Japan to the north. This wide geographic distribution provides an opportunity for many countries to start mud crab farming, particularly those that have a history of exporting wild mud crabs. Some of the countries where mud crab farming has significant potential, but are yet to have any consistent mud crab aquaculture activities, are listed in Table 4.

Overfishing of wild mud crab populations has been recognized as a common issue in most countries with an active fishery sector. These typically exhibit decreasing catch per unit effort (CPUE) and a decreasing average size of crab, both for direct sale and for use as broodstock in hatcheries. An example of the potential effects of overfishing are seen for *S. olivacea*, comparing sizes of crabs between locations. In Bangladesh, finding female crabs over 200 g (carapace width approximately 100 mm) is becoming increasingly difficult, whilst in Western Australia – a resource that has so far not been fished – *S. olivacea* can grow to over 150 mm in shell width and weigh 1.5 kg (Government of Western Australia - Department of Fisheries, 2013). Also of concern is Sri Lanka, which had a reputation for supplying many of the very large mud crabs (>1 kg) for the international market, however, in recent years it is understood that the average size of crabs traded has reduced, with crabs greater than 1 kg becoming less common.

An issue that makes discussion of capture-based and hatchery-based production difficult is that no official statistics appear to distinguish between them. Indirect measures such as the number of hatcheries and nurseries, their production and pricing of crablets may provide some indication of the state of development of the hatchery-based sector in a country or region. Together with hatchery-based production is the need for juvenile pond production of mud crabs to farm small crabs for soft-shell crab farming (80–100 g) and for grow out to a larger size for hard-shell markets. These provide an additional economic opportunity for coastal aquaculture, supporting livelihoods and new employment opportunities.

TABLE 4
Regions and selected countries/states with a potential in mud crab aquaculture

Region	Country/State
Africa	Kenya
	Madagascar
	Mozambique
	Somalia
	South Africa
	United Republic of Tanzania
Middle East	Iran (Islamic Republic of)
	Oman
	Saudi Arabia
Asia/Indian Ocean	Maldives
	Mauritius
	Pakistan
	Réunion
	Sri Lanka
Southeast Asia	Brunei Darussalam
	Cambodia
	Timor-Leste
Pacific Islands	American Samoa
	Australia
	Fiji
	French Polynesia
	Guam
	Hawaii (USA)
	New Caledonia
	Palau
	Papua New Guinea
	Solomon Islands
	Vanuatu
	Samoa

Statistics are also difficult to interpret when it is known that there is significant cross-border trade, much of it informal, in both juvenile and adult crabs between countries. Official international transfer or translocation of stock is more likely to include professional health certification and appropriate veterinary control, however, informal trade increases inherent biosecurity risks.

MANAGEMENT AND SUSTAINABILITY

Regulation and licencing for both wild mud crab fisheries and aquaculture need careful management to optimize the economic benefits of both and can provide areas for conflict and concerns within the sector. For example, in Madagascar all export licences for mud crabs from its fishery were owned by overseas companies, much to the concern of locals who quite rightly expect to be able to share in the economic benefits of the fishery in an equitable and transparent manner (Gorez, 2021). In the Philippines there are official regulations in place, both to safeguard wild stocks and to indirectly support hatchery production. However, enforcement is sometimes an issue.

Small crablets are still being harvested from the wild fishery for use by farmers, negatively impacting the wild fishery and making hatchery development difficult. As the cost of wild stock in some locations is currently less than hatchery production, some farmers are preferentially taking the cheaper product, placing less value on other attributes of hatchery produced crablets. In Bangladesh, seasonal mud crab fishery closures have been ignored, as they have coincided with peak prices obtained from China during the Chinese New Year season.

In developing countries, where fisher numbers are high and enforcement resources limited, the management of sustainable mud crab fisheries has proved extremely difficult, with most country's mud crab fisheries overfished to varying degrees.

Two key areas to improve the sustainability of the mud crab farming sector moving forward is the transition of farming from capture-based to hatchery-based and for formulated feeds to become adopted, removing the dependence on trash fish and other unsustainable wild fisheries resources.

WASTE MANAGEMENT

Some losses during the transportation of live products, such as hard-shell mud crabs, are unavoidable; however, much can be done to reduce waste. The adoption of best practice packing techniques has been shown to dramatically reduce losses of live mud crabs. Despite this, in some countries they are not being used. Training and sharing of knowledge are simple strategies to reduce waste in this area.

The soft-shell crab (SSC) sector experiences higher waste compared to the hard-shell sector, which is related to a variety of factors including storage of fished product, transport, grading and farming practices. Waste is evident at all stages of the value chain, significantly impacting the wild fishery, where a greater number of small crabs need to be collected to stock farms due to high losses along the value chain. Within the SSC sector, on-farm losses vary from lows of 10 percent to highs of over 50 percent. These losses are related to poor storage of harvested crabs, substandard packing and transportation, unnecessary damage to stock from aggressive grading by traders and dealers, feeds, feed frequency and water quality issues. Adoption of improved techniques across the value chain can drive major increases in average survival rates, thereby positively impacting the demand on wild fisheries.

FUTURE OPPORTUNITIES FOR MUD CRAB FARMING DEVELOPMENT

Mud crab farming is possible in at least 29 other countries than those currently practising it (see Table 4) considering the distribution of the genus *Scylla.* To support such development, inter-regional technology transfer will be required. Countries including various Pacific Island Countries and Territories (PICTs), Sri Lanka and coastal East African states are amongst the most promising candidates for such activity and investment.

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Mud crab production in Viet Nam

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ABSTRACT
Mud crab breeding and culture in Viet Nam were initiated during the late 1990s. There are only two *Scylla* species, *Scylla paramamosain* and *Scylla olivacea,* distributed in Viet Nam specifically in the Mekong Delta. *S. paramamosain* is the dominant species (> 95 percent) and is an economically important commodity in Viet Nam. Wild crablets and other marketable size crabs have been exploited in all fishing areas. In the past, mud crab farming relied mainly on the collection of the wild seeds. Due to the rapid development of hatchery technology, a more reliable and sustainable alternative for the sourcing of seedstocks now exists.

Mud crabs are farmed using various culture systems including the grow-out of juveniles to marketable size in ponds, fattening of lean crabs, and soft-shell crab production. However, there are several issues that need to be addressed for the future growth of the mud crab industry in Viet Nam. These include alternatives to antibiotics to improve hatchery efficiency, lack of a formulated feed for crab larvae and low-cost formulated diet for growing the crabs in ponds, cannibalism, lack of market product standard. Once these problems are addressed the risks associated with mud crab culture will be reduced significantly, and mud crab production may become more profitable.

INTRODUCTION
Mud crabs are an important crustacean commodity and one of the main sources of income for farmers in the coastal areas of Viet Nam, particularly the Mekong Delta. Farmers are interested in mud crabs due to their high economic value and potential as an export commodity. Mud crabs were either directly exploited from natural resources or cultured using wild seeds before the 1990s. The breeding techniques developed in late 1990s and early 2000 have made hatchery-reared seeds available and this accelerated the advancement and expansion of mud crab aquaculture. The number of mud crab hatcheries have significantly increased, particularly in the Mekong Delta. A preliminary survey showed that there are up to 600 hatcheries operating (mostly seasonal) in the Mekong Delta, mainly in Bạc Liêu and Cà Mau, producing up to 1.5 billion crablets each year. This is sufficient to satisfy the demand for seeds for many types of mud crab culture systems in the Mekong Delta. In recent years, interest in mud crab farming has increased due to growing domestic and international markets. However, there are still some constraints that need to be addressed to make the industry more sustainable.

Species of mud crabs
Mud crab aquaculture has been practised for many years in Southeast Asia, primarily involving fattening of crabs from the wild. Based on the samples collected from South Viet Nam, Serene (1952) categorized four species, namely *Scylla oceanica, Scylla tranquebarica, Scylla serrata* and *Scylla crassimana*. Keenan (1999) reclassified the species to *S. serrata* (Forsskål, 1775), *S. tranquebarica* (Fabricius, 1798), *S. olivacea*

(Herbst, 1796) and *S. paramamosain* (Estampador, 1949) based on morphological and genetic features. Following the classification by Keenan (1999), mud crabs obtained from central Viet Nam consisted of *S. paramamosain, S. olivacea* and *S. tranquebarica*, where *S. paramamosain* accounted for more than 90 percent of over 3 000 crab samples (Thach, 2001). However, according to recent taxonomic revisions, *S. paramamosain* and *S. olivacea* are the target of large local fisheries in Viet Nam. *S. paramamosain* is the most prevalent and preferred species for culture in Mekong Delta (Keenan, 1999; Macintosh *et al*., 2002; Hai, 2017). Mud crabs are important source of income and food for many coastal communities and are considered a luxury item appreciated for their taste and texture, as well as their low-fat, high-protein, vitamin and mineral content (Petersen *et al*., 2013; 2016).

Wild stock status

Mud crabs occur in most central coastal provinces of Viet Nam (Binh Dinh, Phu Yen, Khanh Hoa) and the Mekong Delta (Bến Tre, Trà Vinh Bạc Liêu, Sóc Trăng and Cà Mau). Artisanal fisheries for mud crabs are an important source of income in coastal communities of the Mekong Delta. *S. paramamosain* was found to be the dominant mud crab species within an estuarine system, comprising over 96.8 percent of crab fishery landings while *S. olivacea* accounts for 3.2 percent. Mature females were observed throughout the year, with a peak occurrence from September to October (Le Vay *et al*., 2001).

In most Southeast Asian countries, mud crabs have traditionally been exploited allowing capture of all sizes including crablets for pond culture, adults and subadults for fattening, juveniles for soft-shell crab production or for food (Le Vay *et al*., 2001). Mud crab fisheries employ gears such as gill nets, trawls and traps, while in some areas handpicking in the intertidal is common, sometimes with the use of crabbing hooks. The most frequently used gears are baited traps or pots.

Varying levels of overfishing or reduced landings (decrease in size and abundance) have been reported throughout Southeast Asia due to the demand of crabs in national and international markets. Mud crabs are closely associated with mangrove habitats; thus populations may be subjected to the combined pressure of overexploitation and habitat loss. Total sustainable catch from the wild stock should be estimated by assessing the size of the mud crab and its yearly increment. Catching of crabs during spawning season and berried crabs throughout the season must be banned to allow recruitment of wild stock.

INDUSTRY STATUS

Production status

Mud crab resources are abundant and distributed throughout the seas, estuaries and bays. Large quantities of mud crabs are produced and handled every year, with Viet Nam among the top crab producers in the world (Table 1). In recent years, due to increased domestic consumption and export demand along with natural exploitation, mud crab farming developed in the coastal regions in many of the southern and northern provinces, especially in the Mekong Delta region, where the productivity of crab farming reached over 1 000 kg/ha annually (DoF, 2019). According to the Viet Nam Association of Seafood Exporters and Producers (VASEP), the export of crabs and other crustaceans grew by 3.9 percent, reaching a total value of USD 189 million in 2021, thus contributing a 6 percent market share in the total seafood export value of USD 3.4 billion in 2021. Moreover, the total export value of crab in Viet Nam amounted to approximately USD 111 million up to July 2022.

TABLE 1
Crab production in Viet Nam and other countries (t)

Ranking	Country	2016	2017	2018	2019	2020
1	Indonesia	835.2	1 276.4	1 286.5	875.0	987.0
2	China	1 091.2	947.3	1 056.2	673.0	765.0
3	Philippines	307.1	308.1	309.2	222.1	213.0
4	Viet Nam	322.1	255.2	378.3	102.1	112.0
5	Thailand	190.4	124.0	124.5	154.3	102.0
6	India	112.1	87.3	98.2	43.0	44.0
7	Mexico	119.0	160.3	167.2	86.0	90.1
8	Venezuela (Bolivarian Republic of)	132.9	148.3	156.0	32.0	43.0
9	Other countries	387.5	729.9	654.2	312.0	342.0
Total		**3 497.5**	**4 036.8**	**3 174.1**	**2 499.5**	**2 698.1**

Source: FAO. 2024. Fishery and Aquaculture Statistics – Yearbook 2021. FAO Yearbook of Fishery and Aquaculture Statistics. Rome. https://doi.org/10.4060/cc9523en

From 2016 to 2020, the Mekong Delta region was considered the "crab granary" of Viet Nam with a production accounting for 73 percent of the country's total crab production. In 2020, the whole region reached a production of 68 000 tonnes, an increase of nearly 8.2 percent of total output within 5 years. However, the average productivity of mud crabs is still low in integrated extensive farming systems (shrimp–mud crab–mangrove or shrimp–mud crab–rice) due to low stocking densities of 0.1–0.2 ind./m^2. Kiên Giang, Cà Mau and Bạc Liêu provinces have the highest production, accounting for 80 percent of the entire Mekong Delta's production (Table 2).

TABLE 2
Mud crab production in some provinces in the Mekong Delta (t)

Province	2016	2017	2018	2019	2020
Kiên Giang	17.7	16.7	17.3	18.7	20.3
Cà Mau	17.4	20.1	22.0	22.2	24.0
Bạc Liêu	14.6	15.8	14.7	12.7	10.2
Trà Vinh	8.0	8.1	7.4	7.9	8.1
Bến Tre	4.8	4.8	4.9	4.7	5.1
Sóc Trăng	0.2	0.2	0.1	0.1	0.2
Total	**62.7**	**65.7**	**66.4**	**66.3**	**67.9**

Source: Danh, L.N. 2023. Economic analysis of the mud crab (*Scylla paramamosain*) supply chain in the Mekong Delta. PhD dissertation in Agriculture Economic. Can Tho University, 165pp (In Vietnamese).

Farming areas

In addition to wild stock harvest, mud crabs have been farmed in many coastal provinces in Viet Nam, including Quang Ninh, Hai Phong, Thanh Hoa, Ninh Binh, Nghe An, Thua Thien–Hue, Ba Ria–Vung Tau, Can Gio (Ho Chi Minh City), and the Mekong Delta using hatchery-reared crablets (Figure 1). Different farming systems have been applied such as grow-out in the improved extensive shrimp ponds, integrated shrimp–crab–mangrove, integrated shrimp–crab–rice, fattening in tanks or cages, and soft-shell crab production (Phuong and Hai, 2004). Various methods for crab culture have been developed to suit the diverse conditions in different provinces. Farming areas have increased in most of the provinces of the Mekong Delta since 2016 (Table 3).

FIGURE 1
Major mud crab farming areas in Viet Nam and hatchery locations

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

TABLE 3
Mud crab farming areas in the Mekong Delta from 2016 to 2020 (ha)

Province	2016	2017	2018	2019	2020
Cà Mau	273.2	271.2	273.5	276.4	277.0
Kiên Giang	58.7	64.3	64.3	65.5	73.2
Bạc Liêu	111.9	111.2	98.3	87.2	73.0
Bến Tre	26.8	27.0	27.2	27.8	28.6
Trà Vinh	10.5	11.0	11.3	12.8	13.0
Sóc Trăng	0.4	0.4	0.1	0.1	0.2
Total	**481.5**	**485.1**	**474.7**	**469.8**	**465.0**

Source: National Agriculture Extension Center. Retrieved from https://khuyennongvn.gov.vn/ky-thuat-thuy-san (25 August 2023)

In 2016, the farming area in the Mekong Delta increased by 50 percent compared to 2012, then the farming area began to stabilize from 2016 to 2020. In 2020, the farming areas in the Mekong Delta reached nearly to 465 000 ha, mainly located in the provinces of Cà Mau, Kiên Giang, and Bạc Liêu. Cà Mau province has 277 000 ha and leads in farm area followed by Kiên Giang (73 000 ha) and Bạc Liêu (72 962 ha) (Figure 2). Due to high profitability of integrated crab farming, people have heavily invested in crab farming and expanded the areas.

Hatcheries, nurseries and grow-out ponds

Mud crab breeding and culture in Viet Nam were initiated during the late 1990s. Commercial hatchery production of crab seeds has been developed for several years in the Mekong Delta. Shrimp hatcheries were converted to produce mud crab seeds to operate full-cycle or alternately produce crab and shrimp based on demand. Recently, there

FIGURE 2
Culture areas and production of mud crabs in Mekong Delta in 2021 (t)

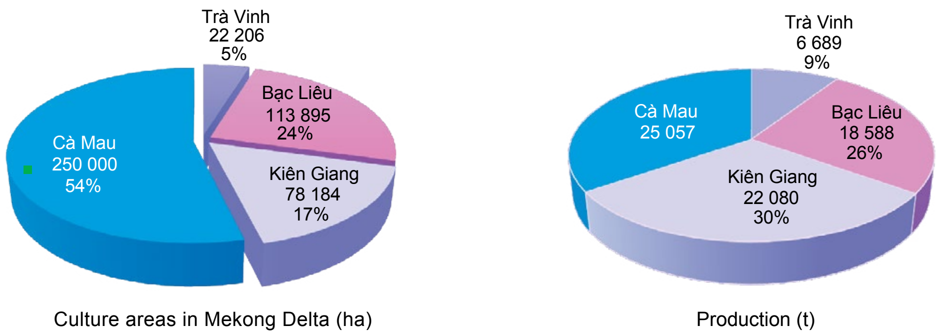

TABLE 4
Number of mud crab hatcheries and production outputs in selected Mekong Delta provinces

Province	2014	2015	2016	2021
Bạc Liêu				
Number of hatcheries	40	40	40	–
Production (million)	–	–	500	–
Cà Mau				
Number of hatcheries	372	394	438	523
Production (million)	618.4	802.6	935.8	1 000
Kiên Giang				
Number of hatcheries	136	136	136	–
Production (million)	167.2	172.4	157.5	–
Total no. of hatcheries	**548**	**570**	**614**	–

Source: Hai, T.N., Vinh, P.Q. & Viet, L.Q. 2018. Technical and financical aspects of mud crab hatcheries in the Mekong Delta. Can Tho University. *Journal of Science*, (2018)(1): 169–175.

Ngoan, L.H. 2023. Analysis of technical aspects and financial efficiency of the seed production of mud crab hatcheries in Ca Mau. Master thesis in Aquaculture, Can Tho University. 72pp.

are 523 mud crab hatcheries in Cà Mau province (Table 4), some operating seasonally. Each of these hatcheries can produce 0.7–10 million crablets annually, with survival rates of 5–11 percent. Nurseries are operated for the culture of megalopa and crab instar to juvenile stage in lined ponds or net cages within 2–3 weeks before stocking in grow-out ponds. Mud crabs are grown in extensive shrimp farms and mangrove forests. Recently, indoor crab culture has been developed for soft-shell crab production.

AQUACULTURE PRACTICES

Broodstock management

In Viet Nam, crab spawning occurs throughout the year. Hatcheries rely on the collection of ovigerous (egg-bearing) females from the wild or ponds. Wild broodstock showed better performance than those obtained from ponds (Table 5). Because females store viable spermatophores for months after mating, mature females can also be brought into maturation tanks and spawn naturally, although spawning can be accelerated by eyestalk ablation. Broodstock are fed fresh foods such as fish, blood cockle, squid and clam. Broodstock culture is also an economically important activity in Cà Mau province where high-quality broodstock are supplied to hatcheries in the Mekong Delta.

TABLE 5
Comparison of reproductive characteristics between wild and farmed crabs

Reproductive parameters	Wild crabs	Farmed crabs
Spawning time (day)	19.5±7.9	29.0±7.7
Spawning percentage (%)	85.7±10.3	77.5±5.2
Fertilization percentage (%)	88.1±3.53	78.2±2.48
Hatching (%)	74.9±2.84	64.2±2.08
Fecundity (× 1 000 larvae/female)	1 768±476	1,236±369
Survival from zoeae1 to crablet (C1) (%)	11.3±2.07	9.70±1.41

Larval rearing

Crab larval rearing has been adopted from shrimp larviculture, where the feeding of rotifers at the first larval stage, a practice more common with finfish larval rearing, has been eliminated. Feeding of early "teardrop" or "umbrella" stage *Artemia* to zoea 1 is also possible where *Artemia* of appropriate nutritional quality is available (Nghia *et al*., 2007). Small crab larvae should not be fed with large prey. Relatively high mortality can occur during larval rearing of *Scylla* spp., and tanks (composite and cement) with darker background are recommended to reduce stress. Rotifers and *Artemia* are used for convenience in aquaculture, with rotifers being good live food for early zoea stages since they are small and slow moving.

Several issues still must be addressed in larval rearing. Nutritional problems affect the survival and growth of larvae. Cannibalism can be a problem at high densities. Asynchronous moulting may result in cannibalism. The clawed megalopae prey on their conspecific which are still at zoea 4 and 5. Likewise, moult death syndrome (MDS) is sometimes observed. This occurs when zoea 5 are unable to free themselves from their old exoskeleton and eventually die. The exact cause of this syndrome is not fully understood, but inadequate nutrition is often suspected.

Larval nutrition studies have resulted in the development of particulate larval diets, but more research is needed. Live feeds are not nutritionally sufficient and are routinely fortified either with algae or commercial booster formulations. Commercial pelleted larval diets are preferred because of the expense and labour involved in growing algae and other live feeds. Initial trials using microbound diets are promising although there is still a long way to go before these can be produced and used commercially. Artificial diets are accepted by the zoeae, which is already an achievement considering that size and quality must be manipulated to avoid fouling of the water.

Nursery phase

Nursery production at high density has emerged as an important intermediate phase between hatchery (production of megalopae and crab instars) and grow-out phase at low density. The megalopae are transported in water. However, benthic crab instars are more robust and can be shipped to farms in damp packing materials only. Conditioning in the nursery is also beneficial in cases where juveniles are reared for restocking in the wild. Mortalities of 50 percent or more are still reported during the nursery phase mostly due to cannibalism. Within a few weeks of stocking, the crab juveniles prefer a mixed diet of pellets and krill. Mortality is reduced by providing shelters or artificial substrates in the nursery.

Grow-out culture for hard-shell crabs

Aquaculture of mud crabs *Scylla* spp. was originally based on the collection and extensive culture of juveniles in earthen ponds. This farming system is commonly practised in the coastal areas of Viet Nam (Figure 3). While crabs are generally harvested for the hard-shell live market, production of soft-shell crabs is becoming more popular. Mud crab females with mature ovaries also sell at premium price, presenting an opportunity for mono sex culture.

Mud crabs are grown in earthen ponds, with perimeter fences to prevent the crabs from escaping. They are known to burrow in the wild, but this behaviour has not been apparent when crabs are reared in ponds. Soon after stocking, the existing natural food in the pond is sufficient for the crablets. Their diet is eventually supplemented with low-cost fishery products and wastes. Selective harvesting is done using traps when some crabs attain market size.

Polyculture is possible with mud crabs and other species under certain circumstances. However, polyculture of carnivorous fish and crabs is not recommended. Depending on the timing of the introduction of each commodity and the relative size and growth rate of the fish fry, the fish can eat the newly moulted juvenile crabs or vice versa. Species cultured together with mud crabs are usually tiger prawn (*Penaeus monodon*), white leg shrimp (*Litopenaeus vannamei*), mullet, tilapia, oyster, clam and seaweeds (such as *Gracilaria tenuistipitata*) (Hai, 2017). Polyculture of fish or shellfish and crabs

FIGURE 3
Mud crab culture in extensive shrimp (a) and mangrove-shrimp farms (b) in the Mekong Delta

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may have the advantage of lower disease occurrence because they do not have common type of diseases.

Soft-shell crab production

Large mud crab juveniles up to 60 g are induced to moult using multiple limb autotomy (removing all claws and legs, leaving only the paddle-like legs), stocked at high density in earthen ponds and fed with fish. After about one and a half weeks, the pond is drained and the pre-moult crabs with well-developed limb buds are transferred to floating baskets for closer monitoring. Crabs are harvested as soon as they moult. Confining crabs in this manner allows them to be maintained and checked efficiently at higher density than the typical communal crab culture. However, feeding and water management should be appropriately done to avoid stress to the crabs, particularly while they undergo moulting (Dat, 1999).

Recently, the mud crab farming model in plastic boxes using Recirculating Aquaculture System (RAS) has been introduced in Viet Nam, bringing in high economic efficiency (Figure 4). RAS system is installed with oxygen aerators. The leftover feeds and other wastes are filtered before going to a probiotic tank and UV-based sterilization system. Microorganisms living on *Kaldnes* media serve as coral to filter leftover feeds and other crab waste, resulting in a clean environment. The crabs are reared separately in perforated plastic boxes to prevent cannibalism and facilitate management. Some of the problems in soft-shell crab production are the lack of supply of small-sized crabs, and that the transfer of pathogens from one crab to another is difficult to prevent since each box is connected to the same system.

FIGURE 4
Soft-shell crab production in plastic boxes

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HEALTH AND DISEASE MANAGEMENT

In some cases, mass mortality is largely attributed to bacterial infection. For this reason, there has been too much reliance on antibiotics such as oxytetracycline (OTC) to manage the risks of batch rearing failures. Fungi have also caused problems in crab hatcheries, requiring a different treatment, but widespread use of antimicrobials in this manner is not recommended and it is often illegal in many countries. The major problem in the use of antimicrobials is not the residue that might persist in the larvae beyond the hatchery phase; the greatest threat is that unregulated drug use leads not only to antimicrobial-resistant bacteria in the hatchery but also to the occurrence of antimicrobial resistance in other animals or even in humans.

Virus

White Spot Syndrome Virus (WSSV) is considered as one of the most dangerous viruses so far observed in crustaceans. WSSV is characterized by rapid disease onset that may infect up to 90 percent of the crab stocks within 2 to 7 days. WSSV can infect the crabs by vertical transmission from wild broodstock or by horizontal transmission in monoculture of mud crabs, from feeds, and co-habitation with WSSV-infected shrimps. Hence, it is extremely important to inform the shrimp farmers regarding the mode of transmission of WSSV, especially in the polyculture of crabs and shrimps.

Bacteria

Pathogenic *Vibrio* species have been implicated as one of the major causes of disease in aquatic organisms. Zoeae are very sensitive to luminous bacteria, with *V. harveyi* being a major contributor to disease along with several *Vibrio* species, such as *V. alginolyticus* and *V. parahaemolyticus*, which have been isolated and tested for their pathogenicity to zoea. *Vibrio* spp. are also found to be involved in shell disease associated with captive crab broodstock as a result of a combination of fouling organisms and chitinoclastic bacteria (Figure 5).

FIGURE 5
Shell disease caused by *Vibrio* spp. in mud crab

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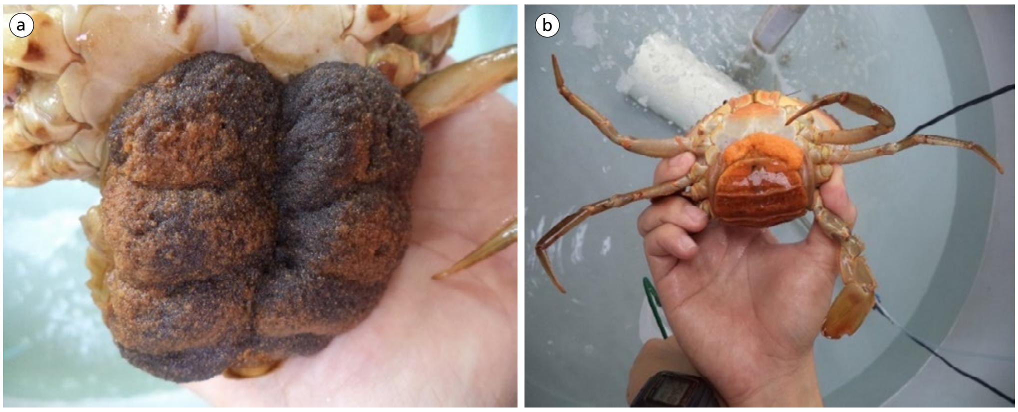
Fungi

Several fungi including *Lagenidium scyllae*, *Haliphthoros philippinicus* and *Atkinsiella fluminensis* have been frequently observed to infect the eggs, larvae and ovaries of mud crabs. Fungal infection can more easily penetrate unfertilized eggs than fertilized eggs. Larvae suffer from devastating infections by the non-host-specific pathogen *Lagenidium* sp. resulting in high mortalities. Loss of eggs in berried females occurs during the incubation period, resulting in partial hatching or complete loss of egg mass (Figure 6). *Haliphthoros* sp. causes the abortion or resorption of eggs. *Fusarium* sp.,

FIGURE 6
Mud crab eggs infected with fungus (a) that may cause egg loss in berried female (b)



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Lagenidium sp. and *Sirolpidium* sp. usually infect the damaged and dead tissues caused by lesion or mycelia growth, making it difficult for the larvae to swim. Mycosis causes secondary infection in crab larvae and leads to mortalities. Bath treatment using formalin and fungicides were found to be effective in minimizing the infection.

Parasites

Protozoans such as stalked peritrich ciliates *Epistylis* sp., *Zoothamnium* sp. and suctorian ciliates, such as *Acineta* sp. and *Lagenophry* sp., have been observed to attach to the shell and gills of crabs (Figure 7). The ciliates *Zoothamnium* and *Lagenidium* were observed to attach to eggs of berried females sourced from brackish-water areas (Figure 8). Peritrichs are usually associated with water that is high in organic matter and other nutrients. Apart from suctorians that feed on other protozoans, most peritrichs feed primarily on bacteria. Bacteria thrive in water with high organic matter and is probably the reason why peritrichs are also common in such conditions. In addition, settling larvae of barnacles are often found attached as parasites in the gills, especially in females.

FIGURE 7
Mud crab eggs colonized by *Zoothamnium alrasheidi*

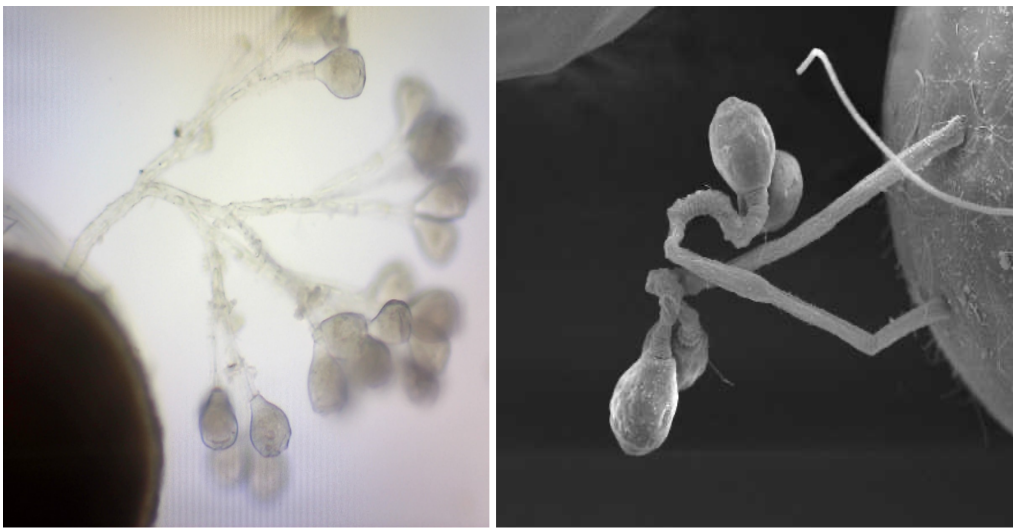

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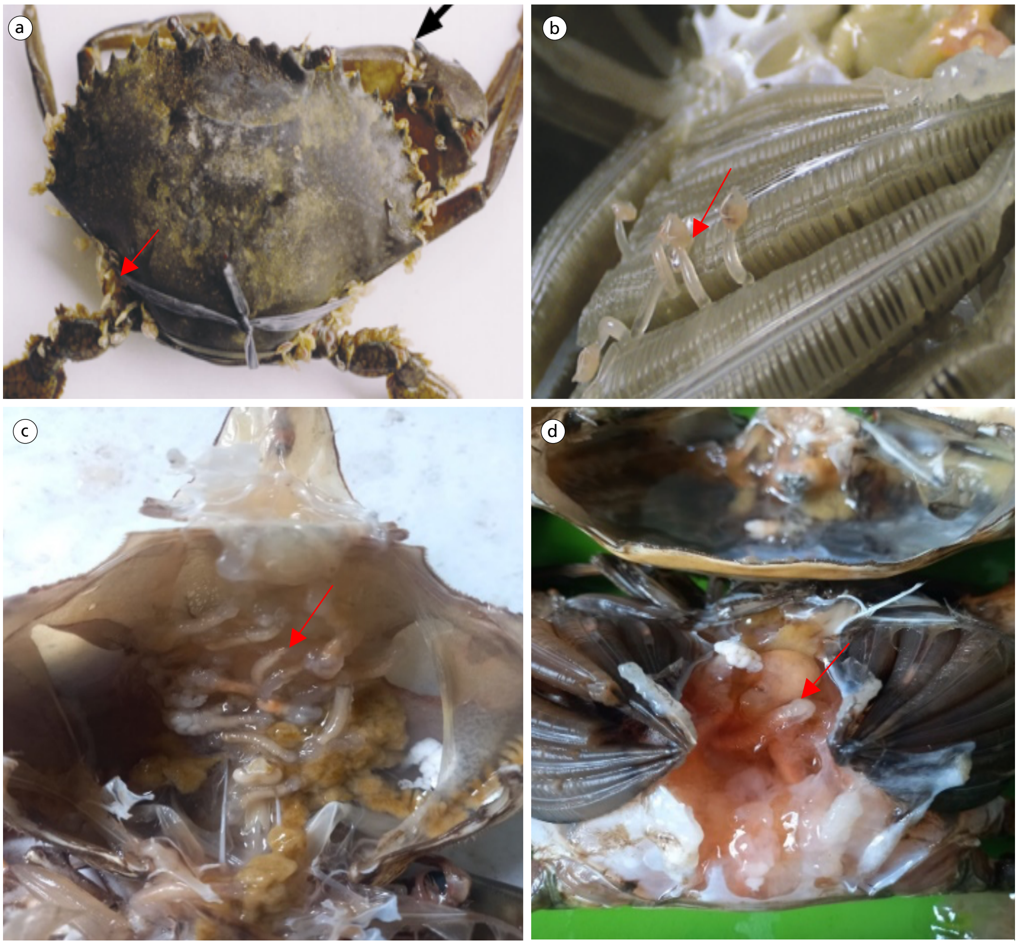
FIGURE 8
***Octalasmis* sp. on exoskeleton (a); *Octalasmis* sp. on gills (b); *Sacculina* sp. attached to the crab's abdomen (c, d)**



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Abnormalities/deformities

In the hatchery, delay or failure to moult from zoea 5 to megalopa leads to several negative impacts such as abnormal swimming behaviour and inability to consume feed. Delay or failure to moult is believed to be due to unsuitable environmental conditions in the tank and deficiency of nutrients given to the larvae. In grow-out culture, newly moulted crabs are sometimes attacked by hard-shelled crabs resulting in missing limbs or deformities such as chitinolytic spots on the abdominal flap, injuries on the exoskeleton, broken claws, among others.

Albinism

Many kinds of albinism have been observed. Partial albinism or discoloration either on limbs or carapace has been found in crabs cultured in ponds.

Treatment of diseases

Treatment of diseases in mud crabs is quite limited. Probiotics have been used in crab larviculture to overcome bacterial disease. Water quality, larval stage index, percentage of metamorphosis to megalopa stage, as well as yellow and green *Vibrio* colony counts are also monitored during the utilization of probiotics. It is recommended that further investigation into the larval rearing of mud crabs using probiotics be done, as it can be applied to produce consistent quantity of mud crab seeds at commercial level. A recent study on the use of ozone treatment during egg incubation and larval rearing revealed a promising alternative to control bacterial infection and parasite infestation in the hatchery (Bac and Ut, 2020a; 2020b).

RESEARCH AND INNOVATIONS

One of the main challenges of mud crab hatchery operation is the lack of appropriate larval diets. Current hatchery production relies heavily on live foods such as rotifers and *Artemia* nauplii. Furthermore, live food production requires skilled manpower, more facilities, and maintenance of microalgae culture as food for the live prey. To overcome the nutritional deficiency in rotifers and *Artemia*, many hatchery operators or technicians enrich the live food to enhance the levels of highly unsaturated fatty acids (HUFA), particularly docosahexaenoic acid (22:6n-3, DHA) and eicosapentaenoic acid (20:5n-3, EPA), prior to feeding to crab larvae. The recent employment of umbrella stage *Artemia* instead of *Artemia* instar 1 or 2 to feed zoea 1 has resulted to improved survival of the larvae. The application of this in several hatcheries has made the industry more successful in the Mekong Delta.

Despite the current technology, mass mortality during larval metamorphosis, especially from zoea 2, still occurs. Mortality may be caused by *Vibriosis*, nutritional deficiency and poor water quality. Alternative means to improve the non-specific immune response of crab to prevent outbreak of diseases have been considered, with one such feasible option being the use of dietary supplements and herbal extracts in crab hatcheries and farms.

Prebiotics and probiotics have been applied for better health conditions of aquatic animals. Recent studies showed that probiotics can also improve growth and digestion, enhance immune responses, and control diseases in mud crab larvae (Khoa *et al.*, 2018).

Recently, Khoa *et al.* (2023) applied light-emitting diodes in mud crab larviculture. It was reported that certain spectra of light in clear water systems have been shown to affect crab growth by increasing the activity or moulting rates. The photoperiod used may also affect appetite, food intake, and feed conversion ratio in crabs, thus affecting their growth and survival. Light intensity and photoperiod may influence most physiological functions and endocrine control or may increase cannibalism.

MARKET INFORMATION

According to the VASEP, exports of crab to major markets increased in 2022. Viet Nam exported mud crabs to the United States of America valued at around USD 38 million, making the United States of America the leading importer of mud crab. During this period, the total export value of crabs in Viet Nam amounted to approximately USD 111 million. The top markets of crabs include China, United States of America, Japan, and France, accounting for over 92 percent of Viet Nam's total export value. As of 15 July 2022, Viet Nam obtained over USD 38 million through the export of crabs to the United States of America, a 27 percent increase from the same period last year. Viet Nam's sales of crabs to the United States of America grew in the second quarter of 2022. The market of the United States of America has totally opened, leading to a high consumption of crabs. China is the second biggest market, with USD 37 million from sales reported by 15 July 2022, a 76 percent increase from the same period last year. Crab exports continued to grow in 2022, although more slowly. As for the Japanese market, over USD 24 million was recorded in sales, a 51 percent increase from the same period last year. Crab exports reached nearly USD 15 million in the second quarter, up by 64 percent from the same period last year. Japan is still the biggest market for crabs among the Comprehensive and Progressive Agreement for Tran-sPacific Partnership (CPTPP) members. Viet Nam's crab exports to European Union countries increased sharply in 2022. France continued to be the largest market for crabs, with over USD 3 million recorded as of 15 July 2022, a 60 percent increase on the prior year

(Vietnam Fisheries Magazine, 2022). Likewise, exports are skyrocketing in Belgium and the Netherlands.

Product prices

The export price of crabs from Viet Nam has seen a steady increase over the last five years. In 2016, the price was USD 12.57/kg, and by 2020 it had increased to USD 15.52/kg. This represents an increase of USD 2.95/kg, or 23.5 percent. The highest price was seen in 2019, when the export price was USD 20.82/kg. Based on this trend, it is predicted that the export price of crab from Viet Nam will be approximately USD 18.45/kg in 2023 and USD 21.38/kg in 2024. According to Viet Nam Fisheries Magazine (2022), Viet Nam sold 3 166 tonnes of crabs in 2019 that were categorised as:

- Fresh or chilled, dried, salted, smoked or in brine (HS code 0306Xe).
- Prepared or preserved (excluding smoked) (HS code 160510).

MAJOR ISSUES AND CHALLENGES

Improving hatchery efficiency

Alternatives to antibiotics in larviculture is a major priority. While acceptable levels of survival to metamorphosis is obtained in hatcheries, bolstering these figures by using antibiotics to control the bacterial flora is not acceptable. More work needs to be done to adopt other alternatives such as ozonation or use of specific probiotics. Development of appropriate artificial diets for mud crab larvae is worth examining. This helps reduce the use of live feeds that may eliminate a major source of microbial contamination, via mass culture and enrichment of live food.

Feed development

Nutrition, particularly protein and lipids, play an essential role in obtaining good quality ovigerous female crabs. Information on lipid requirement is crucial in the development of artificial diets to ensure that the nutrients necessary for good growth and maturation in crustaceans are included. At present, crab hatcheries still rely on the use of natural food such as fish, clam, squid and shrimps, since these provide high protein, essential fatty acids (EFA), and other micronutrients, which help hasten growth and induce maturation of broodstock.

Formulated feeds developed for shrimp can be used successfully in mud crab larviculture. These are used in addition to live feeds but their usefulness depends on the particle size. Some feeds may need to be screened to obtain the appropriate size for a particular stage of larvae. It has been reported that 50–70 percent of live feed can be replaced with formulated larval feeds. While significant work has been undertaken on the use of microbound diets for crab larvae, there is no commercially available feeds designed for crabs that have been developed. Some operators utilize minced bivalve or fish as supplementary feeds for megalopae. However, such feeds can lead to water quality issues, hence the need for the quality of water to be monitored closely. Alternatives to trash fish is also becoming a research priority because low-cost feed is emerging as the next bottleneck in the expansion of the crab farming industry.

Addressing aggression and cannibalism

Cannibalism remains a major obstacle to improve the productivity of crabs in the grow-out phase. Studies showed that mortality from cannibalism is reduced by adding shelters and lowering the stocking density, thereby reducing encounters between individuals. Understanding the social behaviour of crabs in ponds is likely one of the keys to reducing cannibalism. Likewise, the feasibility of crab production using individual containers to reduce cannibalism needs to be determined. This is based on the experience gained from individual rearing of crabs in feeding experiments.

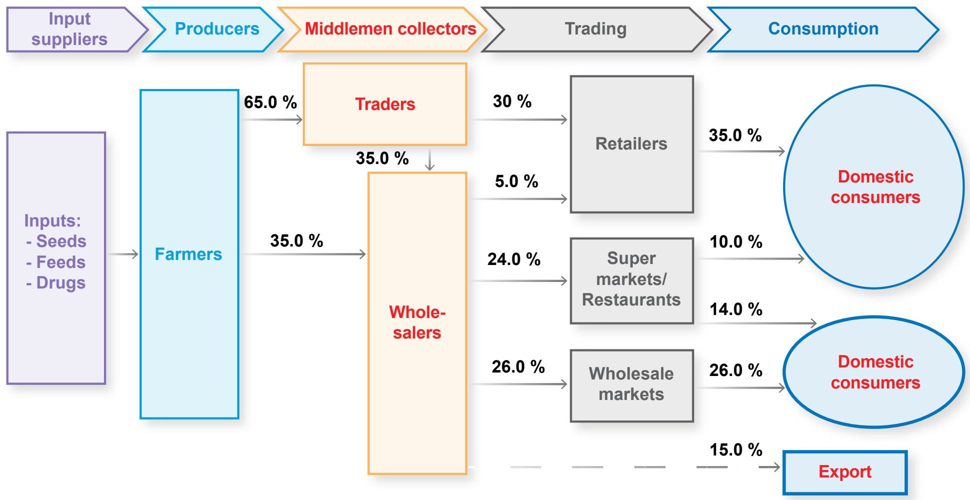
Culture in individual containers

Individual rearing of crabs is an obvious solution to the mortality and injury that occur when crabs are reared communally. Crab mortality is almost absent when they are raised in a properly maintained system, albeit with a slower growth rate than those in ponds. Operating the RAS at maximum efficiency means there is little margin for error. The recirculation and remediation systems in place must be determined based on the designed output of the facility. However, large RAS farm requires enormous numbers of individual containers, which need to be cleaned and maintained, as well as including a more expensive and complicated water recirculation system.

Market and product standardization

There is a lack of information on the total volume of mud crab-based products and their percentage sold in the domestic market. For support programmes and policy makers to recognize the contribution of mud crab farming, detailed information on production value chain and market values are required (Figure 9). Moreover, mud crab products in particular markets need to be standardized.

FIGURE 9
Supply chain of mud crab in the Mekong Delta



Source: **Hien, H.V.** 2022. Supply chain of some potential species in the Mekong Delta. Survey Report, College of Aquaculture and Fisheries, Can Tho University (CAF-CTU), Viet Nam. 54pp.

CONCLUSION

There are many issues concerning the sustainability of mud crab aquaculture. Major issues include deforestation of mangroves to construct shrimp ponds, pollutants, intensification of culture system, diseases, food safety, certification schemes, and trade. Government and development organizations should develop more programmes to disseminate technical knowledge on mud crab production to stakeholders, which may help them overcome constraints. Likewise, the government should focus on establishing enough hatcheries to ensure the supply of high quality crablets. The cost-effectiveness of pelleted diets for mud crab grow-out farming requires attention. Improved practices and reduced fluctuations in prices are likely to reduce the overall risk of the crab industry. Such improvements would lead to higher profitability considering that demand for export is high.

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Potential and challenges of mud crab (*Scylla* spp.) cultivation in Indonesia

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ABSTRACT
Mud crabs are one of the leading fishery commodities in Indonesia. There are four species of mud crabs in the world, namely *Scylla serrata*, *Scylla paramamosain*, *Scylla tranquebarica*, and *Scylla olivacea*, all of which are found in Indonesia. The market demand for mud crabs continues to increase each year. However, a significant portion of this demand is being met through unregulated wild catches, thereby further threatening the sustainability of the mud crab industry. The Ministry of Maritime Affairs and Fisheries of the Republic of Indonesia (Kementerian Kelautan dan Perikanan Republik Indonesia [KKP]) has reported that mud crab fisheries in almost all regions of Indonesia are fully exploited or even overexploited. The situation forced the KKP to issue a regulation to restrict mud crab capture and promote mud crab aquaculture.

In Indonesia, mud crab aquaculture started in the 1900s but still facing several important challenges. One of the main problems is the inability to produce seed from hatcheries. Current mud crab farmers would like to increase their production but the seed supply provided from local hatcheries is not enough. The Government operates two hatcheries and continuously provides seed to farmers. The private sector is reluctant to invest in mud crab hatcheries as the hatchery technology is not well established. There are many problems facing hatchery operations, such as high mortality in the larval stage, live feed and disease outbreaks. In the nursery phase, cannibalism is a significant problem, so lower stocking density is practised resulting in lower income for the farmers. Although the hurdles in the mud crab industry are still many, the high price of mud crab in the global market motivates farmers to stay up-to-date with mud crab aquaculture and attempt to deal with the problems faced, for example, using seaweed in ponds to reduce cannibalism. Indonesian researchers have taken part in developing some farming innovations, including the development of herbal treatments to increase immunity, moulting, growth and to improve water quality. Formulated feeds have been developed for crablets and juveniles to counteract the constraints in the availability of fresh feed during the rainy season. At present, researchers are encouraging aquasilviculture to increase mud crab production as Indonesia has large areas of mangrove forest. For this, community development and capacity building are paramount.

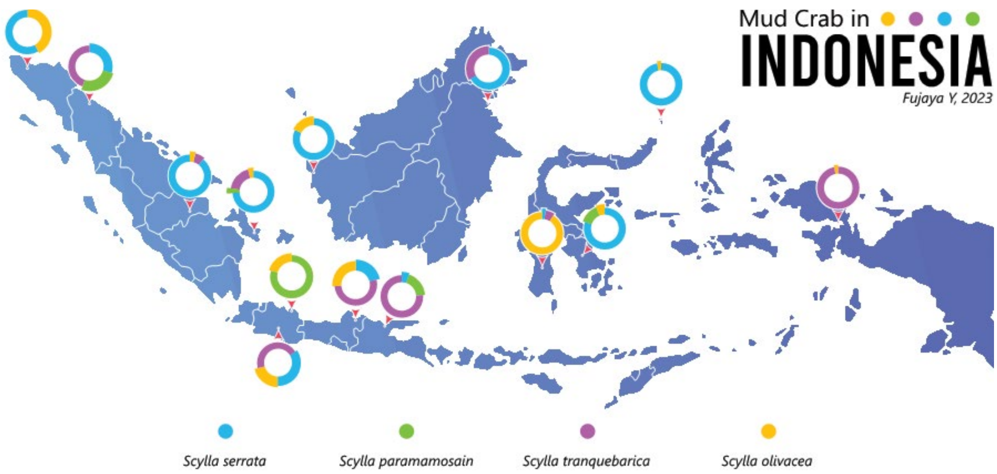
INTRODUCTION
Crabs are important fishery resources that are abundantly found along the Indonesian coastline. Two types of crabs, the mud or mangrove crab (*Scylla* spp.) and the blue swimmer crab (*Portunus pelagicus*) hold significant economic importance. They are primarily sourced from wild catches and cultivation.

Species of mud crab

In Indonesia, mud crabs of the *Scylla* genus are abundantly found from Sumatra Island to Papua. This is not surprising because as an archipelagic country with an extensive coastline, most coastal zones of Indonesia are covered by mangroves, making it an ideal habitat for mangrove crabs to thrive and reproduce.

The common names of the four mud crab species in Indonesia follow that of Keenan *et al*. (1998), i.e. the giant mud crab *S. serrata*, the green mud crab *S. paramamosain*, the purple mud crab *S. tranquebarica*, and the orange mud crab *S. olivacea* (KKP, 2022a). Figure 1 illustrates that almost all islands have all four species of *Scylla* with varying levels of abundance.

FIGURE 1
Distribution and species composition of mud crabs (*Scylla* spp.) in Indonesia



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Wild stock status

Mud crab market demand continues to increase annually, causing increased exploitation of mud crabs and consequently impacting the health natural population of wild crab stocks. The high demand for female crabs, especially those with late-stage ovaries, also contributes significantly to their overexploitation. According to the KKP (2022b), almost all national fishery management areas (Wilayah Pengelolaan Perikanan [WPP]) have been fully exploited, with several areas already experiencing overexploitation (Table 1).

The level of exploitation of aquatic resources is determined by the Ministry (KKP) in accordance with statutory regulations. The exploitation rate (E) is estimated as the total number of mud crabs caught compared to the total number of crab mortality, due to natural factors or fishing activities. An exploitation rate of $E < 0.5$ indicates that the fishing effort can still be increased or intensified; a rate from $0.5 < E < 1$ indicates that the fishing effort should be maintained and under strict supervision; while a rate of $E \geq 1$ indicates that fishing has exceeded the maximum exploitation level, and hence management measures are required to reduce fishing efforts and avoiding the overexploitation of the resource.

Conservation and management of wild resources

To address the overfishing issue, KKP issued a regulation to limit destructive fishing which threatens the sustainability of this fishery resource (including mud crabs), which was implemented in 2015 (KKP, 2015). This regulation was further updated in 2016 (KPP, 2016), 2020 (KKP, 2020), 2021 (KPP, 2021) and 2022 (KPP, 2022b).

TABLE 1
Estimated potential of crab resources, allowed catches and level of resource exploitation in the state fisheries management areas of Indonesia (WPP)

Water body	National fishery management area	Estimated resources (t)	Allowable annual crab catch (t)	Exploitation rate
Strait of Malacca and Andaman Sea	571	10 870	5 435	1.5
Indian Ocean	572	6 787	6 108	0.1
Indian Ocean south of Java to the south of Nusa Tenggara, Savu Sea and Western Timor Sea	573	585	410	0.7
Karimata Strait, Natuna Sea and North Natuna Sea	711	3 388	1 694	1.9
Java Sea	712	7 360	5 152	0.9
Makassar Strait, Bone Bay, Flores Sea and Bali Sea	713	6 213	4 349	0.7
Tolo Bay and Banda Sea	714	1 758	879	1.4
Tomini Bay, Maluku Sea, Halmahera Sea, Seram Sea and Berau Bay	715	336	235	0.7
Sulawesi Sea and North of Halmahera Island	716	1 470	1 029	0.8
Cendrawasih Bay and Pacific Ocean	717	545	491	0.2
Aru Sea, Arafuru Sea and East Timor Sea	718	1 498	1 198	0.85

Under the KKP (2022b) provisions governing the capture, trade and/or release of crabs (*Scylla* spp.) for consumption purposes are listed below. It is important to note that these provisions do not apply to educational, research, development, assessment, implementation or pilot farming activities.

- Crabs must not be in egg-laying condition.
- Crab carapace width should be > 12 cm and the body weight should be > 150 g.
- Fishing activities must be carried out using passive and environmentally friendly equipment, in accordance with statutory regulations.
- Trading female crabs bearing mature eggs is prohibited, except during the period from December to the end of February.

Management and regulation of mud crab aquaculture

The management and regulations governing crab cultivation in Indonesia are also regulated by the KKP (2022b). According to this regulation:

- For cultivation purposes, the minimum weight of wild crab seed must be 30 g/ind., except for crablets obtained from hatcheries.
- Berried crabs can be caught for hatchery purposes. However, hatcheries that use berried females from the wild are obligated to carry out restocking of at least 1 percent of their harvest.
- Berried crabs and crablets of < 30 g/ind. sourced from hatcheries can be traded, provided they are accompanied by a certificate of origin from the technical implementing unit in charge of aquaculture or the Fisheries and Maritime Service.

INDUSTRY STATUS

Production status

Mud crabs from Indonesia are exported in various forms, including live, frozen or canned. Based on data released by the official fisheries statistic website (https://statistik.kkp.go.id/home.php), the United States of America is the largest importer of Indonesian crabs, followed by China, Japan and Canada. Despite fluctuations, the volume of crab exports from 2012–2022 consistently exceeded 20 000 t/year with a

TABLE 2
Indonesian crab exports and contribution from aquaculture (2015–2020)

Year	Export		Aquaculture	
	Volume (t)	Value (USD 1000)	Volume (t)	Contribution to the export volume (%)
2015	23 746	309 735	12 546	53
2016	29 040	321 846	11 407	39
2017	27 067	409 816	10 589	39
2018	27 792	472 962	13 795	50
2019	25 943	393 498	14 205	55
2020	27 616	367 520	10 749	39

Source: National fishery statistics, Ministry of Maritime Affairs and Fisheries, 2023. https://statistik.kkp.go.id/home.php

value exceeding USD 400 million in 2017 and 2018 (Table 2). These crabs were obtained from the wild as well as farming operations. Aquaculture accounts for about 46 percent of total annual production.

Farming areas

Mud crabs are primarily cultivated along the coastal regions, especially in areas with mangrove forests and with muddy or sandy mud substratum. Indonesia has extensive suitable locations for mud crab cultivation. The total area of brackish-water cultivation land in Indonesia in 2021 was approximately 666 309 ha, consisting of intensive, semi-intensive and traditional ponds (Table 3). Currently, most of this area is used for shrimp and milkfish farming activities. Traditional ponds are very well-suited for crab cultivation with lower ecological impacts.

TABLE 3
Land area (ha) of brackish-water aquaculture according to farming systems

Cultivation systems	2018	2019	2020	2021
Intensive pond	15 924	16 758	33 571	39 535
Semi-intensive ponds	66 329	98 352	53 099	50 911
Traditional pond	676 162	852 489	592 778	575 863

Source: National fishery statistics, Ministry of Maritime Affairs and Fisheries, 2023. https://statistik.kkp.go.id/home.php

In addition to land-based pond cultivation, mud crabs are also farmed using the silviculture concept – an integrated approach that promotes sustainable mangrove management while balancing ecological and economic interests. Implementing this cultivation method presents a unique challenge for Indonesia due to its vast mangrove forests. According to the 2021 National Mangrove Map, Indonesia's mangrove coverage spans approximately 3 364 076 ha (Table 4). This extensive mangrove area plays a critical role in ensuring the success of silviculture-based crab farming while also supporting the country's broader environmental and conservation goals.

Hatcheries

The availability of high-quality crab seeds is a limiting factor in the expansion of crab aquaculture. Generally, seeds are obtained from the wild, and their availability is not consistent. Crab seeds are usually abundant during the rainy season but become scarcer in the dry season. One major concern is the decreasing number of wild seeds caught year after year, resulting in failure to meet the increasing cultivation needs and, consequently, unsustainable and overharvesting of crab seeds.

To sustain and grow the mud crab aquaculture industry, it is essential to develop the capacity for mass-producing high-quality crab seeds in controlled environments like

TABLE 4
Mangrove forest areas in Indonesia

Main Indonesian islands	Mangrove areas based on tree density level * (ha)			Total (ha)
	High	Moderate	Low	
Sumatera	621 802	19 158	19 484	660 444
Jawa	32 160	17 130	7 209	56 499
Bali Nusa Tenggara	30 495	2 629	1 850	34 974
Kalimantan	590 088	89 068	8 869	688 025
Sulawesi	98 897	29 174	9 112	137 183
Maluku	219 024	3 798	1 224	224 046
Papua	1 528 773	27 406	6 726	1 562 905
Indonesia Total:				3 364 076

* Mangrove coverage High: > 70%; Moderate: 30–70%; Low: < 30%.

Source: National Mangrove Map, 2021. Directorate of Soil and Water Conservation, Directorate General of Watershed Management and Forest Rehabilitation. Ministry of Environment and Forestry.

hatcheries. This is particularly critical for the soft-shell crab production sector, where large quantities of crab seeds are required to raise juveniles, which are then induced to moult and produce soft-shell crabs. Consequently, the current practice of relying on wild-caught juveniles for soft-shell crab production is highly unsustainable.

Currently, there are only a few crab hatcheries in Indonesia and most of them are operated by Government agencies. Among them, two crab hatcheries, namely the Takalar Brackish Water Aquaculture Development Center (Balai Perikanan Budidaya Air Payau Takalar [BPBAP Takalar]) and the Jepara Brackish Water Aquaculture Development Center (Balai Besar Perikanan Budidaya Air Payau Jepara [BBPBAP Jepara]), operate regularly and supply crab seeds to farmers. However, due to limited infrastructure, seed production remains constrained, preventing them from meeting the needs of local communities. A commercial crab hatchery has been established in Belitung, Sumatra, but it has yet to fully engage in serving the broader community. In addition, several former shrimp hatchery facilities were re-purposed into research-scale mud crab hatcheries.

AQUACULTURE PRACTICES AND SYSTEMS

Crab culture systems, including hatchery operations, are generally based on the protocols outlined in Shelley and Lovatelli (2011), with various adjustments and adaptations. Nursery activities of hatchery-produced crabs are carried out in earthen ponds, and co-cultured with seaweed and milkfish. The abundant availability of ponds in Indonesia facilitates this practice, but the high level of cannibalism is still a challenge in crab farming.

Hard-shell farming

Mud crab farming includes various approaches, such as crablet grow-out, fattening, and production of berried and soft-shell crabs. Each strategy requires different pond sizes, depending on the availability of land in the region. In Bone Regency, South Sulawesi, fishers stock small crabs in large ponds (about 1–2 hectares), while larger crabs are sold immediately. These smaller crabs are cultured for several months until they reach marketable size, allowing them to be sold at a higher price. In Losarang, West Java, fattening is done in smaller, enclosed ponds that are fenced to prevent the crabs from escaping. Some farmers also practice integrated farming, using feed sources to enhance the fattening process. For instance, in Kupang, East Nusa Tenggara, farmers cultivate snails to feed their crabs. They grow water spinach (*Ipomoea aquatica*; *Kangkong* in Indonesia) in the same area to sustain the snails as a food source.

Aquasilviculture is currently practiced widely across various regions of Indonesia. This aquaculture approach integrates fish production with the conservation of mangrove ecosystems (Velsa *et al*., 2022). In Indonesia, the concept is like silvofishery, a system that combines crab farming with mangrove reforestation, supported by a management strategy aimed at minimizing inputs and reducing environmental impacts (Paruntu *et al*., 2016). This model not only promotes mangrove conservation but also enhances the economic benefits for local communities (Hilmi *et al*., 2021).

Soft-shell crab production

Soft-shell crab production consists in raising hard-shell crabs until they moult or shed their shell. Soft-shell crabs are harvested about 2–3 hours after moulting when their shells are still soft (Fujaya *et al*., 2012). Several methods are used to accelerate moulting, including autotomy, the "Popeye" technique, or allowing the crabs to moult naturally.

- Autotomy is a technique used to accelerate moulting by removing the crab's appendages, including the chelipeds and the first three pairs of walking legs. The crabs, left with only their swimming legs, are then placed in bamboo cages divided into small compartments. These cages are floated on the surface of the pond, where the crabs are kept until they moult.
- The "Popeye" method is like autotomy but differs in that only the first three pairs of walking legs are removed, while the claws (chelipeds) are left intact. The retained large chelipeds resemble Popeye's muscular arms, giving this technique its name.
- The natural method does not involve any appendage removal, and crabs are reared naturally until their next moult. Crabs subjected to "Popeye" and natural methods are kept in crab boxes to avoid cannibalism when they moult.

Two primary systems are commonly used in soft-shell crab production in Indonesia: the horizontal and vertical systems. In the horizontal system, crabs are kept in individual boxes that float on the surface of pond water. In contrast, the vertical system – often referred to as "crab apartments" – cultures crabs in vertically stacked boxes inside an indoor facility, utilizing a recirculating aquaculture system (RAS). Each system has its own advantages and disadvantages. The horizontal system has a lower dependency on electricity, as the crab boxes float naturally on pond water. However, workers must operate in direct sunlight, which can be challenging. The vertical system, on the other hand, relies heavily on electricity to maintain the RAS and is more sensitive to changes in water parameters. Additionally, it requires careful maintenance of the crab box installations to ensure proper functioning.

Soft-shell crab cultivation is highly labour-intensive, requiring workers for tasks such as stocking, feeding, monitoring, harvesting, and post-harvest processing. As a developing country, Indonesia can leverage this activity to create employment opportunities. The general process for soft-shell crab production, as outlined in Figure 2, involves the following key steps: seed preparation, stocking the seeds into crab boxes, feeding, monitoring, harvesting, and soft-shell crab processing.

MUD CRAB HEALTH AND DISEASE MANAGEMENT

Health management in mud crab farming is still inadequate, as evidenced by the recurring mass mortalities in both hatcheries and rearing ponds. The main problem appears to be associated with cleanliness. In Indonesia, many farmers still believe that mud crabs thrive on decaying matter since they are scavengers, thus neglecting the importance of maintaining a healthy environment in crab farming. Various reports show that poor living conditions will trigger the emergence of diseases.

FIGURE 2
The general steps for soft-shell crab production
(a) seed preparation; (b) putting the seeds in the crab boxes; (c) feeding; (d) monitoring; (e) harvest; and (f) soft-shell crab harvest

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Diseases can still occur when water parameters such as salinity, pH, dissolved oxygen (DO) and temperature are at their optimal levels. One of the contributing factors is believed to be the high content of organic matter in the water and substrate. Apart from that, natural feed sources such as livestock waste, trash fish and molluscs also play a role in facilitating the entry of pathogenic microbes into the holding tanks or grow-out ponds. This condition was observed in a soft-shell crab farm in North Sumatra, where crabs died and the body fluids turned milky and whitish in colour (Figure 3). The disease is caused by dinoflagellates of the genus *Hematodinium* sp., which infects the haemolymph and tissues of crabs, causing a condition known as "milky disease". This condition is characterized by symptoms such

FIGURE 3
Milky disease observed in soft-shell crab culture in North Sumatra

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as moribund behaviour, opaquely discoloured carapace, a cooked appearance, milky body fluids, unpalatable flavour, and high mortality (Jithendran *et al*., 2011).

According to the report by Sarjito *et al*. (2018), bacterial diseases present a significant challenge in mud crab culture in Pemalang, Central Java, Indonesia. Infected mud crabs (*S. serrata*) exhibit clinical signs such as red and dark spots on the carapace, as well as wounds on the body surface, including the claws and carapace. Similar clinical signs can also be observed on the abdomen. Through 16S DNA sequencing analysis, it was determined that the bacteria associated with these diseases in mud crabs from extensive brackish-water ponds in Pemalang are closely related to *Vibrio harveyi*, *Vibrio alginolyticus*, *Bacillus marisflavi*, and *Exiguobacterium aestuarii*.

In addition to bacterial diseases, ectoparasites pose a significant threat to mud crabs due to their potential to damage various body organs, including the carapace and gills. This damage can impair the host's immune defense, leading to disrupted growth and increasing susceptibility to secondary infections from other pathogens, such as bacteria and viruses, ultimately resulting in death.

Three types of ectoparasites commonly found in Indonesian waters infecting mud crabs are *Octolasmis* sp., *Zoothamnium* sp. and *Epistylis* sp. (Indarto *et al*., 2021). Most of these ectoparasites are found on the gills of mud crabs. For instance, *Octolasmis* infestations in farmed mud crabs have been reported in Surodadi Village, Central Java (Herlinawati *et al*., 2017). Infected mud crabs often display clinical signs, such as blackened gills with sprout-like structures.

RESEARCH AND INNOVATION

In response to the various challenges encountered in the field, universities and research centres have conducted extensive research to identify effective farming solutions. Several research and development initiatives have been launched to create innovative practices, including a RAS with an individual compartment design developed by the Takalar Brackish Water Aquaculture Fisheries Center. This system addresses the issue of cannibalism during the nursery phase, significantly reducing mortality rates and allowing crabs to grow to approximately 2 cm in size, making them suitable for grow-out culture.

Several innovations have been developed by Hasanuddin University, including a herbal extract formula (Figure 4) that enhances growth and moulting, improves the overall health of crabs, and boosts water quality through the incorporation of probiotics and phytobiotics (Fujaya *et al*., 2011; Fujaya *et al*., 2021; Kanna *et al*., 2021). This formulation aims to provide an alternative to the autotomy method, which raises animal welfare concerns (Fujaya *et al*., 2020). To address feed limitations, researchers have also developed artificial feed (Figure 5) specifically designed for mud crabs (Aslamyah *et al*., 2022). This research indicates that herbal extracts can serve as effective feed additives, enhancing feed utilization, stimulating growth, and promoting moulting in crab cultivation.

FIGURE 4
Herbal extract (moulting stimulant) for soft-shell crab production

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Further innovations include the development of an automated feeding system for soft-shell crabs utilizing a microcontroller (Niswar *et al*., 2017), as well as the design and implementation of an IoT-based water quality monitoring system for crab farming. This system provides farmers with real-time alerts to maintain acceptable water quality levels in their ponds (Niswar *et al*., 2018). Additionally, advancements in digital image processing have been made for the detection of megalopa phase crab larvae (Nurlaela *et al*., 2019).

FIGURE 5
Formulated crab feed

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MARKET INFORMATION

In 2023, the KKP reported that crabs from Indonesia are exported to 184 countries, with the largest importer being the United States of America, followed by China and Japan (Table 5).

The price of crabs is influenced by their condition, quality and size. Several characteristics indicate high-quality crabs, including intact and unbroken claws, swimming legs that quickly return to their original position when pulled and released, responsive eyestalks that retract into the eye sockets when touched, a mouth that does not produce foam, and a vibrant carapace colour. These factors can all be used to assess crab quality (Desyana *et al*., 2023).

TABLE 5
Top ten countries importing Indonesian mud crab based on export value percentage

Importing country	Export value (%)				
	2018	2019	2020	2021	2022
United States of America	39	37	40	44	37
China	14	17	16	16	18
Japan	14	13	12	11	12
Viet Nam	3	3	3	3	5
Malaysia	2	3	3	2	3
Thailand	3	3	4	2	2
Taiwan, Province of China	2	3	3	2	2
Italy	3	2	2	2	2
Singapore	2	2	2	2	2
Australia	1	2	2	2	2

Source: National fishery statistics, Ministry of Maritime Affairs and Fisheries, 2023. https://statistik.kkp.go.id/home.php

In Indonesia, several categories determine the selling price of mud crabs. Live crabs typically command higher prices and are classified into three grades:

- **CB** - Large female crabs with mature gonads, weighing > 200 g.
- **LB** - Large males weighing between 500–1 000 g.
- **BS** - Rejected live mud crabs, which may have missing body parts, be undersized, or possess thin carapaces. Notably, mature female crabs without eggs, even if they are large, are also classified as BS grade. At the collector/trader level, CB crabs generally achieve the highest market prices.

Soft-shell crabs are priced twice that of comparable hard-shell crabs and are also classified into three grades:

- **Grade A** - All legs are intact, in perfect soft condition.
- **Grade B** - Some legs are missing, but in perfect soft condition.
- **Grade C** - Missing legs, hardened shells or deceased.

Grade A soft-shell crabs command the highest selling prices (Khotimah *et al*., 2018).

MAJOR ISSUES AND CHALLENGES FACING THE INDUSTRY

Crab cultivation in Indonesia is not yet widely practised using hatchery-produced seeds. In Indonesia, most of the crab farms rely on sourcing crab seeds from nature, indicating that the full potential of mud crab aquaculture is yet to be realized. The primary challenges in cultivating mud crabs are inadequate seed supply, cannibalism, disease outbreaks, and feed development. Seed supply can be increased through hatchery-based seed production. However, various culture parameters still lack optimization, leading to inconsistent survival of larvae and crablets. Besides this, high mortality rates are also prevalent in the nursery phase, primarily due to cannibalism. One of the useful solutions to address this challenge is the provision of shelter. Disease outbreaks can be controlled and minimized with proper water and feed management. Developing artificial feed optimal for mud crab growth and maturation is a complex challenge as reliance on fresh feed such as trash fish is season dependent.

CONCLUSION

Based on this description, it appears that Indonesia has great potential as the biggest mud crab producer in the world. Indonesia has all four species of mud crab (*Scylla* spp.) found in the world, and these crabs are spread throughout Indonesia. The species distribution appears to be closely related to the environment and region so, when determining which species to develop, regional differences will need to be considered.

Existing ponds and extensive mangrove areas are Indonesia's geographical advantages for crab cultivation. However, no matter how big the natural potential is, if environmental management is poor, the sustainability of this business can be threatened. Aquasilviculture is the hope for the future to promote crab cultivation while simultaneously protecting the environment, especially existing mangrove forests. Mangroves serve as natural protectors of the coastal area, nursery ground, and a source of food for cultivated crabs.

Efficient and environmentally friendly cultivation technology is also a future challenge. Technology for providing healthy and quality seeds; controlling cannibalism, disease, and water quality to reduce mortality; as well as developing artificial feed are the tasks that await researchers. Apart from this, innovation to produce quality cultivated crabs needs to continue because quality crabs have a higher value and can greatly increase farmers' income.

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Status of mud crab aquaculture in India

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ABSTRACT

It is estimated that the potential crab resource in India, particularly from its 7 770 km² of estuaries and backwaters, amounts to 13 209 t. This figure is part of a total potential resource of 43 816 t, derived from approximately 8 103 km of coastline with highly productive coastal waters. The estimated brackish-water area in India totals roughly 1 190 900 ha, out of which 170 000 ha are developed for shrimp farming with the potential to become suitable for crab farming – as seen in Tuticorin, Tamil Nadu. Live mud crab export from India was higher in 2020–2021 (4 519 t) compared to 2021–2022 (3 219 t) and 2022–2023 (3 481 t). Andhra Pradesh is the largest producer of mud crabs in India (17 529 t) in 2022–23. Mud crab farming, fattening and soft-shell crab production are now emerging as lucrative business ventures in India.

The genetics team of the Rajiv Gandhi Centre for Aquaculture (RGCA) has deciphered the taxonomic ambiguity of mud crab species commonly available in Indian coastal waters using multiple molecular genetic markers and concluded that only two species of mud crabs, *Scylla serrata* and *Scylla olivacea* are commonly found in Indian coastal waters.

The decline in the mud crab populations in the natural habitat throughout Indian coastal waters is due to overexploitation and indiscriminate fishing of juvenile crabs by artisanal fishers. Wild seeds are collected throughout the year from Chilka Lake of Odisha; backwater zones of Sundarbans, Kakdwip and Namkhana of West Bengal; coastal waters of Kakinada, Visakhapatnam and Rajahmundry of Andhra Pradesh; Pulicat Lake, Killai backwaters, Muthupet saline swamps, Punnakayal estuarine complex and Colachel coastal waters of Tamil Nadu; Neendakara, Cochin and Kozhikode backwaters of Kerala to meet the demand for farming.

Recent disease surveillance showed the occurrence of mud crab reovirus (MCRV) in farms and in wild broodstocks which is now becoming a major threat. RGCA's genetic study showed that Indian mud crabs have low genetic variations among and within the populations. It may become a threat for future selective breeding programmes and management of the viable genetic stocks. Establishment of more private hatcheries and nursery rearing facilities in different parts of India is essential.

INTRODUCTION

Commercial-scale mangrove or mud crab aquaculture is fast developing in the coastal areas of Andhra Pradesh, West Bengal, Odisha, Tamil Nadu and Kerala. There is a huge demand for mud crabs both in local and export markets and this has led to the overexploitation of natural resources in many areas. Indiscriminate exploitation of mud crab without paying attention to the size, maturity status (ovigerous on non-ovigerous) and physiological status (soft- or hard-shelled crabs) exerts much pressure on the natural population. All the phases of culture have been developed in India. However, due to the major knowledge gaps in seed production such as lack of artificial feeds and standardized culture technology in all phases of culture, commercial-scale production has not expanded in the country.

Mud crab species in India

The genetics team of the Rajiv Gandhi Centre for Aquaculture (RGCA) has deciphered the taxonomic ambiguity of mud crab species commonly available in Indian coastal waters using multiple molecular genetic markers and concluded that only two species of mud crabs, *S. serrata* and *S. olivacea,* are commonly found in Indian coastal waters (Mandal *et al.*, 2014a; 2014b). Both species have huge demand for export market but only *S. serrata* is widely cultured in India because of its quality and higher price.

Identification of mud crabs, *Scylla* spp. is always confusing because of their wide variations in colour, size, spination, habitat, etc. Most of the researchers from India reported only *S. serrata* (Forskål) or *Scylla tranquebarica* from Indian coastal waters and many of the reports are contradictory. Mandal *et al.* (2014a; 2014b) collected adequate crab samples from a wide geographical range of natural habitat and developed multiple molecular genetic markers including ITS, RAPD, PCR-RFLP and mtDNA gene sequencing to confirm that only *S. serrata* and *S. olivacea* are commonly found in Indian coastal waters. This was validated by the taxonomic identification of Keenan *et al.* (1998). The results of gene sequencing and other molecular markers clearly indicated that the "green" morph of Indian mud crab is *S. serrata*, while the "brown" one is *S. olivacea* (Figure 1 and 2). The species *S. tranquebarica*, as described by several Indian researchers, is most likely *S. serrata*, as identified by Keenan *et al.* (1998).

FIGURE 1
***Scylla serrata* collected from Indian coastal waters**

© RGCA

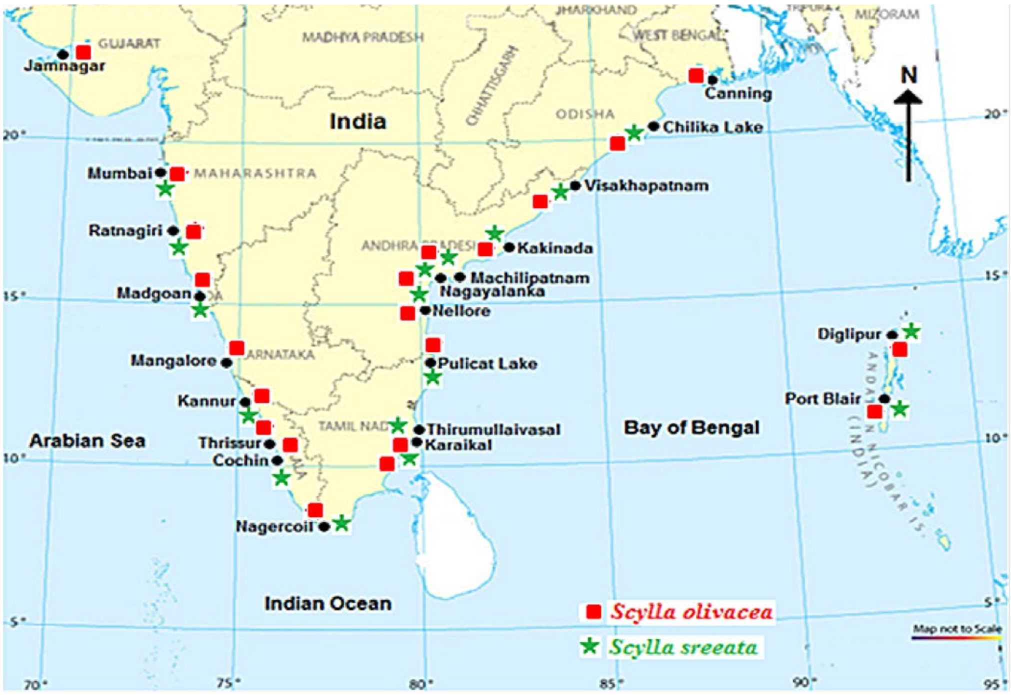
FIGURE 2
***Scylla olivacea* collected from Indian coastal waters**

© RGCA

Distribution

With a coastline of approximately 8 103 km, India offers vast near-shore water resources in addition to the 1.2 million ha of brackish water area in the adjoining coastal zone. Mud crabs are available from the entire stretch of east (Tamil Nadu to West Bengal), west (Kerala to Gujarat) and Andaman coastal waters (Figure 3). The distribution of *Scylla* spp. is characterized by significant ontogenic changes and predominantly related to hydrological circulation along the areas of coastal shelf. The juveniles up to 8 cm carapace width (CW) are most abundant on intertidal flats, while

FIGURE 3
Availability of mud crab species in different coastal sites (solid black circle) and commonly available species (*Scylla olivacea* and *Scylla serrata*)



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

the habitat of subadult and adult crabs is more subtidal. Occurrence of *S. olivacea* is evident throughout the year from mangrove-dominated coastal waters of India including Andaman waters, but the scarcity of *S. serrata* (green crab) in many localities is noticeable. In southeast India, the greatest catch of juvenile *S. olivacea* occurs in the post-monsoon period, in muddy substrates in shallower water with areas of rich seagrass and algal community, and almost nil during the monsoon when the salinity is very low. In the Chilika Lagoon (Odisha), the juveniles of *S. olivacea* can be found throughout the year, while the peak abundance of *S. serrata*, is restricted during the monsoon period (June–September). *S. olivacea* is abundant in the mangroves of Sundarban area of West Bengal and various parts of Gujarat throughout the year, but the scarcity or even the absence of *S. serrata* was noticeable in both states.

Habitat

India has 4 663 km^2 of mangrove forest, which is known to be the best natural habitat for mud crabs (Table 1). They are mostly found in estuarine and sheltered coastal habitats. In general, large populations are usually associated with established mangroves (*Avicennia* spp., *Rhizophora* spp. or *Bruguiera* spp.), especially in estuaries where they feed predominantly on molluscs and other less mobile invertebrates. The bottom substrate in estuaries in the Indian coast varies from sandy to muddy with wide fluctuating hydrobiological parameters. The large mangrove forest coverage of many coastal states has huge potential for development of mud crab aquaculture.

Wild mud crab resources and conservation status

Due to lack of national policies and regulations for mud crab aquaculture and conservation, wild crabs are being overexploited and there has been a notable decline in their population in the natural habitat throughout Indian coastal waters. The genetics

TABLE 1
Coastal length and mangrove resources in India and potential brackish water area suitable for mud crab culture

State/Union Territory	Coastal length (km)	Mangrove cover (km^2)	Potential brackish-water area (ha)	Area under shrimp culture (ha)
Andhra Pradesh	1 037	352	150 000	76 687
Goa	113	22	18 500	650
Gujarat	1 915	1 058	376 000	2 271
Karnataka	258.15	3	8 000	3 500
Kerala	560	6	65 000	14 106
Maharashtra	510	186	80 000	1 281
Orissa	457	222	31 600	12 877
Tamil Nadu	865	39	56 000	5 286
West Bengal	374	2 155	405 000	50 405
Puducherry	31	1	800	130
Andaman and Nicobar Islands	1 962	617	–	–
Daman and Diu	21	1.6	–	–
Total	**8 103.15**	**4 662.6**	**1 190 900**	**167 193**

Source: Forest Survey of India. 2011. India State of Forest Report 2011. Dehadrun, India, Forest Survey of India, Ministry of Environment and Forests.

FIGURE 4
Members of Women Self-Help Group in Maharashtra conducting *Scylla serrata* nursery and grow-out along with mangrove conservation

FIGURE 5
Crab expert providing technical input to members of Women Self-Help Group in Maharashtra

team of RGCA (unpublished data) found low genetic variations among mud crab populations in Indian coastal waters, particularly for *S. serrata*, which is a cause of great concern for their conservation and management.

Marine Products Export Development Authority (MPEDA)-RGCA is continuously working with different agencies in India, particularly with the Mangrove Foundation, Government of Maharashtra for restoring mangroves and promoting sustainable mud crab grow-out through a Women Self-Help Group (Figure 4). The RGCA team, along with mud crab experts, provided the required scientific input to the members of Women Self-Help Group encouraging them to engage in crab farming in tide-fed areas of Maharashtra (Figure 5).

Crab export from India

India is one of the largest exporters of live mud crab in the world and exports most of its crabs to China, Singapore and the United States of America. Likewise, frozen form of sea crabs such as *Portunus pelagicus* and *Portunus sanguinolentus,* along with other crab meats, soft-shell crabs, crab cutlet, crab curry, etc. make up a major share in the export market (Table 2). The top three global exporters of crabs are India with 121 656 shipments, followed by Viet Nam with 41 617 and Indonesia in the third spot with 36 168 shipments in 2023 (data up to October).

TABLE 2
Export of crab and crab products from India (2013–2023)

Year	2013–14	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21	2021–22	2022–23
Quantity (t)	7 338	7 460	6 937	8 423	7 235	9 119	15 852	5 509	6 938	7 438
Value (INR 10 million)	377.18	439.08	403.38	507.09	448.49	629.79	738.14	398.34	880.11	693.44
USD million	62.76	72.42	62.45	76.66	70.90	90.76	105.69	54.33	119.53	87.86

Source: MPEDA. 2023. Annual report of Marine Product Export Development Authority, 2023–2024. Ministry of Commerce and Industry, Government of India.

INDUSTRY STATUS

Production status

The only commercial mud crab hatchery in India operated by MPEDA-RGCA was awarded patent for its hatchery technology and production of disease-free seeds under strict biosecurity condition. Since its inception in 2005, the hatchery facility capable of producing 1 million seeds annually located at Thoduvai, Tamil Nadu has produced 9.62 million crab instars/crablets that were supplied to 991 farmers and other stakeholders. During the last 10 years, more than 9.17 million mud crab instars/crablets were supplied to 970 beneficiaries (Table 3). There is a huge deficiency in the supply of crab seeds required by the industry.

TABLE 3
Quantity of crab instars/crablets supplied by MPEDA-RGCA and the corresponding number of beneficiaries

Year	Crab instars/crablets	Beneficiaries
2013–14	730 981	96
2014–15	735 605	77
2015–16	1 060 375	104
2016–17	807 162	105
2017–18	982 043	121
2018–19	1 237 575	144
2019–20	1 017 497	133
2020–21	435 389	47
2021–22	882 290	82
2022–23	1 285 910	61
Total	**9 174 827**	**970**

Source: MPEDA. 2023. Annual report of MPEDA, 2022–2023. Kerala, India, Marine Product Export Development Authority (MPEDA).

Farming areas

The main and largest crab farming sites are in the Sundarbans coastal areas of West Bengal, Chilka Lake of Odisha, Godavary estuary of Andhra Pradesh, Pulicat Lake, Killai backwater and Punnakayal backwater of Tamil Nadu, Veerampatnam backwater and Karaikal estuary of Puducherry, Vembanad Lake of Kerala and mangrove forests of Karnataka, Goa, Maharashtra and Gujarat. The large mangrove resources of south, middle and north Andaman Islands have huge resources of mud crab. The total

FIGURE 6
Mud crab farming demonstration by MPEDA-RGCA in West Bengal

potential resource of Indian coastal waters was more than 43 816 t, out of which estuaries and backwaters had a potential resource of 13 209 t.

Organized mud crab farming in land-based earthen ponds, pens and cages using hatchery-produced crab seeds is lacking in India. Considering the potential and high export value, MPEDA-RGCA established a pilot scale mud crab hatchery at Thoduvai, Nagapattinam District, Tamil Nadu at the end of 2004 for seed production, and developed the nursery and grow-out technology at the Aquaculture Demonstration Farm in Karaikal, Union Territory of Puducherry. In 2013, the newly renovated hatchery was inaugurated and recently the hatchery received a patent for 20 years. RGCA is providing hands-on training on mud crab aquaculture for the benefit of farmers across the country. As a result of RGCA-MPEDA's demonstration effort, many farmers have been involved in mud crab farming (Figure 6). In Bhimavaram District of Andhra Pradesh (~1 050 ha for crab culture currently in operation), farmers are purchasing 70–130 g size crabs from local agents for stocking (most of the agents are obtaining crabs from Chennai and some are collecting crabs from Repalli area, Guntur District, Andhra Pradesh). In West Bengal, production is mainly from MPEDA crab demonstration farms, from fattening of wild collected juveniles, or from watery/soft-shell crabs. The fattening areas are located at Jharkhali, Sonakhali, Basanti, Gosaba of South 24 Parganas district, and Dhamakhali, Rampur, Bermajur, Hingalganj and Hasnabad of North 24 Parganas district, West Bengal. Apart from fattening, wild catch of adult *S. olivacea* is the major contributor to crab production from West Bengal.

AQUACULTURE PRACTICES

Larval rearing

Healthy hard-shelled and mature female crabs (500–800 g) are sourced from Tuticorin, Kodiyakarai (Vedaranyam), Palayar, Killai (Pitchavaram) and Pamban, Tamil Nadu, as broodstock source for the hatchery. Crabs are subjected to conditioning, formalin bath and screening before holding them in the broodstock tank. Regular sampling is done for the presence of ovigerous females, which are transferred to separate spawning tanks (1 crab/tank). Newly hatched *S. serrata* zoeae are stocked at 70–80 ind./L. Rotifers (10–20 ind./ml) and *Artemia* 0.5–1.0 ind./ml) are the major food for the crab larvae. About 30–50 percent of the water is replaced every 3 days or depending on the water quality. Some zoea 5 are usually transferred to other tanks and the rest of the larvae are reared until crab instar in the same tank where they were originally stocked. The survival rate from zoea 1 to crab instar 1–2 (25–35 days) is 7–10 percent (Thampi Samraj *et al.*, 2013).

Nursery rearing

Megalopae or crab instars are reared up to juvenile stage in brackish-water ponds or net cages in creeks with salinity range of 15–35 ppt for 30–40 days. PVC pipes, shade nets (used for plants), seaweeds (*Gracilaria* sp.), etc., are used as shelters in nursery rearing to minimize cannibalism. Apart from natural food available in the culture system, the megalopae are fed with either *Artemia* biomass or with chopped minced fish. After nursery rearing, the crablets (> 2.5 cm CW) are used for grow-out farming. Bamboo baskets, plastic dust bins and plastic fruit baskets are commonly used as packing containers. Wet grass, shade nets, mangrove leaves, sand, etc., are used to maintain the moist condition during transport of crablets (Figure 7).

FIGURE 7
Transport of crablets using wet mangrove leaves to maintain moist condition

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Grow-out culture in earthen ponds

Mud crab farming started in India with low stocking density of wild juveniles in polyculture with fish or shrimp during the early 1980s when cages, pens and small ponds with nets were used to hold crabs for 4–8 weeks. At present, mud crab culture is fast developing in the coastal areas of Andhra Pradesh, West Bengal, Tamil Nadu, Odisha and Kerala. *S. serrata* is widely preferred for aquaculture as it grows to 2.0 kg (shooters) and causes little damage to pond dikes or fences compared to *S. olivacea*. Recently, farmers are stocking crab instars with tiger shrimp, *Penaeus monodon*, in polyculture in some of the brackishwater farms particularly in coastal Andhra Pradesh.

Brackish water ponds in mangrove areas, as well as existing or abandoned shrimp ponds are utilized for grow-out culture of crablets. Net enclosures are installed along the inner side of the pond dike to prevent the escape of crabs and entry of unwanted species (Figure 8). Nursery-reared crablets are used for grow-out culture whenever available. Crablets attain the marketable size of ≥ 500 g within 6–7 months of culture.

FIGURE 8
Net enclosures along the inner side of the pond dike to prevent crab escape and entry of predators

© RGCA

Another way of grow-out culture is growing the juvenile crabs initially in small brackish water earthen ponds for a period of two months to attain an average size of 50–75 g. These juveniles are then further cultured in grow-out ponds to marketable size within 4–5 months.

Pen culture

In many areas in India, pen culture of juvenile crabs is gaining momentum (Figure 9). The pens (about 20 × 10 × 1.2 m) are usually made of high-density polyethylene (HDPE) net with mesh size of about 10 mm and has a culture period of 4–5 months. The pen culture method allows for easy growth monitoring and selective harvesting, while also enabling the stocking of crabs of various sizes in separate pen compartments. This approach can help increase overall yield.

FIGURE 9
Pen culture of mud crabs

© RGCA

Fattening of mud crabs

In Andhra Pradesh, the farmers in the coastal region have been practicing crab fattening since 2006. Crab fattening is concentrated in the Krishna, Guntur, West and East Godavari districts of the state. Fishers collect juvenile and adult crabs from mud flats and estuarine areas. Hard-shell crabs weighing more than 350 g are sold to the exporters, while smaller crabs along with soft-shell crabs are sold to those engaged in crab fattening (Figure 10). As the natural stock is becoming depleted due to the overexploitation, most of the fattening facilities and farms are not getting sufficient crabs. The culture, including the fattening period, lasts about 90 days. Farmers prepare their crops for harvest between November and January to take advantage of the high market demand during the festival season in other countries, which drives up market prices. Crabs weighing 500–750 g are sold for INR 700–750/kg while those above 750 g at INR 850–900/kg. The harvested crabs are primarily purchased by traders in Kakinada, Andhra Pradesh, and Chennai, Tamil Nadu, who mainly export live crabs to Singapore.

Soft-shell crab production

Existing tide-fed shrimp or fish ponds are used for soft-shell crab farming in India (mainly on an experimental basis). Ponds ranging from 0.4 to 0.6 hectares with water

FIGURE 10
Mud crab fattening farm supported by MPEDA-RGCA

© RGCA

salinity levels between 15 and 30 ppt are ideal for crab culture. Perforated plastic boxes are used for soft-shell crab production. The boxes are inspected by retrieving from the pond the frame that holds multiple boxes. Newly moulted crabs are monitored daily at 3–4 hours interval while the operator is seated on a wooden catwalk or platform. Once newly moulted crabs are detected, the boxes are immediately removed, and the crabs collected for further processing (Figure 11). The soft-shell crabs are processed either chilled or frozen and exported to Japan, the United States of America, Republic of Korea, Malaysia, China, Hong Kong SAR and the European Union. Soft-shell crabs are sourced partly from local landing centres and from Chennai. The price of soft-shell crab (100–300 g) ranges from INR 320–480/kg (approx. USD 6/kg).

FIGURE 11
Newly moulted *Scylla serrata* in the plastic box

© RGCA

MPEDA-RGCA is promoting soft-shell crab culture which could fetch good returns in just a short time. The results of soft-shell farm operated by an MPEDA-RGCA trainee at Tajpur, West Bengal (Figure 12) and few others in Odisha and West Bengal are quite encouraging.

HEALTH AND DISEASE MANAGEMENT

The Central Aquaculture Pathology Laboratory (CAPL) of MPEDA-RGCA, accredited by the National Accreditation Board for Testing and Calibration Laboratories (NABL), routinely monitors the health of crabs in the RGCA hatchery and provides

FIGURE 12
Soft-shell crab farm operated by MPEDA-RGCA in West Bengal, India

© RGCA

guidance on maintaining strict biosecurity measures. Disease-free crab instars and crablets are supplied to farmers to support sustainable production. However, during recent disease surveillance, the RGCA team detected mud crab reovirus (MCRV) in both farm-reared crabs and wild broodstocks (Sathiyaraj *et al*., 2023). Moribund *Scylla serrata* samples were collected from various farms, wild breeders, and the hatchery quarantine sections in Tamil Nadu, Andhra Pradesh, and Odisha. Infected crabs from culture ponds, tanks, and the wild exhibited lethargic movement. Wet mount analyses revealed a high presence of viral giant cells in the hepatopancreas and connective tissues. Histopathological analysis showed MCRV inclusion bodies in the connective tissues of the hepatopancreas, gill lamellae, muscles and gonads. Similarly, viral particles proliferated within the cytoplasm of the cells without affecting the host nuclei. The presence of the virus in crab samples was confirmed by PCR using specific primers (ReoF and ReoR), and rDNA sequence analysis revealed a 99 percent similarity with mud crab reovirus and *S. serrata* reovirus (OL466868 and OL466869). Transmission electron microscopy showed that MCRV viral particles measured 70–75 nm in diameter, had an icosahedral shape, were non-enveloped, and possessed two capsid layers located in the cytoplasm. The prevalence of MCRV infection ranged from 80 to 100 percent in farmed crabs within 25 days and 19 to 33 percent in wild samples. In pathogenicity studies, an intramuscular injection bioassay resulted in 100 percent mortality, while a cohabitation assay led to 70 percent mortality 14 days post-infection, indicating that MCRV is highly pathogenic in mud crab culture. To ensure disease-free production, strict biosecurity measures are recommended during the collection and culture of mud crabs.

RESEARCH AND INNOVATION

Mud crab hatchery technology is now available in India, with the RGCA initially launching a pilot-scale project in late 2004. The technology, originally adopted from the Southeast Asian Fisheries Development Center, Aquaculture Department (SEAFDEC/AQD), was later modified to suit Indian conditions, leading to steady progress in the production and supply of mud crab seeds. Through continuous refinement, the hatchery technology has achieved higher survival rates at every critical stage. Equipped with state-of-the-art infrastructure, RGCA's mud crab hatchery now has the capacity to produce over 1 million seeds annually, meeting the growing demand from farmers.

MARKET INFORMATION

Chennai, Mumbai and Kolkata are major hubs for live mud crab collectors, who export primarily to Southeast Asian countries and the United States of America. Andhra Pradesh, Maharashtra, Odisha, and West Bengal are the leading producers of *S. serrata* and *S. olivacea*. A notable increase in total crab production was observed in 2020–21 (Table 4), with natural collection from the coastal waters of West Bengal being the highest. Apart from the period between 2020 and 2022, Andhra Pradesh consistently produced the largest volume of crabs, with Bhimavaram District being the major contributor.

Processing of live mud crabs and crab products follows a similar pattern throughout India. The live crabs are collected and carefully packed in gunny bags or bamboo baskets after tying the legs. In the case of cut crabs, the sections are prepared after cleaning and removal of the carapace, gut, gills and gonads. The sections are frozen and stored in shallow layers of shaved ice. The crab meat extraction is normally carried out using whole raw or cooked crabs. Meat extraction from uncooked crabs requires more care since contamination from hepatopancreas, gills and gonads must be avoided.

Southeast Asian countries are the major importers of Indian live crabs, while hard-shell crabs and crab products are primarily sold to China and the United States of America. These products are mainly exported from the ports of Tuticorin, Chennai, Kolkata, Visakhapatnam and Mumbai. Live crabs command a higher market price compared to other crab products. Due to high export demand, local agents charge exporters over INR 900/kg (approximately 2–3 crabs per 2 kg) for larger crabs that can be sold at a premium. India exports live mud crabs primarily to Singapore, Malaysia, China and Taiwan. Recently, soft-shell crabs or watery crabs (newly moulted crabs) weighing 90–100 g have been exported to Japan, the United States of America and Southeast Asian countries. Table 2 shows mud crab export data from India over the past 10 years.

TABLE 4
Mud crab production (t) by State in India (2018–2023)

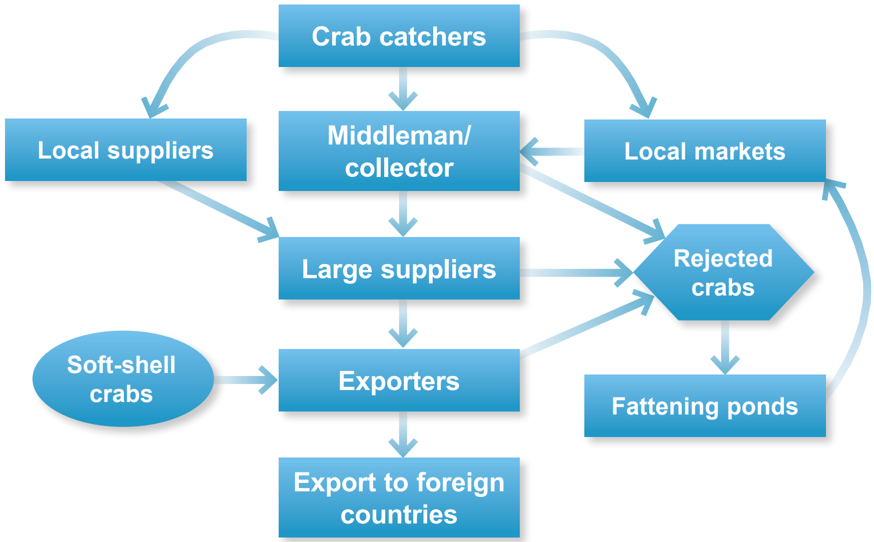
State	Production (t/yr)				
	2018–19	2019–20	2020–21	2021–22	2022–23
West Bengal	158	325	1 830	1 485	657
Odisha	356	462	576	488	344
Andhra Pradesh	665	977	1 709	797	2 061
Tamil Nadu and Pondicherry	15	19	22	51	124
Kerala	10	21	8	7	3
Karnataka and Goa	22	10	8	0.4	0
Maharashtra	445	187	366	390	292
Gujarat	0	0	0	0.6	0
Telangana	0	0	0	0	0
Total	**1 671**	**2 001**	**4 519**	**3 219**	**3 481**

Source: MPEDA. 2023. Annual report of MPEDA, 2022–2023. Kerala, India, Marine Product Export Development Authority (MPEDA).

Marketing channel of live mud crab

The mud crab trade involves a series of intermediaries, ranging from crab collectors to

FIGURE 13
Common marketing channel of mud crabs in India



exporters and local consumers. While the process does not follow a strict pattern, it typically includes crab catchers, local collectors, large suppliers, agents and exporters (Figure 13). Chennai serves as the major export centre in India, with crabs from the Andaman Islands highly sought after in the Chennai market.

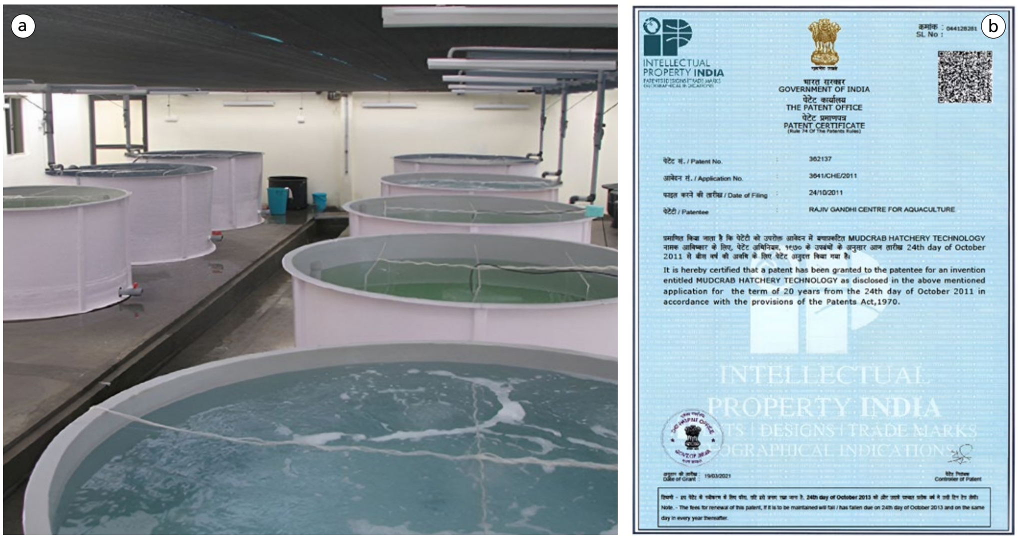
Crab collectors from the mangrove forests of north, middle, and south Andaman transport the crabs by bus to Port Blair daily. Once there, traders classify the crabs and send them to major exporters in Chennai or Kolkata by plane after enough have been gathered. *S. serrata* crabs are typically sent to Chennai, while S. *olivacea* crabs are dispatched to Kolkata. Exporters from Chennai and other parts of India primarily ship crabs to foreign markets. Crabs weighing less than 100 g as well as those rejected for other reasons, are used for domestic consumption or sent to fattening ponds.

MAJOR ISSUES AND CHALLENGES FACING THE INDUSTRY

Indiscriminate harvesting of juvenile crabs is prevalent in many commercial fishing grounds across India, including the coastal waters of the Andaman Islands. The shortage of wild seeds and the limited availability of hatchery-produced seeds are significant barriers to the expansion of crab farming in the country. Additionally, the inconsistent supply of trash fish and the unavailability of artificial feeds for mud crabs pose major challenges to the industry. Currently, MPEDA-RGCA operates the only commercial mud crab hatchery in India, highlighting the urgent need for additional hatcheries to meet the growing demand for crab seed stock in the farming sector.

Recent outbreaks of mud crab reovirus (MCRV) in both farms and wild populations present a significant challenge for mud crab aquaculture in India. Furthermore, RGCA's genetic studies have revealed that mud crabs exhibit notably low genetic variation both among and within populations (unpublished data), which could threaten future selective breeding programs and the management of viable genetic stocks. To address these issues, establishing more private hatcheries and nursery rearing facilities across different regions of India is essential. Additionally, MPEDA-RGCA should consider establishing a brood bank to produce quality broodstock, which can then be

FIGURE 14
Larval rearing tank at the MPEDA-RGCA mud crab hatchery (a) and the technology patent awarded by the Government of India (b)



supplied to hatcheries for disease-free seed production.

RECOGNITION OF MUD CRAB HATCHERY TECHNOLOGY

The mud crab hatchery technology developed by RGCA has been granted a patent by the Controller General of Patents, Designs, and Trademarks, Government of India, valid from 2011 to 2030 (Figure 14). In response to the significant demand for mud crabs, particularly in Southeast Asian countries, MPEDA launched a pilot project for mud crab seed production in 2004. This initiative led to the establishment of India's first commercial hatchery in 2013, with an initial capacity of 1 million seeds per annum. The hatchery technology for *S. serrata* was developed with technical assistance from Dr Emilia Quinitio from the Philippines. Currently, the hatchery produces approximately 1.5 million seeds annually, significantly enhancing mud crab aquaculture in India.

CONCLUSION

To achieve sustainable mud crab production that supports the livelihoods of coastal communities, it is crucial to ensure an uninterrupted supply of high-quality seeds and implement organized farming practices. A cluster farming approach could be an effective strategy to meet export demand. However, emerging diseases pose a significant threat to the future of mud crab farming, making it essential to maintain strict biosecurity measures throughout all stages of the culture process to control the spread of pathogens.

Given that wild populations are already under threat due to overexploitation, it is necessary to establish more hatchery and nursery facilities to meet the growing demand for seed stock, thereby alleviating pressure on natural habitats. Additionally, the creation of a national broodstock bank is essential for the sustainable management of mud crab resources.

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Status of mud crab industry in Bangladesh

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ABSTRACT

Capture fisheries, aquaculture and trading of mud crab in Bangladesh is widely practised and has a long history of commercial exploitation of wild stocks. The two common species of mud crabs in Bangladesh are *Scylla olivacea* and *Scylla serrata*, of which *S. olivacea* is the dominant species. The status of the wild population is unknown, but with long and continuous exploitation of the wild resources, the crab population has shown a significant decline in abundance and size. Therefore, several regulations and policies have been introduced and a few more proposed to warrant the sustainability of the industry. The effective implementation and enforcement of these regulations and policies are essential.

Production of mud crabs has increased over the last 10 years. Hard-shell mud crabs from aquaculture contribute 32–40 percent of the total national production. In 2022, the production of hard-shell mud crabs stood at 13 397 tonnes (9 110 t from capture fisheries and 4 287 t from aquaculture) while soft-shell crab production was around 404 tonnes. Broodstock management as well as larval and nursery standard rearing practices and efficient technologies are still limited. At present four medium- to large-scale crab hatcheries have been established in the country. The protocol for mud crab production is continually being refined to enable commercial scale crablet production. Crab fattening is widely practiced in shrimp ghers and grow-out ponds. Recent advancements in technology and increased investments in soft-shell crab farming have expanded aquaculture activities. However, sudden crab mortality during culture is a common issue in grow-out ponds and fattening systems. Other challenges include delayed moulting, shell hardening issues, and disease outbreaks. Farmers occasionally face mass crab mortality in ponds, which may be linked to White Spot Syndrome Virus (WSSV), a common pathogen in shrimp farming.

At both the local and national levels, there are significant gaps and challenges that hinder the strategic management and development of the mud crab industry. Key approaches have been identified to address these issues and support the sustainable growth of mud crab aquaculture in the country.

INTRODUCTION

Mud crab aquaculture has been practised for many years in the brackish water coastal regions of Bangladesh (Chakraborty, Azad and Sarker, 2018). Mud crab is an economically important aquaculture species in many Asian countries (Yalin and Qingsheng, 1994; Overton and Macintosh, 1997; Fazhan *et al*., 2017; Apine *et al*., 2023). The Organization for Economic Cooperation and Development (OECD) reported nearly 424 000 tonnes of crab production through aquaculture in 2021 of which Bangladesh contributed 2.9 percent (Table 1) (OECD, 2024). The first crab export was in 1977, sourced mainly from the wild (Ali *et al*., 2004). Capture fisheries and trade have gradually developed and gained viability in Southwestern coastal Bangladesh since the 1990s (Azam, Kamal and Mostofa, 1998) due to the abundance of

TABLE 1
Crab aquaculture production in selected OECD and non-OECD countries (2012–2021)

Country		Crabs and sea-spiders (t)									
		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
OECD Members	Greece	38	22	–	50	29	11	62	95	70*	144
	Japan	0	0	–	–	–	–	–	–	–	–
	Spain	1	1	1	3	0	0	–	2	2*	–
Non-OECD Economics	Bangladesh	–	–	–	–	13 160	14 421	11 787	12 084	12 562	12 337
	China	233 648*	247 843*	259 564*	26 2044*	282 653	286 031	293 797	293 643	287 500	282 655
	India	3 000*	4 000*	5 000*	6 000*	6 500*	7 000*	7 500*	7 600*	7 900	8 400*
	Indonesia	14 268	11 911	13 606	12 546	11 407	11 657	33 807	14 217	10 784	12 839
	Malaysia	42	14	36	61	14	96	15	234	210	206
	Philippines	16 360	15 794	16 160	16 199	16 860	18 100	20 770	20 772	20 766	23 112
	Taiwan Province of China	231	142	125	113	535	163	134	132	96	46
	Thailand	700*	700*	800*	800*	1 000*	1 100*	1 773	1 561	2 558	3 482
	Viet Nam	13 000*	13 000*	49 140*	54 588	64 633	65 463	36 000	198 729	80 162	81 144

* Estimated values.

Source: OECD. 2024. Agriculture and Fisheries. Fisheries and Aquaculture. Fisheries and Aquaculture statistics. Aquaculture production; Species - Crabs, Sea Spiders. [Accessed on 08 Apr 2024]. https://stats.oecd.org/Index.aspx?DataSetCode=FISH_AQUA#. License: CC BY 4.0.

crabs in Sundarbans mangrove forests and adjoining coastal areas (Chandra, Paul and Das, 2012; Rouf *et al*., 2021).

Mud crab species

Sarower *et al*. (2017) reported that *S. olivacea* is the dominant mud crab species in Bangladesh. Similarly, studies by Habib *et al*. (2016, 2022) and Akter (2016) confirmed that *S. olivacea* is the most common species along the coastlines of Bangladesh, including the Sundarbans. In coastal regions, approximately 82 percent of the sampled crab population consists of *S. olivacea*, while the remaining 18 percent consist of *S. serrata*.

Wild stock status

It is difficult to assess the status of existing natural crab stocks in Bangladesh due to the absence of population data on wild crabs. However, it is widely speculated that wild crab stocks, particularly in the Sundarbans mangrove forest, are at risk and possibly overexploited (Azam, Kamal and Mostofa, 1998; Kosuge, 2001). Rahman *et al*. (2017) reported that crab collectors have observed a decline in catch per unit effort. For instance, 4–5 kg of crabs could be collected daily five years ago, but now only 2–5 kg are sourced. Additionally, the average size of crabs has decreased from 250–350 g to 100–150 g. Collectors are also forced to venture deeper into the dense forests to meet their daily collection targets (Rahman *et al*., 2017). A market study in coastal Bangladesh further confirmed a declining trend in the availability of different crab grades.

A decline in the wild female crab population in natural habitats has been observed (Chakraborty, Azad and Sarker, 2018). Additionally, the availability of larger size-grade crabs has significantly decreased compared to 10–20 years ago (Sakib *et al*., 2022). This depletion in both the abundance and size of wild crab populations is attributed to indiscriminate harvesting, overexploitation, habitat loss, environmental degradation, and the impacts of climate change (Kosuge, 2001; Hoq, 2007; Rahman *et al*., 2017; Istiak, 2018). The recent establishment of over 300 soft-shell crab farms in the coastal regions of Bangladesh is entirely dependent on wild seed supply, which has resulted in intense harvesting pressure on small crabs from natural sources to meet the high seed demand (Noorbaiduri, Abol-Munaf and Ikhwanuddin, 2014; Hungria *et al.*, 2017; Rahman *et al.*, 2018).

Conservation and management of wild resources

There are a limited number of regulations and policies instituted for the management of mud crab fisheries. Existing regulations are applicable to fisheries in general, encompassing mud crab fishery. Under the legislation of major fisheries regulations for the Sundarbans Reserve Forest (SRF), the Forest Department has implemented the following regulations that are relevant for mud crab fishery management:

- Collection and Export of Live Crab Regulation (1995): Closure of the entire SRF for crab fishing from December to February to ensure crab breeding.
- Closed Season Regulation (2000): Closure of fishing in the entire SRF for five species (*Pangasius pangasius*, *Plotosus canius*, *Lates calcarifer*, *Macrobrachium rosenbergii* and *Scylla* spp.) from 1 May to 30 June to ensure natural breeding.

Under the legislation of Wildlife Sanctuary Regulations, 1999, the Forest Department further implements the following regulations that also protect the mud crab fisheries:

- Fishing is permanently prohibited in the three wildlife sanctuaries of SRF.

A proposed regulation for the management of mud crab fisheries in Bangladesh aims to maintain current exploitation rates for commercial species, except for *Penaeus monodon* fry, as recommended by the FAO (Project BGD/84/056) in 1994 and implemented by the Forest Department. This regulation is intended to ensure the sustainable management of mud crab resources.

The World Bank proposed the following regulations back in 1998:

- Establishment of annual harvest limits for various species, starting with hilsa shad (*Tenualosa ilisha*), all catfish and mud crab species.
- Prohibition on harvesting gravid or egg-bearing female crabs.
- Implementation of minimum harvest size limits: 200 g for male and 120 g for female crabs.
- Permanent closure of wildlife sanctuaries and other protected areas to all fishing activities.
- Maintenance of detailed records for permits issued and the catch of all species by individual fishermen.
- Enforcement of the National Fish Act to uphold minimum harvest size limits and enforce seasonal fishing bans.
- Penalties for violations, including fishing without a permit, fishing in restricted areas, using poisons, explosives, or banned materials, catching undersized fish during prohibited months, or continuing to fish after reaching the individual quota.

Furthermore, the Forest Department in Khulna under the Sundarbans Biodiversity Conservation Project (SBCP) proposed new management regulations for the 17 fisheries in the Sundarbans that include mud crab as follows:

- Mud crab fishing to be prohibited annually from December to February.
- A minimum size limit of 10 cm carapace width is required for male mud crabs.
- Catching or possessing female mud crabs is strictly illegal.

Management and regulation of mud crab aquaculture

Currently, there are no regulations, licensing and certification in both hard-shell and soft-shell crab production.

Industry status

The mud crab production status over the past 10 years, as reported by the Department of Fisheries (DoF, 2022), Fish Inspection and Quality Control (FIQC, personal communication, 2023) and soft-shell crab farm data, is summarized in Table 2. Hard-shell crabs from aquaculture contribute 32–40 percent of total production. Capture fisheries harvest only hard-shell crabs from wild sources, primarily for live export, while aquaculture similarly focuses on live exports of hard-shell crabs.

TABLE 2
Hard-and soft-shell crab production from capture fisheries and aquaculture (2012–2021)

Fiscal Year	Capture fisheries hard-shell crab		Aquaculture hard-shell crab		Aquaculture soft-shell crab	
	Volume (t)	Value (BDT 10 million)	Volume (t)	Value (BDT 10 million)	Volume (t)	Value (BDT 10 million)
2021–2022	9 110	464.17	4 287	218.43	403.82	69.78
2020–2021	8 389	352.28	3 948	165.78	147.43	28.66
2019–2020	8 542	838.28	4 020	394.48	289.54	59.41
2018–2019	8 217	784.26	3 867	369.07	542.57	105.48
2017–2018	7 072	557.41	4 715	371.60	216.94	49.20
2016–2017	8 653	694.34	5 768	462.89	279.39	51.30
2015–2016	7 896	528.14	5 264	352.09	120.58	20.84
2014–2015	8163	129.60	4 395	69.78	140	22.68
2013–2014	5 010	107.09	2 697	57.66	–	–
2012–2013	4 828	110.17	2 600	59.32	–	–

Source: DoF. 2022. Yearbook of Fisheries Statistics of Bangladesh, 2021–22, Volume 39. Dhaka, Fisheries Resources Survey System, Department of Fisheries, Ministry of Fisheries and Livestock.

Farming areas

Most coastal brackish water bodies in exposed coastal landscapes are well-suited for crab farming. A total of 9 353 ha of water areas have been designated for crab farming (DoF, 2022). Additionally, 262 980 ha of coastal ponds currently used for shrimp farming also hold potential for mud crab aquaculture (DoF, 2022). Salam, Ross and Beveridge (2003) identified, through GIS models, 228 111 ha of highly suitable land, 552 897 ha of moderately suitable land, and 30 072 ha of marginally suitable land for crab farming in coastal areas (Figure 1).

Selected zones in the Sundarbans mangroves and inshore areas may also be considered for cage and pen culture of mud crabs, practices commonly used in other countries (David, 2009). The supply of mud crabs for export comes from three coastal regions: the southwest (Khulna, Bagerhat, Satkhira, Pirojpur, Barguna, and Patuakhali districts), southeast (Chattogram and Cox's Bazar districts) and central coastal areas (Bhola, Laxmipur, and Noakhali districts) (Figure 2).

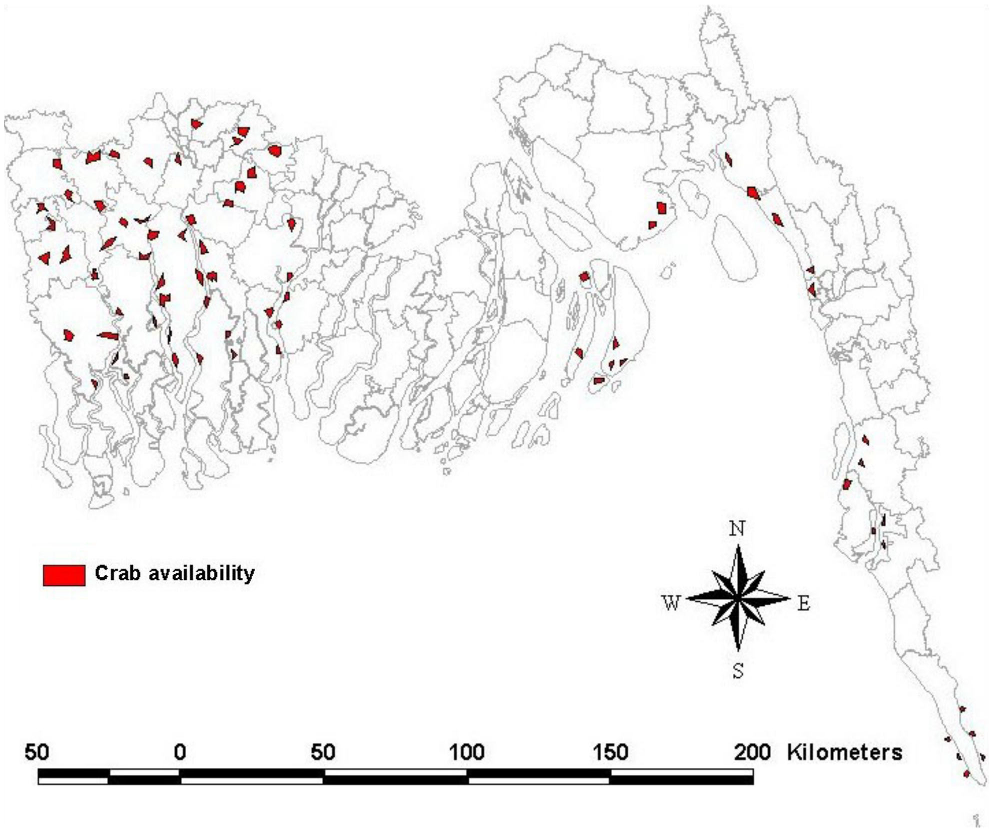
According to DoF (2019), over 90 percent of crab farming occurs in the southwest coastal region, followed by 8 percent in the southeast, and 2 percent in the central coastal region. Most crab farming is concentrated in Khulna, followed by Bagerhat and Satkhira districts, with smaller farming areas in Chattogram and Cox's Bazar districts (Figure 3).

AQUACULTURE PRACTICES AND METHODS

Broodstock management

Since 2013, various initiatives have been undertaken by research institutions, government agencies, non-governmental organizations (NGOs), and international non-governmental organizations (INGOs) to culture mud crabs in hatcheries.

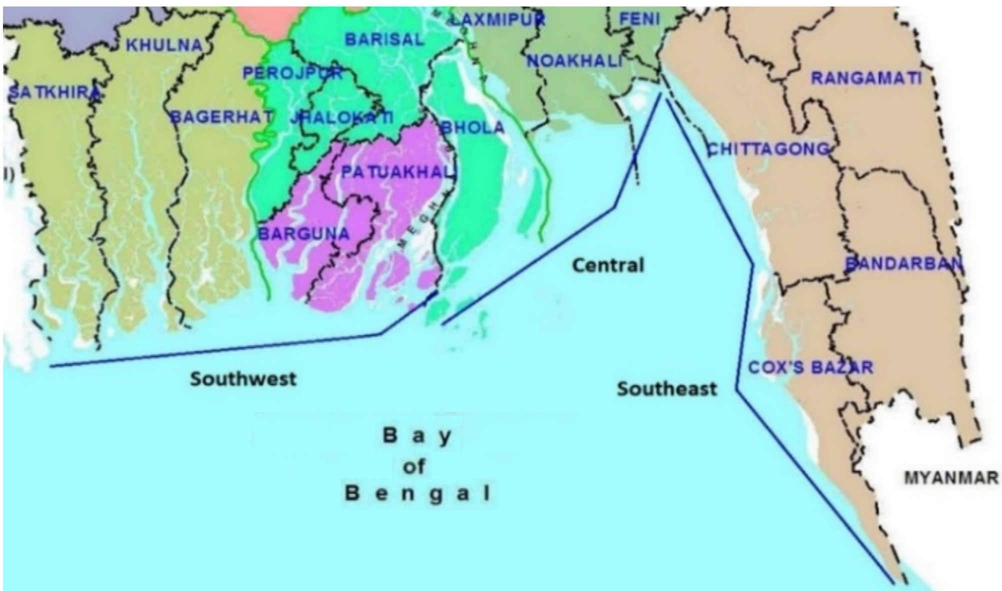
FIGURE 1
Available coastal areas for mud crab aquaculture in Bangladesh



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Salam, M.A., Ross, L.G. & Beveridge, C.M.M. 2003. A comparison of development opportunities for crab and shrimp aquaculture in southwestern Bangladesh, using GIS modelling. Aquaculture, 220: 477–494.

FIGURE 2
Coastal regions and districts where most mud crabs are cultured and sourced in Bangladesh



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

FIGURE 3
Mud crab farming areas (ha) by districts in coastal regions of Bangladesh

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: DoF. 2022. Yearbook of Fisheries Statistics of Bangladesh, 2021–22, Volume 39. Dhaka, Fisheries Resources Survey System, Department of Fisheries, Ministry of Fisheries and Livestock.

However, none of the hatcheries have achieved commercial production of crablets. The Department of Fisheries in Cox's Bazar has reported a 3 percent survival rate from zoea 1 to crab instar.

Mature female crabs with dark orange ovaries, referred to as broodstock or ovigerous females (berried females with eggs attached to their flap), are collected from mangrove forests (such as the Maheshkhali Channel in Cox's Bazar) and transported to hatcheries. These ovigerous females are carefully transported in buckets or boxes containing water from their source, along with aeration provided by portable aerators. Upon arrival at the hatcheries, the crabs are gradually acclimatized to a salinity of 27–30 ppt and disinfected using a 100–150 ppm formalin bath. Ovigerous females are then stocked individually in 30–50 L plastic buckets filled with aerated clean seawater, while non-ovigerous females are placed in tanks with sand substrates and aeration. In some cases, eyestalk ablation is performed to induce maturation. Feeding consists of molluscs, fish, squid and other affordable protein sources available in the area, with crabs fed to satiation twice daily.

Broodstock that have spawned are transferred to the bucket with aerated clean seawater. Feeding of ovigerous females is stopped when their egg mass turns brown or grey in colour. Newly hatched zoeae are stocked in concrete or fiberglass tanks.

Larval rearing

Seawater used for larval rearing is disinfected with 15–20 ppm of chlorine, and additional treatment using UV light or ozone is sometimes employed. Newly stocked larvae are introduced at a density of 50–100 ind./L and are initially fed umbrella-stage *Artemia* or rotifers when available. Starting from zoea stage 2 or 3, formulated shrimp feed is introduced. Newly hatched *Artemia* are provided to early zoeae, while biomass *Artemia* are given to older zoea until they reach the early megalopa stage.

The rearing environment is maintained at a water temperature of 27–30 °C and salinity levels of 27–32 ppt, with limited water changes to minimize disturbance and stress to the larvae. Prophylactic measures are implemented until the megalopa stage is reached. The duration from zoea 1 to megalopa stage is approximately 18–20 days. Once the zoea reach stage 5 or megalopa, they are transferred to other tanks equipped with hanging shelters that allow the megalopae to cling to surface areas. The crab instars are then harvested and transferred to a nursery facility.

Nursery rearing

The nursery system is still in its early stages, as the number of crablets produced in the hatchery has not yet reached a commercially viable level. However, hatchery-reared crablets are further cultured in nursery tanks or ponds until they reach a size that is acceptable to farmers.

Grow-out culture

Farmers depend entirely on wild stocks for both farming and export (Rahman *et al.*, 2018). Following disease outbreaks in shrimp farms during 1995–1996, many shrimp ponds along the coast were converted into crab farms (Karim and Stellwage, 1998). The water culture parameters for crabs and shrimp are similar; however, crab farming has demonstrated potential to support vulnerable coastal communities due to its resilience and adaptability in the face of climate change (Rahman *et al.*, 2017).

In Bangladesh, several mud crab culture systems are practiced, including grow-out culture from juvenile to market size, polyculture with shrimp and fattening, as summarized in Table 3. These systems vary in terms of stocking density, feeding practices, culture duration and production outcomes.

TABLE 3
Mud crab culture systems in Bangladesh

Culture system	Stocking/ practice	Stocking density (crabs/ha)	Feeding/ practice	Feeding rate (body weight %/frequency)	Culture period (days)	Production (t/ha/crop)	Production (%)
Grow-out culture	Not standard practice	5 000–10 000	Not standard practice	1–5/weekly	180–210	0.4–0.5	5
Shrimp gher* production	Not standard practice	–	Not standard practice	Satiation	120–180	0.3–0.5	30
Fattening	Following a stocking protocol	9 000–16 500**	Following a feeding protocol	5–10/daily	15–45	0.7–1.3	65
Total							**100**

* Earthen enclosure.
** Crabs usually tied to prevent cannibalism.

Some farmers engage in grow-out culture by stocking small crabs (1–50 g) in ponds and ghers to raise them to market size (Figure 4). Marginalized coastal fishers collect seed stocks using push nets in the marshes of the Sundarbans mangrove forest, estuaries, canals and tidal rivers from January to March. They sell the seed to grow-out farmers at USD 0.01–0.02/piece. The crablets are then stocked in confined waters enclosed by bamboo or net pens. Most farmers follow traditional practices without adhering to specific stocking densities or implementing measures to enhance growth and survival. The crablets often enter shrimp ghers during water exchange, where they grow alongside the shrimp until they reach marketable size. In this system, farmers primarily focus on shrimp cultivation, while the crabs grow without direct management, with no additional stocking or feeding.

During the first half of the year, farmers stock crablets in ponds for 3–4 months, providing minimal feed on an irregular basis. In the second half of the year, the crabs

FIGURE 4
Wild crablets for grow out culture in brackish water ponds

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are fattened in the same ponds. The lack of separate nurseries and grow-out ponds leads to increased cannibalism due to significant size variations among the crabs.

Crab production in shrimp gher

Coastal brackish waters in Bangladesh have primarily been used for shrimp farming. Crablets are introduced into traditional shrimp ponds during water intake from adjacent canals. Initially, crabs in shrimp ghers were regarded as an invasive species because they could damage pond dikes and compete with shrimp for food and space. However, due to the high market price of crabs and the socioeconomic and environmental challenges associated with shrimp farming, their cultivation along with shrimp has become acceptable, providing farmers with an additional source of income. Currently, thousands of hectares of traditional shrimp ghers are being utilized for crab farming (Figure 5). It is estimated that nearly 30 percent of the total production of hard-shell crabs comes from traditional shrimp farms, with Kamal, Khanom and Rheman (2007) reporting this figure to be around 45 percent.

FIGURE 5
Shrimp ponds used for mud crab production

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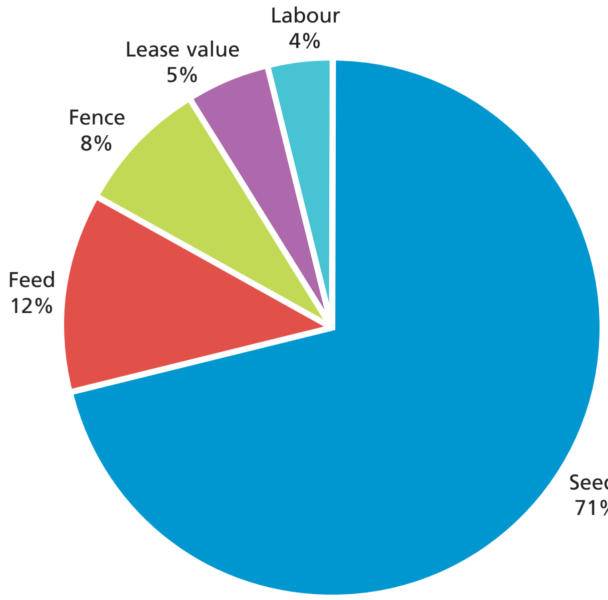
Fattening of crabs

Crab fattening has been widely practiced by coastal fishers and farmers. Grow-out culture began in enclosed ponds in the early 1990s, followed by the introduction of bamboo cages, pens, and pots in the early 2000s (Rahman *et al*., 2020; Kamal, 2002; Khatun *et al*., 2009). Farmers typically stock small, undersized male crabs weighing between 100–280 g, along with female crabs that have undeveloped gonads, ranging from 60–110 g. Over 90 percent of farmers engaged in fattening prefer polyculture, raising crabs along with other fish species such as tilapia (*Oreochromis niloticus*), parshe (M*ugil cephalus*), tengra (*Mystus gulio*), bhangan (*Labeo boga*) and khorsula

(*Rhinomugil corsula*). In terms of profitability, better economic returns are achieved by co-cultivating mud crabs with tiger shrimp, milkfish, and/or mullet (Marichamy and Rajapackiam, 1996; Venugopal *et al.*, 2012; FAO, 2015). Most farmers involved in crab fattening (approximately 68 percent) stock juvenile crabs during the wet season (June–November), while only 32 percent do so in the dry season (December–April). In coastal areas, 43 percent of farmers produce crabs year-round, whereas 57 percent alternate farming, dedicating six months to shrimp and six months to crab.

FIGURE 6
Percentage of fixed and variable costs in mud crab fattening in Bangladesh



Source: Rahman, M.M., Haque, S.M., Islam, M.A., Paul, A.K., Iqbal, S., Atique, U., Wahab, A., Egna, H. & Brown, C. 2020. Assessment of mud crab fattening and culture practices in coastal Bangladesh: understanding the current technologies and development perspectives. AACL *Bioflux*, 13(2): 582–596.

The average culture duration for fattening both male and female crabs ranges from 32 to 46 days. Most farmers purchase juvenile crabs from local depots, while a few buy directly from wild crab collectors (Rahman *et al.*, 2017). Crabs are primarily fed fresh minced tilapia, along with other marine and freshwater fish and snails. When available, they are also given boiled rice, chicken entrails, wheat, maize, and shrimp or prawn heads. The average survival rate of the crabs is 64–68 percent. The highest average production from crab fattening systems is estimated at 1 383 ± 67 kg/ha/crop, while the lowest average production is around 815 ± 22.6 kg/ha/crop (Rahman *et al.*, 2020). Overall, the productivity of crab aquaculture in Bangladesh is reported to be 678 kg/ha (DoF, 2017).

The average estimated cost of mud crab fattening is BDT 316 654 ± 37 042 per crop/ha. The largest expense is the purchase of crab juveniles, accounting for approximately 71 percent of the total cost, followed by feeds (12%), fencing (8%), land lease (5%) and labour costs (4%) (Figure 6). Ferdoushi and Xiang-Guo (2010) and Sathiadhas and Najmudeen (2004) reported that seed input costs represent about from 74–87 percent of operational expenses. In a cost and return analysis, the average gross return is approximately BDT 514 748 ± 32 056/ha/crop, while the average net benefit is BDT 198 094 ± 8 387/ha/crop. The benefit-to-cost ratio in current fattening systems is 1.63, whereas previous studies reported a benefit-to-cost ratio ranging from 1.18 to 1.94 (Jahan and Islam, 2016; Begum *et al.*, 2009; Ferdoushi and Xiang Guo, 2010). Generally, 90 percent of those engaged in crab fattening sell their crabs to preferred depots in nearby markets, while the remaining farmers sell their crabs to local middlemen.

Soft-shell crab production

The production of soft-shell crabs in small, perforated plastic boxes was first introduced in Cox's Bazar in 2010 and gradually expanded to the Satkhira region on a limited scale (Islam, Aleem, and Rahman, 2015; Lahiri *et al.*, 2021). Due to the higher profitability of soft-shell crabs in the international market, the establishment of medium- and large-scale farms in this area has significantly increased from 2018 to 2022 (FAO, 2015; He, 2015). Crabs weighing between 50 and 150 g (Figure 7) are sourced from nearby depots or directly from suppliers and middlemen, and are individually stocked in

FIGURE 7
Juvenile crabs of various sizes (50–150 g) used for soft-shell crab production

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FIGURE 8
Crab boxes positioned in PVC frames for soft-shell crab production in brackish water ponds

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small, perforated plastic boxes placed within PVC frames (Figure 8). As of 2023, approximately 400 farms are operational in the southwestern coastal region of the Satkhira district. Based on production capacity, 361 farms are categorized as small (2 000–30 000 cage capacity), 35 as medium (31 000–200 000 cage capacity), and only four as large (200 000–800 000 cage capacity). These farms occupy 170–190 hectares of coastal areas that were previously used for shrimp farming. Most of these operations are owned by affluent non-local businessmen, with land leased for a minimum of five years. Due to the substantial investment and large-scale management required, soft-shell crab farms are predominantly operated by corporations (Rahman *et al*., 2017).

Crabs are primarily fed minced tilapia, which makes up 75–80 percent of their diet, along with small snails comprising 20–25 percent, at a feeding rate of 5–10 percent of their body weight every 3 days or as needed (FAO, 2015). During high tides, pond water is gradually replaced, up to 30–50 percent. Moulting is monitored every 4 hours, and once crabs have moulted, they are immediately retrieved and placed in containers with aerated freshwater for 30–60 minutes. After this period, the crabs are transferred to trays, covered with wet cloths and transported to the processing plants (Figure 9). This labour intensive monitoring of moulting facilitates the prompt harvesting of soft-shell crabs.

The production of soft-shell crabs is widely recognized as having significant potential to enhance the livelihoods of coastal communities by generating income from lucrative foreign markets. However, sourcing seed stocks has become a growing concern.

The Nowabenki Gonomukhi Foundation (NGF), an NGO based in Shyamnagar, Satkhira district, has initiated a program for recycling crab waste shells from moulting (Figure 10). The discarded shells are dried on bamboo platforms, crushed into small pieces, and mixed with leaves and manure. This mixture is kept moist for 10–15 days to facilitate decomposition, after which it is used as organic fertilizer for various plants, including vegetables.

MUD CRAB HEALTH AND DISEASE MANAGEMENT

Sudden mortality of crabs during the grow-out or fattening stages is often observed, likely due to poor quality and rough handling of juvenile crabs sourced from depots or middlemen. Other issues include delayed moulting, incomplete hardening of shells and disease. Farmers occasionally experience mass mortality in their ponds, which may be attributed to the white spot syndrome virus (WSSV), a pathogen commonly found in shrimp culture (Karim and Stellwagen, 1998). Unfortunately, farmers rarely implement preventative measures during their operations, relying mainly on the application of lime during pond preparation. In some cases, potassium permanganate is used as a disinfectant for pond water. Additionally, prior to stocking, some farmers splash seawater on juvenile crabs that have been exposed to air during transport.

While no specific diseases have been reported in soft-shell crab farming in coastal regions, farm operators frequently encounter delayed moulting and mortality. Deterioration of pond water quality, along with abrupt fluctuations in salinity and temperature, can also lead to crab mortality. To address this, pond water is treated with dolomite or other types of lime to adjust pH and alkalinity, and probiotics are applied in some instances. Regular water changes are performed to prevent deterioration in water quality and minimize the risk of disease outbreaks.

FIGURE 9
Soft-shell crabs in plastic boxes ready to be delivered to a processing plant

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FIGURE 10
Exoskeletons of moulted crabs from soft-shell crab production farms in Satkhira district, Bangladesh

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For biosecurity measures, pond dykes used for soft-shell crab production are constructed higher than usual. The entire farm is enclosed with nets to prevent the entry of unwanted animals.

RESEARCH AND INNOVATION

Aquasilviculture

Aquasilviculture was implemented by NGF using eight enclosed pens. These enclosures, located in mangrove areas, were stocked with wild juvenile crabs and grown to market size. While the initiative achieved moderate production, it demonstrated promising potential for small-scale crab farming within mangrove ecosystems.

Small-scale crab hatchery

Several NGOs, with financial support from donors, have established small-scale crab hatcheries in various locations across the southwest and southeast coastal regions. These hatcheries utilize the same technologies employed in commercial crab hatcheries. Collectively, they have an estimated annual production capacity of 300 000 to 500 000 crablets.

Nursery

A comparative study was conducted to assess the overall performance (growth, survival, morphometric variations, etc.) of wild-sourced versus hatchery-reared *S. olivacea* crablets in earthen ponds. The results indicated that hatchery-reared crablets outperformed their wild-sourced counterparts in all measured parameters. This finding has positively influenced farmer perceptions regarding the use of hatchery-reared crablets (Sarower *et al*., 2021).

Integrated crab learning centre

Coast Foundation, an NGO based in Cox's Bazar, has established an Integrated Crab Learning Center. This facility allows individuals to observe the full spectrum of crab farming operations, including hatchery, nursery, grow-out and soft-shell crab production. The centre also provides comprehensive technical information and documentation. Training is delivered by resource experts as a public service to interested farmers, who can also access technical support and obtain crab seedstock for their farming operations.

MARKET INFORMATION

The major markets for hard-shell and soft-shell mud crabs are outlined in Table 4. China is the primary market for hard-shell crabs, followed by Hong Kong SAR, Taiwan Province of China, and, to a lesser extent, Japan. Demand for live mud crabs in these markets remains consistently high throughout the year, with peak demand and prices during the Chinese New Year (January/February). Other markets exhibit less stability in terms of regular demand. The hard-shell crab export market in Bangladesh is predominantly controlled by Chinese importers.

For soft-shell crabs, the largest importer is Japan, followed by Australia, the United States of America, the United Kingdom of Great Britain and Northern Ireland, and the Kingdom of the Netherlands. Australia maintains a steady demand for soft-shell crabs while small volumes are occasionally imported by Germany and Spain.

TABLE 4
Major markets for hard- and soft-shell crabs produced in Bangladesh

Products	Top export destinations	Export share (%)
Hard-shell mud crabs	China	62
	China, Hong Kong SAR	13
	Taiwan Province of China	11
	Republic of Korea	7
	Japan	3
	Thailand	2
	Malaysia	1
	Singapore	1
Soft-shell mud crabs	European Union	3
	Australia	33
	Japan	37
	United States of America	9
	United Kingdom	8
	Netherlands (Kingdom of the)	8
	China	1

Product prices

Table 5 shows the pricing structure for hard-shell and soft-shell crabs in both primary aggregation and export markets. Hard-shell crabs are exported live, with market prices fluctuating throughout the year, irrespective of grade or sex. Soft-shell crabs consistently command a higher market price compared to hard-shell crabs.

TABLE 5
Price of hard- and soft-shell crabs at primary aggregation, farm and export markets from 2013 to 2022

Year	Price			
	Hard-shell crabs		Soft-shell crabs	
	Primary mud aggregation market (t/BDT million)	Export market (t/BDT million)	Farm (t/BDT million)	Export market (t/BDT million)
2022	1.45	1.51	1.19	1.73
2021*	0.44	0.52	1.40	1.94
2020*	0.92	0.98	1.51	2.05
2019	1.36	1.45	1.40	1.94
2018	1.39	1.44	1.84	2.27
2017	1.38	1.43	1.40	1.84
2016	1.25	1.36	1.30	1.73
2015	1.32	1.41	1.19	1.62
2014	1.25	1.33	–	–
2013	1.22	1.31	–	–

* Peak of COVID-19 pandemic.

MAJOR ISSUES AND CHALLENGES FACING THE INDUSTRY

- Lack of seedstocks for grow-out culture and soft-shell crab production; limited hatchery-reared crab seed forcing the farmers to depend on wild stock. Farming of crabs is dependent on wild stocks which have been depleted due to indiscriminate harvesting and degradation of the natural habitat.
- Lack of technical expertise, training and extension services in crab fishery development and management.
- Lack of data on wild stocks (e.g. population status, breeding season, breeding and nursery grounds).
- Inadequate post-catch handling practices, including insufficient storage facilities and suboptimal transportation systems, contribute to high mortality rates.
- Inadequate data on production quantities, markets (price and demand) and export volume.
- Lack of appropriate policies for the sector, and inadequate coordination among relevant government agencies and stakeholders.
- Limited domestic consumption, coupled with the absence of a standardized grading and pricing system.
- Collaboration challenges between the Forest Department and the Department of Fisheries regarding crab fishery management.
- Lack of artificial or commercial feeds for crab culture.
- Absence of cooperatives and social support services for crab fishers and farming groups.

CONCLUSION

Recent increases in mud crab fisheries and aquaculture activities, coupled with advances in technology, indicate that the industry will continue to develop within coastal communities. However, the sustainability of the mud crab aquaculture industry in the country remains a concern. The following key approaches can be adopted to promote the sustainable expansion of mud crab aquaculture:

- *Development of commercial-scale hatcheries*: Establishing additional hatcheries and producing crablets at a commercial scale is essential to support farmers. This initiative requires backing from the government and other stakeholders, including the private sector and funding agencies.
- *Assessment of wild stocks*: It is crucial to assess the status of wild mud crab populations, including breeding seasons and distribution, particularly in the Sundarbans mangrove areas. This assessment will inform the development of appropriate conservation and management strategies for a sustainable crab industry.
- *Zonation for crab farming*: Identifying the most suitable areas for commercial crab farming and expansion is necessary to optimize production.
- *Training*: Farmers should receive training in improved technologies and best management practices for mud crab culture. Additionally, extension workers should provide ongoing technical support and services.
- *Dissemination of information*: Information, Education and Communication (IEC) materials are needed to effectively disseminate technology and relevant information on crab culture. It is important to share targeted educational products with different stakeholders.
- *Formation of cooperatives*: Farmers engaged in crab fattening should be organized into cooperatives to enhance collaboration and resource sharing.
- *Improved transport facilities*: Enhanced transportation facilities for live crabs should be established to minimize mortality rates during transit.
- *Export markets*: Identifying new export markets is essential for the steady growth of the crab sector, as the domestic market is limited. Concurrently, promotional activities can help expand domestic markets.

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Mud crab aquaculture situation in China

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ABSTRACT

The mud crab, *Scylla paramamosain*, is the most important marine crab species in China. In 2023, it boasted an aquaculture production of 157 012 t and a capture fisheries production of 67 079 t, contributing to a total market value of CNY 44.7 billion (approximately USD 6.2 billion). The most common mud crab culture method involves polyculture in ponds with shrimps or fish. The survival rate from seed to market-sized crab is about 10 percent. Recently, indoor factory farming systems have begun to emerge, primarily focusing on fattening and soft-shell crab culture. In China, there is a substantial market demand for mud crabs, with an estimated annual import of mud crabs from Southeast Asian countries reaching 25 000 t. Most of these imported crabs are hard-shell crabs, whereas soft-shell crabs accounted for less than 1 percent of the total. In the past, trash fish and shellfish were used to feed mud crabs, however, recent advancements have led to the successful adoption of formulated feed. Over the last decade, the hatchery production of crab seed has become economically more feasible. There are at least three commercial crab hatcheries in China, each with an annual capacity ranging from 5–15 million seeds. Under optimal conditions, the survival rates from Z1-C1 stages range from 5–15 percent. Despite these advancements, most crab farming activities still rely on seeds caught from the wild, with hatchery-reared crablets accounting for <2 percent. Therefore, there is an urgent need to further improve hatchery technology. China has initiated mud crab breeding efforts, hoping to produce new and superior breeds in the future.

INTRODUCTION

Species of crabs

In China, the main crab species that are farmed include the mud crab (*S. paramamosain*), the Asian blue crab (*Portunus trituberculatus*) and the Chinese mitten crab (*Eriocheir sinensis*). The first two species are farmed in seawater, while the latter in freshwater.

Along the coastline of China, four species of mud crabs can be found, namely *S. paramamosain*, *Scylla serrata*, *Scylla tranquebarica* and *Scylla olivacea*. Among these four species, *S. paramamosain* is the dominant species and is the only *Scylla* species farmed in China.

Wild stock status

In Guangxi Province, the wild stock population of *S. paramamosian* is estimated at about 140 tonnes. No data is available from other provinces.

Conservation and management of wild resources

Recently, the Ministry of Agriculture and Rural Affairs issued a public call to start the “Implementation Plan for the First National Aquaculture Germplasm Resources Census (2021–2023)”. To assess the status of *S. paramamosain* in East China Sea, 300 mud crabs from Jiangsu, Zhejiang and Fujian provinces were sampled by the East China Sea Fisheries Research Institute in 2021, while 500 wild mud crabs from Zhejiang, Fuajian, Guangdong, Guangxi and Hainan provinces were collected by Jimei University in 2022.

While there are no conservation and management policies dedicated specifically for *S. paramamosian*, China prohibits the sale of illegally harvested catch from restricted fishing areas and during closed seasons (April–July). As a result, mud crab capture fishery is banned for about 4 months each year.

Over the past decade, efforts have been made to enhance *S. paramamosian* stocks through the release of hatchery-reared juveniles into the East China Sea and South China Sea. It is estimated that more than 10 million juvenile crabs have been released during this period.

Management and regulation of mud crab aquaculture

To foster the growth of China's mud crab industry, local governments are encouraged to apply for a geographical indication (GI) trademark for *S. paramamosain*. This initiative is designed to support sustainable resource management, preserve and protect unique, high-quality local products, and drive the development of regionally distinctive industries. By securing GI status, these regions can safeguard the environmental and cultural value of their natural resources, enhancing both product reputation and market demand.

Simultaneously, enterprises are encouraged to pursue recognition as a national famous brand. This designation can greatly enhance market visibility, build consumer trust, and generate significant economic returns for the companies involved. Additionally, establishing these brands can stimulate regional economic growth, creating employment opportunities and reinforcing the mud crab industry's long-term sustainability.

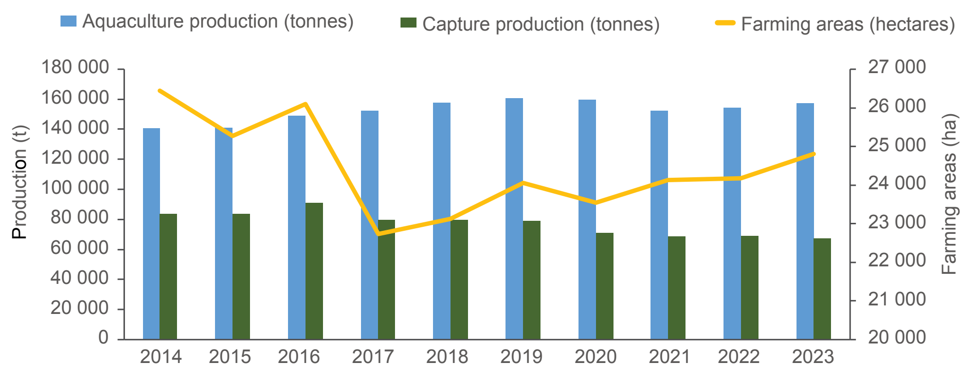
INDUSTRY STATUS

Production status

In China, *S. paramamosian* is primarily farmed in coastal areas. Over the last decade, aquaculture production of this species has remained relatively stable. In 2014, production reached 140 738 t, rising to a peak of 160 616 t in 2019. Subsequent years saw a slight decline followed by a modest recovery, with production reaching 157 012 t in 2023 (Figure 1). This level of production generated a total market value of approximately CNY 30 billion (around USD 4.1 billion).

FIGURE 1

Aquaculture and capture fisheries production and farming areas of *S. paramamosian* in China (2014–2023)



Source: China Fisheries Statistical Yearbook (2015–2024). China Agriculture Press.

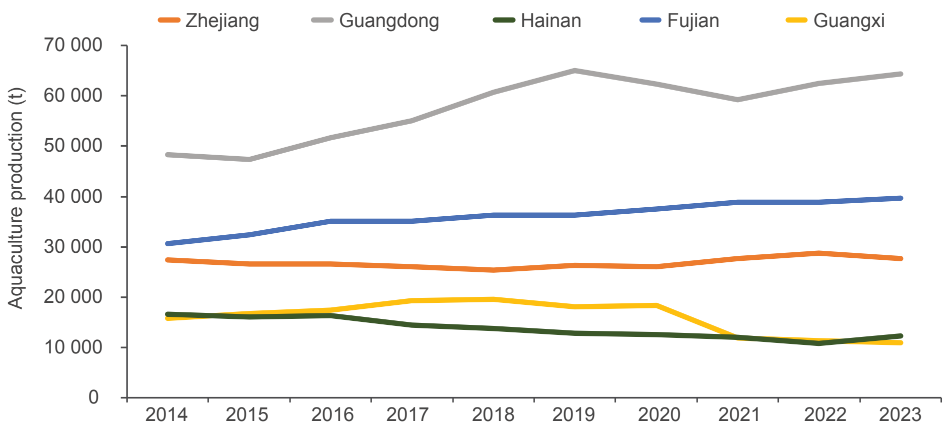
FIGURE 2
The main provinces in China with significant mud crab aquaculture activities

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.
Source: China Fisheries Statistical Yearbook (2015–2024). China Agriculture Press.

In China, mud crab aquaculture is mainly distributed in five coastal provinces, namely, Zhejiang, Fujian, Guangdong, Guangxi and Hainan (Figure 2).

In China, *S. paramamosain* is predominantly cultured in brackish water environments. For nearly a decade, Guangdong has led the nation in the aquaculture production of this species. In 2023, Guangdong's output reached 64 330 t, followed by Fujian and Zhejiang with 39 662 t and 27 601 t, respectively. Additionally, both Guangxi and Hainan each contributed slightly over 10 000 t (Figure 3).

FIGURE 3
Total *S. paramamosain* aquaculture production in five provinces in China (2014–2023)

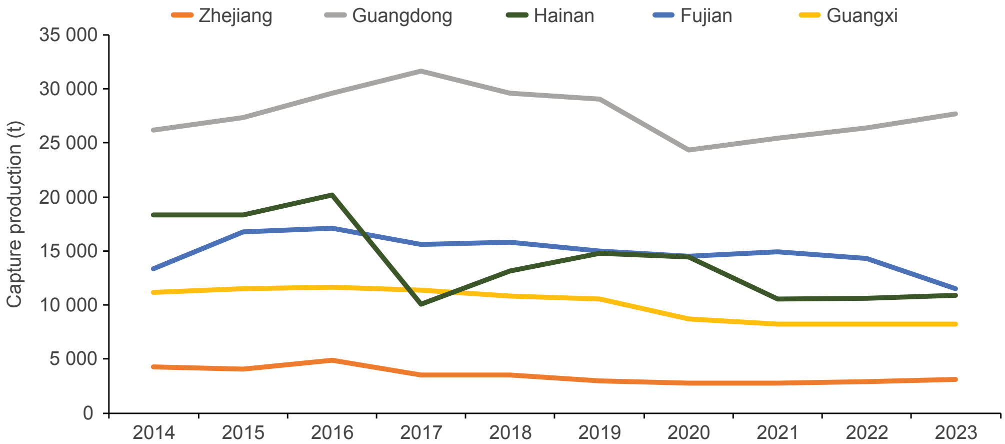


Source: China Fisheries Statistical Yearbook (2015–2024). China Agriculture Press.

S. paramamosain capture fisheries production in China has experienced fluctuations over the past decade. From 83 877 t in 2014, it reached its peak at 91 316 t in 2016. Subsequently, there was a slight decline from 2017 to 2019, with production a little over 79 000 t. However, in the last 3 years, production has decreased to less than 70 000 t (see Figure 1).

In 2023, the top three provinces in terms of capture production were Guangdong, Fujian and Hainan, with production of 27 670 t, 11 510 t and 10 901 t, respectively. The capture production in Guangxi was 8 233 t, while Zhejiang had only 3 113 t (Figure 4).

FIGURE 4
***S. paramamosain* capture fisheries production volumes in China (2014–2023)**



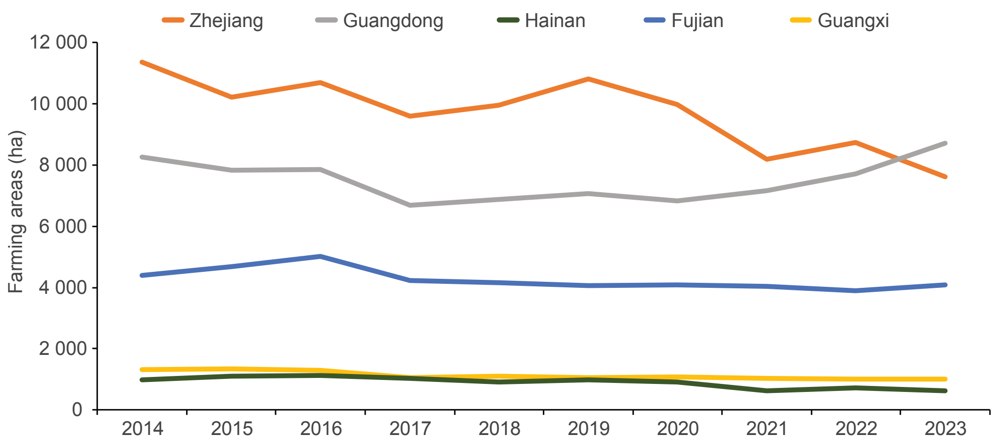
Source: China Fisheries Statistical Yearbook (2015–2024). China Agriculture Press.

Farming areas

In the past 10 years, the farming area of mud crab has undergone great changes in China. In 2014, the total farming area was 26 448 ha. However, in 2017, the farming area reached its lowest point, shrinking to 20 734 ha. Since 2019, there has been a gradual increase, stabilizing at 24 000 ha in the past 2 years (Figure 1).

The provinces with larger farming area are Zhejiang, Guangdong and Fujian. In 2023, the farming areas of these three provinces were 7613 ha, 8709 ha and 4076 ha, respectively. In contrast, the total farming area of Guangxi and Hainan was less than 2 000 ha (Figure 5).

FIGURE 5
***S. paramamosain* farming areas in China (2014–2023)**



Source: China Fisheries Statistical Yearbook (2015–2024). China Agriculture Press.

Hatcheries, nurseries, farms

Generally, shrimp and fish hatcheries are also used for mud crab larval culture and nursery. Currently, there are at least ten specially designed commercial mud crab hatcheries in China, among which Ningbo Huada Haichang Aquatic Products Co. Ltd. has an annual production capacity of 10 million juveniles (crablets), and Guangxi Institute of Oceanography Co. Ltd. has an annual production capacity of 15 million seeds. Under optimal conditions, the survival rate from Z1–Z5 is 30–60 percent, and the survival rate from Z5-C1 is about 10–30 percent. It is estimated that survival is over 10 percent from hatch to C1, and the yield can reach 2 000 seeds/m^2. Although hatcheries in China can produce seeds, the national demand for crab seeds stands at approximately 6 billion, with hatchery-reared seeds accounting for less than 2 percent of the total. Thus, it is urgent to further improve mud crab hatchery technology.

Pond farming is the predominant method for cultivating mud crabs. Brackish water ponds are strategically located in inner bays along the coast or estuaries, where there is optimal seawater exchange. In these culture ponds, the water inlet and outlet systems are distinctly separated. The pond bottom consists of sandy mud, with a sand-to-mud ratio of 1:8–9. The ditches within the ponds range from 0.5 to 1.0 m in depth and 2 to 6 m in width, maintaining a ditch-to-shoal area ratio of 1:3. These ditches are interconnected with sluice gates, and circular ditches around the bottom of pond are also excavated. In overwintering ponds, the ditches are designed to be deeper. To prevent crabs from escaping, various escape prevention measures, such as plastic planks, cement slabs or polyethylene screens, are fixed along the inner sides of the pond banks.

Land-based recirculating aquaculture systems (RAS) are used in China primarily for mud crab fattening and soft-shell crab production. The farming facility, known as a crab apartment, is assembled with boxes manufactured from non-toxic plastic. Each box is equipped with a water inlet and outlet pipe. In addition, each box has its own door for feeding and observation purposes. The crab apartments can be assembled as desired, setting the number of layers and culture chambers in accordance with farm needs and operational skills (normally a unit is composed of ten layers and ten boxes for each layer). At present, there are more than 12 kinds of crab apartments manufactured and used in China.

FIGURE 6
Crab vertical "apartments" for fattening and production of soft-shell mud crabs

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AQUACULTURE PRACTICES AND METHODS

Broodstock management

Broodstock are sourced either from the wild or from culture ponds. To ensure optimal breeding, broodstock must be robust, with all appendages intact, weighing over 350 g, and exhibiting nearly mature gonads that visibly fill the cephalothorax.

The broodstock pond is prepared with a 10–15 cm layer of fine sand at the bottom, and a 3–5 m^2 feeding area is positioned near the water outlet. Crab shelters, constructed from bricks, cement blocks or tiles, provide a habitat and refuge for the broodstock. Stocking density are maintained at 2–3 ind./m^2. Optimal culture parameters include a temperature range of 25–27 °C, salinity of 25–30 ppt, and a pH of 8.0–8.5. Light intensity should be kept below 500 lux, and minimal aeration should be supplied to ensure sufficient oxygen levels throughout the culture period.

Maintaining clean, well-aerated water is crucial for broodstock health. A recommended water depth of 60–70 cm should be maintained, with full water exchange performed once daily to remove feed residue and faeces from the culture system. The bottom sand substrate should be thoroughly cleaned every two days. As broodstock typically spawn at night or early morning, and egg hardening requires time, it is best to perform water exchanges after 08:00 to avoid disrupting the spawning process.

Broodstock should be fed a nutrient-rich diet consisting of clam, squid and fish. Additionally, *Nereis* sp. (polychaetes) should be included in the diet, as they are highly nutritious, promote gonad development and enhance egg quality. Feeding should be done daily following water exchange, and the quantity should be sufficient to leave a small amount uneaten before the next feeding session.

Natural spawning is the preferred method for broodstock. Broodstock with well-developed gonads typically begin spawning 3–5 days after being introduced into the pond. However, if spawning does not occur within 15 days, dry-shade stimulation can be used to induce spawning. This technique involves draining the pond during the daily water exchange and exposing the broodstock to air for 1–2 hours before refilling the pond with seawater. Repeated stimulation over several cycles will usually trigger spawning. It is critical that pond draining is performed when the water temperature closely matches the ambient environmental temperature to minimize thermal stress on the broodstock.

Gravid females with dense, compact egg masses are an indicator of healthy embryonic development. During this period, water temperature should be maintained between 27–29 °C, with salinity levels kept at 26–33 ppt. Maintaining these conditions is essential to preserving water quality and preventing egg shedding. As the embryos develop, the egg mass undergoes distinct colour changes, transitioning from orange to light yellow, then to grey, dark brown and eventually black. Under optimal conditions of 27–29 °C, eggs typically hatch after 11–13 days of incubation.

Larval rearing

Once the egg mass has turned black, the embryos can be examined under a microscope. At this stage, the embryo should have developed into protozoea and with a heartbeat ranging from 150–180 beats/min. The gravid crab can be transferred into a hatching tank at this stage. The hatching tank is prepared by filling the tank to 70 percent capacity and then adding 5 mg/L EDTA disodium salt and 3 mg/L florfenicol. The water temperature should be maintained at 27–29 °C and salinity at 25–30 ppt. Gravid crabs are exposed to 40–50 mg/L nystafungin in a small container for 1 hour prior to transferring them into the hatching tanks. A broodstock weighing 350–500 g can produce up to 1.8–2.5 million eggs. Each larval rearing pond of 30–40 m^3 can accommodate only one gravid female. Larvae typically hatch between 05:00 and 07:00 with the egg hatching process lasting generally for about 1 hour. After the larvae have hatched, the broodstock are promptly removed from the hatching tank.

It is recommended to keep the larval stocking density between 40 000–100 000 larvae/m^3. If the stocking density exceeds 150 000 larvae/m^3, the survival rate will drop significantly. If the larvae density is high the density should be lowered at the beginning of zoea stage.

Common live feeds used in mud crab larval culture include microalgae, rotifers and *Artemia*. After hatching, unicellular algae and rotifers should be introduced immediately as the initial feed for the first-stage zoea (Z1). Common species of unicellular algae used include *Chrysophyta* sp., *Chaetoceros* sp. and *Pyramidomonas* sp. Maintaining an optimal microalgae density in the rearing water is important, as it results in a light brown or greenish hue, which generally indicates suitable feeding conditions. Microalgae not only serve as a direct food source but also play a role in promoting larval metamorphosis and improving survival rates.

During the Z1 and Z2 stages, larvae are primarily fed live rotifers at a concentration of 15–25 rotifers/ml. Rotifers cultured with unicellular algae can be fed directly to the larvae, while those cultured with yeast require additional enrichment to enhance their nutritional profile before use.

At the Z3 to Z5 stages, the larvae are given *Artemia* nauplii as the primary feed. Early-stage megalopa larvae predominantly consume *Artemia* nauplii, with copepods and adult *Artemia* supplementation. As larval development progresses, adult *Artemia* becomes the main diet, with copepods serving as an additional feed source.

Throughout the larval rearing period, regardless of the type of feed used, it is critical to adopt a feeding strategy that ensures rational feeding practices. Specifically, the principle of "small amounts but frequent feedings" should be followed, especially when using copepods and adult *Artemia*, to prevent overfeeding and maintain optimal water quality.

At the Z1–Z2 stages, water quality is primarily maintained by adding seawater and unicellular algae. From the Z3 stage onwards, regular water exchange is implemented. Water exchange is typically conducted once daily, with 15–40 percent of the water volume replaced, depending on the water quality. During the megalopa stage, water exchange frequency increases to twice daily, with each exchange replacing 50 percent of the total volume.

The following water parameters must be strictly controlled during larval rearing: water temperature should be maintained between 25–29 °C, salinity at 25–30 ppt, pH between 8.0–8.5, and dissolved oxygen levels above 5 mg/L. Aeration should be adjusted based on the developmental stage of the larvae: minimal aeration is recommended during the Z1–Z2 stages, moderate aeration from Z3 to Z5, and increased aeration during the megalopa stage to meet the larvae's oxygen demands. Additionally, larvae should not be exposed to intense light during rearing. Illumination levels of around 1 000 lux are optimal to provide sufficient lighting while minimizing stress.

Nursery practices

Cement pond nurseries: In cement nurseries, phototactic behaviour is used to collect the megalopae. The optimal size for a nursery pond is 20–100 m², with a stocking density of 3 000–6 000 megalopae/m³. To provide additional habitat and shelter, netting or oyster shells can be placed at the bottom of the pond. During the megalopa stage, adult *Artemia* is the preferred feed, with a feeding rate of 100–200 percent of the crab's body weight. Feeding amounts should be adjusted based on the crabs' feeding behaviour and leftover feed. Water exchange is carried out twice daily during the nursery phase, with 50 percent of the total water volume being replaced each time. Continuous aeration at high volumes is essential to maintain adequate oxygen levels.

Earth pond nurseries: Earth pond nurseries typically have a surface area of about 500 m². Prior to stocking, the pond must be thoroughly cleaned and disinfected to prevent disease outbreaks and ensure optimal rearing conditions. If the pond contains natural live feed, such as copepods, the megalopae can be stocked at a density of 1 000–2 000 megalopae/m³. Feed density should be regularly adjusted based on the feeding activity of the crabs and the amount of leftover feed. The earthen pond provides natural hiding places, making it ideal for megalopae and juvenile crabs. This method is generally used for rearing crab seed beyond the third crab stage due to the pond's suitability for shelter and growth.

Hard-shell farming

In China, hard-shell crabs are commonly cultured in ponds. Prior to stocking, it is important to eliminate organic residues, harmful organisms and pathogens that could negatively impact the crabs' survival and growth. Tea seed cake can be used after each harvest to clean the pond, ensuring a safe and suitable culture environment.

The recommended stocking density for juvenile crablets is 3–5 juveniles/m². Before stocking, the crablets should undergo a medicated bath – either in potassium permanganate for 15 minutes or in freshwater for 15–30 minutes – to eliminate surface pathogens. It is important to select active crablets of uniform size with intact appendages and no injuries. The juveniles are typically stocked at the first stage. It is preferable to source the crablets from nearby sea areas to enhance adaptation to the culture environment.

In terms of pond management, water exchange is essential for regulating salinity, temperature and dissolved oxygen levels. Typically, water is exchanged every 2–3 days, though this may vary based on weather conditions. During neap tides, water exchange should occur at least once every 7 days to maintain water quality. The pond water depth should be maintained between 1.0–2.0 m. In colder seasons, increasing the water depth helps mitigate temperature fluctuations, while in hotter weather or when stocking densities are high, deeper water levels are beneficial for maintaining water quality.

The juvenile crabs are primarily fed small shellfish and supplemented with formulated feed. Both live and frozen feeds should be disinfected before feeding. The use of formulated feed is encouraged, as it minimizes environmental pollution, improves feed conversion rates, reduces dependence on fishery-derived feeds, and lowers the risk of disease introduction.

When using trash fish or shrimp as feed, it is recommended to feed at a rate of 5–7 percent of the crabs' body weight. If bivalves are used, the feeding rate can be increased to 20 percent of the crabs' body weight. Feed should be consumed within 1 hour, and feeding frequency should be carefully controlled. During the grow-out period, feeding should occur regularly, with no gaps longer than 3 days between feedings.

Regular pond monitoring should be conducted in the morning, at noon and in the evening to check the condition of the crabs and pond conditions. Constant inspection of pond banks, sluice gates and escape prevention facilities is necessary to identify any damage. Additionally, key parameters such as water colour, temperature, dissolved oxygen levels and water depth should be monitored. Crab behaviour should also be observed. Preventive measures against theft and the inflow of industrial or agricultural wastewater are essential.

After 3–4 months of cultivation, mud crabs typically reach the commercial size, weighing about 200 g, and are ready for harvest. Common harvesting methods include the use of trap nets, bottom cages and drop nets. Cages are usually set in the evening and collected the next morning. Alternatively, crabs can be harvested more easily by setting nets at the water inlet and draining the pond. In principle, larger crabs are harvested first, while smaller ones are left to continue growing in the pond.

Soft-shell crab production

The first step in selecting juvenile crabs (50–150 g) for culture is to choose individuals with specific desirable traits. These include crabs with a cyan coloration of the exoskeleton, intact appendages, no visible wounds, and have vigorous response to stimulation. Additionally, disease-free crabs can be determined by inspecting the muscle colour beneath the joints. Healthy crabs display sky-blue muscle tissue with strong contractile response, while diseased individuals may show yellowish-red or white muscle with diminished elasticity.

A fresh, live diet with high nutritional value – especially shellfish – is ideal for promoting the moulting process. The amount of feed should be adjusted based on culture conditions such as water temperature and water quality. The recommended daily feeding rate is 5–7 percent of the crabs' body weight. When fresh feed is in limited supply, frozen feed can be used as an alternative. Feeding is typically done twice daily, in the morning and at nightfall, with a larger portion often given in the evening. It is crucial to remove feed residues before each feeding or water exchange to prevent water quality degradation.

HEALTH AND DISEASE MANAGEMENT

Vibrio infection

Vibriosis in mud crabs primarily arises from poor water quality and suboptimal bottom conditions, as well as the use of stale feed and inadequate removal of residual feed. Signs of *Vibrio* infection in affected crabs include reduced activity, decreased appetite or cessation of feeding, and pink discoloration around the joints of the appendages. Prevention and control measures include regular pond sterilization, enhancing water quality and substrate conditions, ensuring the use of fresh feed, and promptly removing any leftover feed.

White blood disease

White blood disease is associated with drastic environmental changes, particularly fluctuations in temperature and salinity, which often occur during high temperatures and heavy rainfall. Signs of white blood disease include reduced activity, compromised immune response, increased susceptibility to secondary bacterial infections during moulting, whitening of muscles and body fluids, limb loss and increased mortality. Prevention and control methods include the removal of upper layer of freshwater in ponds after rain and readjust the pond salinity with seawater. Incorporating oxytetracycline into crab feed can help alleviate the symptoms of white blood disease.

Ciliate infection

In conditions where water quality deteriorates, resulting in eutrophication, mud crabs may become infested with high numbers of ciliate parasites. Infected crabs often display signs of agitation, frequent swimming throughout the pond, decreased feeding behaviour, and difficulty in moulting, which can ultimately lead to mortality. Effective prevention and control strategies include increasing the frequency and volume of water exchanges and reducing pond transparency to limit ciliate reproduction and growth.

RESEARCH AND INNOVATION

China's efforts to advance mud crab aquaculture are reflected in the support and implementation of various initiatives. The Ministry of Agriculture and Rural Affairs has established specialized scientist positions focused on mud crab genetic resources, breeding and feed development, allocating CNY 700 000 in research funding for each position annually. Furthermore, the establishment of a well-equipped field facility for mud crab farming enables applied research and the development and testing of innovative farming technologies.

The ongoing development of various types of crab farming systems in China, alongside the introduction of automated feeding equipment and crab activity monitoring systems, highlights efforts to enhance land-based farming practices. Additionally, research is being conducted to improve pond facilities to mitigate cannibalism among mud crabs.

A notable achievement in mud crab aquaculture is the successful development of formulated feed with a feed conversion ratio of 1.5. This formulated feed offers several advantages, including a reduced reliance on marine resources and the provision of a nutritionally balanced diet. Furthermore, the use of formulated feed leads to decreased labour requirements, as it simplifies feeding protocols. Ongoing research and development in feed formulation remain vital for enhancing the efficiency and sustainability of mud crab farming operations.

Lastly, initiatives for the genetic breeding of superior strains are underway. These collective efforts contribute to the advancement and sustainability of mud crab aquaculture in China.

MARKET INFORMATION

Major markets for hard- and soft-shell mud crabs

Mud crab is a very popular seafood dish in the coastal provinces of China. In the past 10 years, China's demand for imported mud crabs has increased steadily. In the cities of Shanghai, Guangzhou and Xiamen, the total annual volume of imported mud crabs exceeds 30 000 t. Imports are mainly from Viet Nam, Indonesia, Philippines and Myanmar. These imports supplement domestic production to meet the growing demand for mud crab across various regions in China.

Product prices

The mud crab market is diverse, with distinct size and sex classes commanding significantly different prices. Larger mud crabs are often transported to major cities where they fetch higher prices. Ovigerous female crabs are priced substantially higher than immature females and smaller male crabs. This premium pricing reflects the demand for mature female crabs with late-stage ovaries, which are highly sought after for their perceived quality and flavour.

In general, mud crabs are sold locally at around CNY 160/kg, but high-quality crabs can command up to CNY 240/kg. However, during festive seasons, particularly around the Lunar New Year, prices for mud crabs can exceed CNY 400/kg due to high market demand and limited supply.

MAJOR ISSUES AND CHALLENGES OF THE INDUSTRY

The demand for crab seeds in China is approximately 6 billion units. However, hatchery-reared seeds currently account for less than 2 percent of the total seed supply, which is insufficient to support farming operations. To address this shortfall, further advancements in hatchery technology are essential, particularly in broodstock management and nursery practices.

Although polyculture systems are widely utilized for mud crabs, the survival rate remains relatively low, at around 10 percent. This low survival rate results in reduced production levels. In contrast, soft-shell crabs cultured in crab apartments demonstrate impressive survival rates, often exceeding 80 percent. Despite this high survival rate, market demand for soft-shell crabs remains limited, primarily due to consumer preferences. Chinese consumers generally prefer purchasing live crabs over frozen or preserved products. Consequently, the overall demand for soft-shell crabs in the market is limited.

In the past two years, a formulated feed with a feed conversion ratio of 1.5 has been developed, priced at approximately CNY 10 000/t (or USD 1 400/t), similar to the price of shrimp feed. While the government encourages and supports the use of formulated feed, several processing challenges persist, including issues related to the small size and rapid dissolution of feed particles. These obstacles hinder the widespread use of formulated feed by the industry. Further research is required to improve feed efficiency and usability.

The development of genetically superior breeds presents significant potential for advancing mud crab aquaculture. However, China currently faces a shortage of genetically improved breeds that exhibit superior farming performance.

CONCLUSION

Currently, the design and supporting facilities of mud crab hatcheries are not specifically tailored to the needs of crab larvae; instead, they are primarily adapted from shrimp and fish hatcheries. To improve survival rates and enhance seed production, there is a pressing need to develop specialized culture ponds for megalopae and crablets during the nursery stage.

Cannibalism is a major factor affecting the survival of mud crabs in pond culture. To address this issue, it is crucial to improve pond design that reduces hostile behaviour among the cultured crabs. Also, the development of feed tailored for specific crab products or growth stages – such as soft-shell crabs, fattening, or maturation of ovigerous females – should be prioritized by the industry.

Superior breeds are important to the growth of the aquaculture industry. Through population-level breeding, crossbreeding and genomic selection techniques, it is possible to develop new breeds of mud crabs that exhibit desirable traits, thereby promoting the development of the mud crab industry.

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Mud crab industry status in the Philippines

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ABSTRACT

The Philippines is one of the top producers of mud or mangrove crab in the world. The total production of mud crab from aquaculture was estimated at 15 794 tonnes valued at USD 113 083 in 2013 and increased gradually to 23 112 tonnes valued at USD 238 002 in 2021. Within the country, the production was highest in Northern Mindanao (7 889 tonnes), Central Luzon (5 419 tonnes), Calabarzon (5 172 tonnes) and Western Visayas (1 986 tonnes) in 2021. *Scylla serrata*, *Scylla olivacea* and *Scylla tranquebarica* are farmed in the Philippines. The decline in all sizes of wild crab populations has been documented. To manage and conserve the resources, several ordinances and regulations have been enforced. Hatcheries and nurseries have also been established to sustain the crab farming industry.

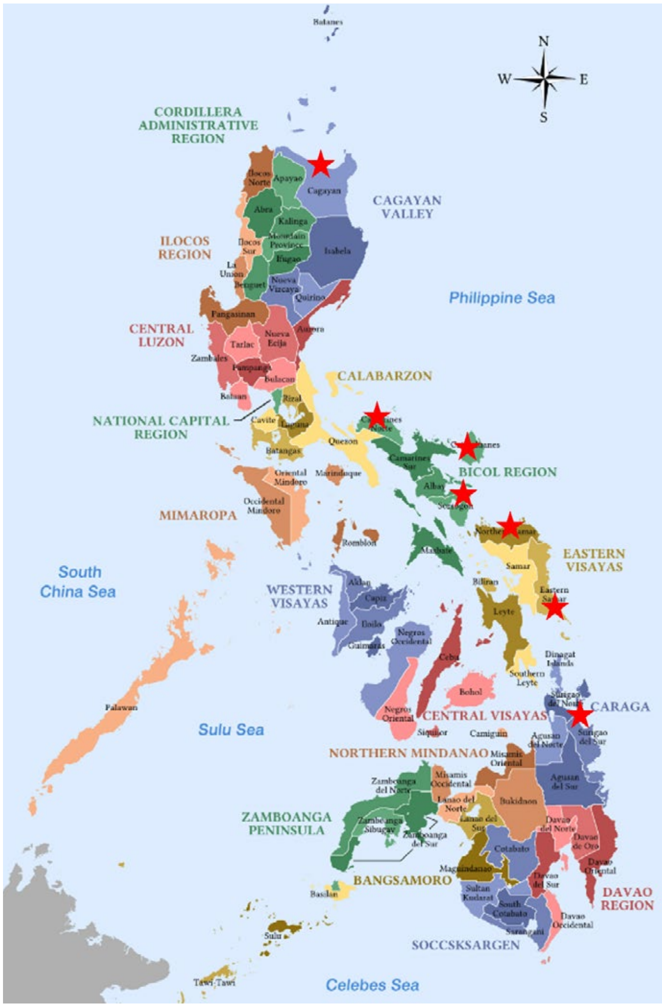
S. serrata has been the focus of hatchery and nursery culture due to the preference for this species by crab growers. Rotifers are used to feed the early crab zoeal stage. A few nurseries have been integrated with the hatchery or grow-out ponds. Small crabs (carapace width < 1.5 cm) from either the hatchery or wild are nursed in net cages for a few days prior to stocking in grow-out ponds. Many crab growers also stock crablets directly in well-prepared ponds. Two phases of nursery culture were developed that utilize grow-out ponds, depending on the desired crab size. Mangrove crab farming involves the long-term culture of juvenile crabs to market size for 3–5 months, short-term fattening of lean crabs for 15–30 days and soft-shell crab for 3–4 weeks per cycle. Polyculture of juvenile crabs to market size with one or two fish species in the pond is commonly practised to maximize pond use and revenue. Seaweeds (*Gracilaria*), which serve as shelters, are also grown with crabs. The common diseases encountered in the grow-out ponds are white spot syndrome virus, vibriosis and *Hematodinium* (dinoflagellate parasites).

The most recent applied research activities include the domestication and selective breeding of *S. serrata*. Other recent innovations include the genetic and genomic applications in mangrove crab farming. The major issues and challenges facing the crab industry are inadequate supply of good quality seedstock; inconsistent quality of broodstock; cannibalism in the nursery and grow-out ponds; diseases in the hatchery and grow-out ponds; and lack of low cost and practical diets. Selective breeding of mangrove crab needs to be continued to have improved growth and disease-resistant or disease-free stocks. Mangrove crabs are not difficult to breed but sufficient facilities are required due to their cannibalistic nature. The selective breeding programme is a multidisciplinary endeavour involving geneticists, aquaculturists and disease experts.

INTRODUCTION

Mangrove or mud crab farming has long been established in the Philippines. *S. serrata*, *S. olivacea* and *S. tranquebarica* are commonly found in the country. *S. serrata* is the focus in the hatcheries and is the preferred species for farming due to its fast growth, large size (Ng, 1998) and less aggressive behaviour compared to *S. tranquebarica*

FIGURE 1
Map showing the distribution of wild *Scylla serrata* (red stars), the preferred cultured species, along the eastern seaboard of the Philippines



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Map from https://en.wikipedia.org/wiki/Template:Provinces_of_the_Philippines

and *S. olivacea* (Meakin, 2006). These two other species are sourced from the wild at a larger size for short-term culture such as fattening and soft-shell crab production. *S. serrata* is often found along the eastern seaboard of the Philippines (Pacific Ocean side) such as Cagayan, Camarines, Albay, Sorsogon, Catanduanes, Samar and Surigao. *S. olivacea* and *S. tranquebarica* are the common species along the western seaboard (West Philippine Sea, Sulu Sea and bodies of water between the islands) (Figure 1).

Wild stock status

The significant decline in the wild populations in the country has been documented (Lebata *et al.*, 2007; Quinitio *et al.*, 2017; Castrence-Gonzales *et al.*, 2018). A study assessed the mangrove community structure, relative abundance of all sizes of crabs (catch per unit effort) in two collection sites in Northern Samar, one of the major sources of *S. serrata*. The decrease in the population of mangrove crabs is associated with the indiscriminate collection of crablets and female crabs at various stages of maturity, degradation of habitat – specifically, the dwindling mangrove areas – and illegal fishing practices.

Conservation and management of wild resources

The Philippine Fisheries Code (Republic Act 8550) provides for the development, management and conservation of fisheries and aquatic resources in the country and the reconstitution or establishment of fisheries institutions both at the national and local level and came into effect in July 1998. This was amended in February 2015 by Republic Act 10654, providing higher penalties while authorizing better monitoring systems to stop illegal, unreported and unregulated (IUU) fishing activities.

Due to the documented decrease in wild stock population and continuous rampant and unregulated collection of various sizes of mangrove crabs from the natural habitat in Northern Luzon, Bicol Region, Eastern Visayas, Northern Mindanao, Caraga and Zamboanga Region, the local government with the joint effort of the Bureau of Fisheries and Aquatic Resources (BFAR) have adopted regulations on mangrove crabs. The ordinances prohibit the catching, trading and transporting of crablets (≤ 3 cm) outside the municipality of origin, especially without permit. This has resulted in the increased acceptability of hatchery-reared crablets by the growers. The most recent issuance of the Fisheries Administrative Order (FAO) No. 264-2020 by BFAR covers the national regulations on mangrove crabs. This Order regulates the catching, possessing, transporting, trading, and exporting of wild crablets (carapace width ≤ 12 cm) and gravid and berried crabs, *Scylla* spp., except when these will be used for research and academic purposes. Penalties shall be imposed on offenders.

Mangroves serve as the habitat of many aquatic animals including crabs. There are several administrative decrees, orders and proclamations[1] that have been promulgated to protect the remaining mangrove areas and mitigate extensive deforestation (Primavera, 2000). Conservation of the country's remaining 100 000 ha of mangrove forests and the rehabilitation of degraded sites are continuously being undertaken. Mangrove-friendly aquaculture (such as crabs, bivalves and fish aquasilviculture or integral mangrove ponds and pens) are promoted (SEAFDEC/AQD, 1999).

Management and regulation of mangroves crab aquaculture

Under the Fisheries Administrative Order No. 264, transportation and trading of hatchery-bred crablets are allowed, provided that the facilities are registered with the BFAR and that a certificate has been issued by the hatchery establishment indicating that the crablets are hatcherybred. There are also ordinances issued by some provinces and municipalities that support crab aquaculture.

Licensing and accreditation

The transport and trading of mangrove crabs (either from hatcheries, ponds or the wild) for aquaculture purposes is accompanied by the Local Transport Permit (LTP) issued by the Fisheries Quarantine Officers or Provincial Fisheries Officers of the BFAR for fish and fishery products. The LTP permits individuals to transport aquatic wildlife, byproducts, or derivatives obtained from legal sources within the country. This domestic movement authorization allows for the transportation of these materials from their point of origin to their intended destination within the country. An Auxiliary Invoice is issued by the local government or BFAR for the transport and domestic movement of fish and aquatic products obtained from aquaculture or conventional fishing. LTP requires the Auxiliary Invoice from the local government unit, the Bill of Lading and a commercial invoice/pro-forma invoice. The fishery products are presented for inspection and then the required fees are paid prior to the issuance of the approved LTP.

There are also some requirements for the export of live food crustaceans and fish (FAO No. 319-2009) such as: registration with BFAR and issuance of a Health Certificate; issuance of Commodity Clearance; and border inspection and verification. This is to strengthen the procedures for the issuance of a health certificate and for the smooth implementation in the processing of necessary documents for the export of live food crustaceans and fish.

INDUSTRY STATUS

Production status

In 2012, the Philippines was the largest producer of mud crab in the world (FAO, 2023) but only the second-largest for the period 2013–2021 (Table 1). The total production of mangrove crab from aquaculture in the country was estimated at 15 794 t valued at USD 113 083 in 2013 and increased gradually to 23 112 t valued at USD 238 002 in 2021 (FAO, 2023) (Figure 2).

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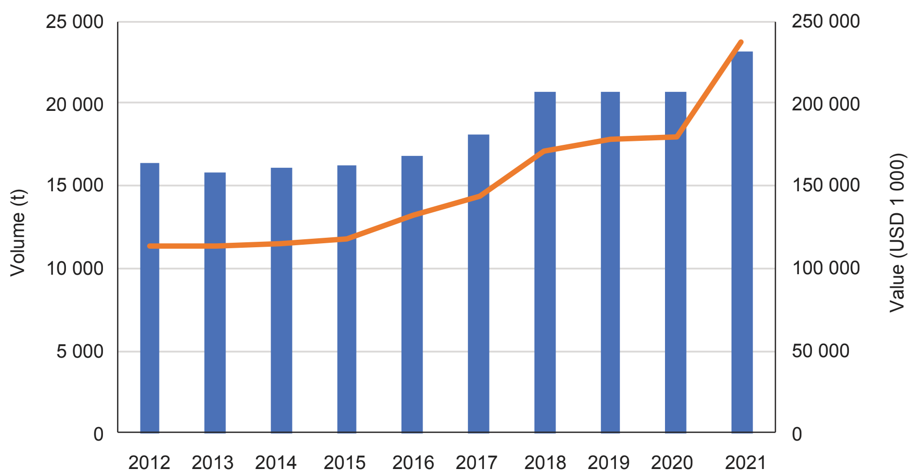
[1] Such as Presidential Decree or PD 705, 1975; P.P. 2151 and 2152, 1981; P.P. 2146, 1982; Ministry of Natural Resources (MNR) Administrative Order or AO 42, 1986; PD 1067; Department of Environment and Natural Resources (DENR) AO 77, 1988; DENR AO 15, 1990.

TABLE 1
Aquaculture production volume of *Scylla* spp. of top producing countries (t)

Country	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Viet Nam	13 000	13 000	49 140	54 588	64 633	65 463	36 000	198 729	80 162	81 144
Philippines	16 360	15 794	16 160	16 199	16 860	18 100	20 770	20 772	20 766	23 112
Indonesia	14 163	11 898	13 594	12 546	11 407	2 704	33 807	14 208	10 767	10 840
Thailand	700	700	800	800	1 000	1 100	1 773	1 561	2 556	3 479
Malaysia	65	45	81	96	79	133	82	318	269	257
Cambodia	40	40	50	50	68	70	80	90	120	100
Singapore	122	89	26	119	55	30	39	21	22	57
Taiwan Province of China	122	89	26	32	21	7	6	6	12	27
Fiji	-	-	7	7	7	10	10	10	10	10
Sri Lanka	2	1	2	12	155	51	69	60	22	7
United Republic of Tanzania	-	0.1	0.2	0.2	2.4	2	1.02	-	-	1.39
Brunei Darussalam	5	-	-	-	-	-	0.5	-	1.38	1.35
Mauritius	1.2	1	1	1	1	1	1	1	1	1
Papua New Guinea	4	4	4	4	4	-	-	-	1	1

Source: FAO. 2023. FishStat: Global Aquaculture Production. Fisheries and Aquaculture. [Accessed on 05 September 2023]. In: FishstatJ. Available at www.fao.org/fishery/en/statistics/software/fishstatj. Licence: CC-BY-4.0.

FIGURE 2
Annual crab production in volume and value from aquaculture in the Philippines from 2012 to 2021

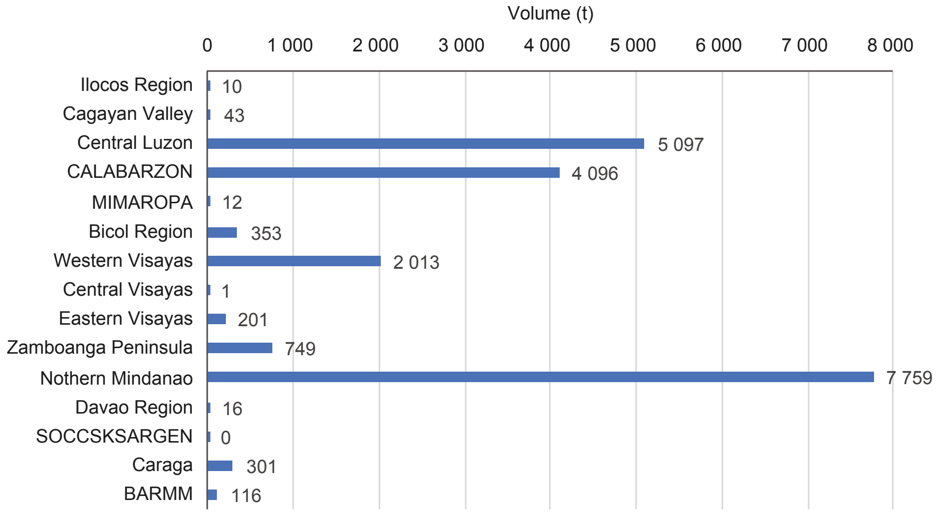


Source: Philippine Statistics Authority. Aquaculture: Volume of production by species, region and province, 1996–2021. Fisheries Statistics Division. Latest update 8 August 2023. Available at https://openstat.psa.gov.ph/Metadata/2E4GVAP1

Farming area

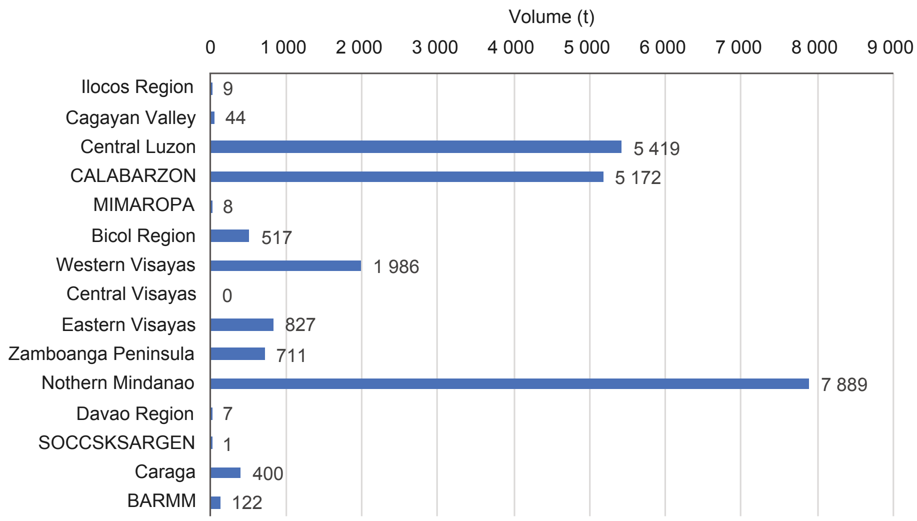
The Philippines is an archipelagic country consisting of 7 641 islands, of which about 2 000 islands are inhabited. It has the fifth-longest coastline in the world, with a total length 36 289 km. Fisheries and aquaculture are major activities in the coastal communities. Mud crabs are farmed in many coastal regions in the country. In 2020 and 2021 the production was highest in Northern Mindanao (7 759 t and 7 889 t), Central Luzon (5 099 t and 5 419 t), Calabarzon (4 096 t and 5 172 t) and Western Visayas (2 013 t and 1 986 t) (Figure 3 and Figure 4). Most of the seedstocks farmed in these regions are *S. serrata* sourced from Cagayan, Bicol region, Eastern Visayas

FIGURE 3
Mud crab production by region in the Philippines in 2020



Source: Philippine Statistics Authority. Aquaculture: Volume of production by species, region and province, 1996–2021. Fisheries Statistics Division. Latest update 8 August 2023. Available at https://openstat.psa.gov.ph/Metadata/2E4GVAP1

FIGURE 4
Mud crab production by region in the Philippines in 2021



Source: Philippine Statistics Authority. Aquaculture: Volume of production by species, region and province, 1996–2021. Fisheries Statistics Division. Latest update 8 August 2023. Available at https://openstat.psa.gov.ph/Metadata/2E4GVAP1

and Surigao. *S. olivacea* and *S. tranquebarica* are sourced elsewhere in the country but *S. tranquebarica* is found in significantly lower quantities.

Hatcheries, nurseries and grow-out farms

Compared to shrimp hatcheries, the number of crab hatcheries (Figure 5) is significantly lower due to the much lower stocking density required for crabs (800–1 000/ha in polyculture) compared to shrimp post-larvae (≥ 20 000/ha). This difference in stocking density is influenced by the culture system and the cannibalistic behaviour of crabs, which limits high-density stocking. To optimize pond space and reduce the risk of cannibalism, mangrove crabs are cultured in polyculture systems alongside herbivorous fish such as milkfish or siganids, and omnivorous species like saline tilapia.

FIGURE 5
Crab hatchery using concrete tanks

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Several hatcheries were operational prior to the COVID-19 pandemic; however, the aquaculture industry, including farmers and fishers, was significantly impacted by the pandemic due to stricter border controls and restrictions on activities aimed at preventing disease transmission. Many farmers either suspended or scaled back farming operations, while some hatcheries halted crablet production to mitigate the risk of incurring additional costs. Recently, hatcheries have been gradually resuming full operations as restrictions ease and industry conditions stabilize.

The Philippine Council for Agriculture, Aquatic, and Natural Resources Research and Development (PCAARRD), a sectoral council under the Department of Science and Technology (DOST), is responsible for allocating government and external funds for research and development, as well as generating resources to support its programs. In response to the needs of the crab industry, PCAARRD has allocated funding for the establishment of hatcheries through the project "Adoption of improved commercial scale mangrove crab hatchery-nursery system" at several sites across the country, including Quezon, Maguindanao, Capiz and Cagayan. Three of these hatcheries have recently begun operations.

The number of crab hatcheries is expected to grow as the volume of wild crabs declines and the demand for both farming and soft-shell crab production rises. Before the COVID-19 pandemic, several hatcheries, including those run by private sectors, Local Government Units (LGUs), and research institutions, were operational. Many of these entities are also involved in marine fish seed production, having already established rotifer production systems. Rotifers remain the preferred feed for early-stage crab zoea due to their small size, suitable nutritional profile, ease of culture and slow mobility. In contrast, *Artemia* nauplii (umbrella stage), though commonly used, are big for early zoea and are becoming increasingly expensive.

A few nurseries have been integrated with hatcheries or grow-out ponds. Small crabs (with a carapace width of < 1.5 cm), sourced either from hatcheries or the wild, are sometimes temporarily held in net cages (*hapas*) for a few days before being released into the pond (Figure 6). However, many crab growers prefer to stock crablets directly into ponds, provided the ponds are well-prepared – this includes predator eradication and the use of fine mesh nets to screen incoming water. Additionally, some shrimp hatchery operators have diversified into crab seed production, adapting their facilities to meet the specific needs of the crab farming sector.

In the Bicol region, megalopae collected from the wild are stocked in ponds for a few weeks until they grow to a suitable size for pond stocking. Although still in the larval stage, megalopae are collected to prevent them from being eaten by natural predators. Crab instars are also gathered and either grown in dedicated nursery ponds or sold to other nursery operators, who then sell the crabs to grow-out pond operators.

FIGURE 6
Net cages in ponds for growing crablets in the nursery phase

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Grow-out farms are widely distributed across the country's coastal regions. Current brackish-water ponds, cover an area of approximately 239 323 hectares, used for the culture of shrimp species (*Penaeus monodon* and *Penaeus vannamei*), milkfish, mangrove crabs and various other marine fish species, either in monoculture or polyculture systems. Additionally, 139 735 hectares of brackish-water swamplands remain available for potential development for these aquaculture commodities.

AQUACULTURE PRACTICES

Hatchery

Although the hatchery technology applies to all three crab species (*S. serrata*, *S. tranquebarica*, and *S. olivacea*), *S. serrata* has been the focus of hatchery and nursery culture due to the preference for this species by the crab growers. *S. serrata* broodstock (500–700 g) for the hatchery is commonly sourced from trading centres, commercial ponds or from the wild, where the major criteria for selection include advance stage of ovarian maturity, completeness of limbs and activeness of crabs (Quinitio and Parado-Estepa, 2008).

Crabs spawn within 2–4 weeks after stocking in the maturation tanks depending on the stage of ovarian maturity when sourced. Ovigerous crabs (berried females or females carrying eggs attached to the abdominal flap) are retrieved, disinfected and transferred to the spawning tanks at one female per tank until their eggs hatch. After hatching, the larvae are examined and transferred immediately into the larval tanks. Newly hatched zoeae are fed rotifers and then *Artemia* at late zoea 2 onwards. If rotifers are not sufficient, umbrella stage *Artemia* or newly hatched small strain *Artemia* are fed to zoea 1. Three to four-day old *Artemia* are fed to later zoea stages. When megalopae start to become benthic, they are fed minced fish and molluscs until crab instar. At present, there are several commercially available shrimp-formulated diets with various levels of highly unsaturated fatty acids (HUFA) and other essential nutrients that can be fed to crab larvae.

Seawater is changed every 3–4 days and then zoea 5 are transferred to other tanks with new seawater and held there until harvest at early crab instar (C). Survival rate from zoea 1 to crab instar ranges from 3–10 percent (Figure 7).

FIGURE 7
Scylla serrata **crablets produced in the hatchery for the nursery phase or grow-out ponds**

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Nursery practices

Wild crablets for farming are often stocked directly in the grow-out ponds, however survival is low. The nursery system was developed to culture the megalopae and crab instars from the hatchery or wild prior to release in the grow-out ponds. The stocking of megalopae were first introduced using net cages installed in earthen brackishwater ponds for easy retrieval of stocks especially for short-term culture of 1–2 weeks. Two phases of the nursery culture were developed depending on the desired size for stocking in grow-out ponds. Phase 1 previously involved megalopae for stocking (Rodriguez *et al.*, 2001). However, C_1–C_2 is often stocked (Quinitio *et al.*, 2009; SEAFDEC/AQD, 2010) in the nursery because not all farmers can handle a larval stage as delicate as the megalopa. Megalopae or C_1–C_2 are grown to a carapace width of 1.5–2.0 cm. Some farmers prefer bigger crabs, hence these crablets are further grown to 3.0–4.0 cm in phase 2 (SEAFDEC/AQD, 2010; Rodriguez, Parado-Estepa and Quinitio, 2007). Phase 2 of the nursery is also carried out in net cages in ponds, or in ponds with or without net enclosures around the dykes (SEAFDEC/AQD, 2010). The net enclosures, as in cages in ponds, prevent the escape of cultured stocks and the entry of other crab species. The culture period is 1–3 weeks. Small earthen pond compartments are also used by collectors to nurse the megalopae or crab instars until these are big enough to be sold to grow-out farmers.

The major problem in the nursery phase is cannibalism since the crablets moult regularly to grow. Strips of used nets (plastic materials are discouraged), and seaweeds (*Gracilaria*) are used as shelters to reduce cannibalism. Food items for the crablets consist of minced low value fish, mollusc meat (snails, mussels, etc.) and commercially available formulated diets used for shrimps at satiation level. Feeding crablets with a combination of minced mollusc meat or low-value fish, and pelleted diet formulated for crab gives better performance in the nursery. About 30–50 percent of the pond water is changed every spring tide or when needed and a water depth of 50–80 cm is maintained depending on the system used.

Grow-out

Mangrove crab farming typically involves either the long-term culture of juvenile crabs to market size over 3–5 months, or the short-term fattening of lean crabs for 15–30 days. Polyculture, where juvenile crabs are cultured alongside one or two fish species in brackish-water ponds, is commonly practiced to optimize pond space. Herbivorous (milkfish or siganids) or omnivorous (saline tilapia) fish species are often co-cultured with mangrove crabs. In some cases, a combination of three species is used, but at lower stocking densities for each.

While co-culturing shrimp (*P. monodon*) with crabs is generally discouraged due to shared disease risks, such as white spot syndrome, some farmers still combine these commodities. Stocking density of crabs is typically reduced during colder months when disease risk is higher. A typical stocking density for mud crab juveniles is 800–1 000 ind./ha, while milkfish fingerlings or saline tilapia are stocked at 1 000–2 000 ind./ha. In some systems, the seaweed *Gracilaria* is cultivated alongside crabs, providing shelter and improving pond conditions. To prevent stock escape, bamboo or polyethylene netting is installed, particularly in ponds where the dyke height is low.

The major food items for mangrove crabs are fish of various species, small bivalves, golden snails, telescope snails and other molluscs, boiled corn, and formulated feeds or whatever cheap source of protein is available in the area. Feeds are provided daily at 10 percent of the total biomass at the start of the culture and then reduced gradually from 8 to 3 percent as the crabs grow to market size. Feeding frequency varies from 1–2 times daily of the appropriate food ration. Water is changed during spring tide or whenever necessary. The depth of pond water is maintained not lower than 80 cm. The optimum water and soil conditions are maintained as far as possible.

Fattening

During harvest, 20–40 percent of crabs generally have missing limbs, unequal claw size, or are undersized or lean which results in rejection by traders for export market and a much lower price in the domestic market. These crabs are fattened to add more value. In the communal fattening system, several lean or undersized crabs are stocked together in pond compartments, pens or cages at stocking density of 1–3 ind./m^2, with lower densities and a shorter holding period for larger crabs. In the individual system, crabs are stocked individually in improvised containers such as perforated plastic water containers, crates, boxes, baskets or compartmentalized bamboo cages. These are positioned in the same pond where polyculture of crabs and fish is done to maximize the pond usage. Containers for fattening are set up in protected estuaries, sheltered coastal waters and bays. Crabs are also stocked in boxes in indoor vertical recirculating aquaculture system (RAS). Some RAS operators modify their setups using locally sourced materials to reduce costs, as purchasing a complete system can be prohibitively expensive and result in higher operational costs. Crabs are fed 1–2 times daily with low value raw fish and molluscs at satiation level. Crabs are cultured for 1–3 weeks to enhance their market value.

Aquasilviculture

Crabs are cultivated in enclosed areas within mangrove forests using pens. Aquasilviculture offers a lower investment for construction and operational costs while preserving the integrity of the mangroves, and it has been implemented in various coastal areas across the country. However, some projects have faced challenges due to unsuitable site conditions. A significant issue encountered has been the presence of crab predators, including carnivorous fish such as groupers and snappers, as well as sea snakes and competitive species like crenate and blue swimming crabs, which often cannibalize newly moulted mangrove crabs. As a result, larger crabs are typically stocked for short-term culture, making aquasilviculture more suitable for fattening.

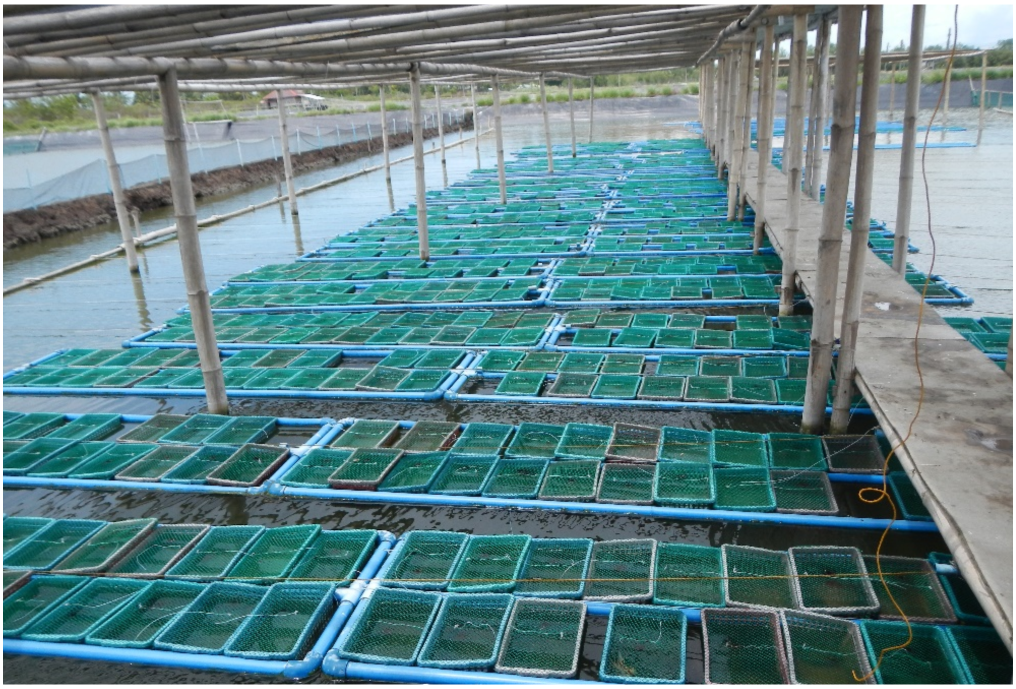
In 2011, the Bureau of Fisheries and Aquatic Resources (BFAR) launched the Philippine National Aquasilviculture Program to rehabilitate and protect mangrove resources, establish aquasilviculture livelihood projects, and support community-based multi-species hatcheries.

Soft-shell crab production

Commercial production of soft-shell crabs in the Philippines started in the 2008 (Quinitio and Noe Lwin, 2009). Sourcing of crablets from the natural environment is not encouraged due to the dwindling population of mangrove crabs. It is recommended that crablets be sourced from hatcheries, grown further in ponds for 1.5–2.0 months or until 60–100 g is attained, and stocked in perforated plastic boxes that are positioned in floating platforms in ponds (Quinitio *et al*., 2015; The Mangrove Crab Technical Committee 2018, 2021) (Figure 8). In some cases, plastic boxes with recirculating water system under a roofed structure is utilized (Figure 9). Crabs are harvested when they are newly moulted and held in basins with aerated clean freshwater. Survival rate ranges from 70–90 percent at the end of a cycle. Crabs are sorted according to size prior to packing in food grade packaging material. Most of the crabs stocked, if sourced from the wild, are *S. olivacea*. Since the local demand still exceeds the supply, soft-shell crabs are imported into the country.

FIGURE 8

Production of soft-shell crabs in modified set-up using perforated plastic trays



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The final product should meet the quality characteristics (quality and sensory attributes) of raw soft-shell crabs and should conform to existing microbiological quality requirements. Likewise, heavy metals and veterinary drug residues should not exceed the maximum levels specified in the Philippines National Product/Bureau of Agriculture and Fisheries Standards No. 235-2022 on fresh/frozen soft-shell crab.

CRAB HEALTH AND DISEASE MANAGEMENT

Live crabs brought to the hatchery may carry pathogens that can cause disease. Prophylaxis is applied or broodstock are quarantined prior to stocking in maturation tanks. Screening of crabs for white spot syndrome virus (WSSV), infectious hypodermal and hematopoietic necrosis virus (IHHN), Hepatopancreatic Acute Necrosis Syndrome (AHPNS) and luminescent bacteria, among others, is sometimes carried out. Because analysis is expensive, several crabs of the same batch are sometimes pooled for analysis. Uneaten food in the broodstock tanks is siphoned out after 4–5 hours prior to the next feeding.

FIGURE 9
Recirculating aquaculture system in vertical "apartments" used for soft-shell crab production

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Common challenges in crab hatcheries include infections of eggs and larvae caused by vibriosis and *Lagenidium*, as well as infestations by various protozoans such as *Vorticella*, *Epistylis* and *Zoothamnium*. To mitigate these issues, culture seawater is disinfected after undergoing a series of filtration processes and, in some cases, treated with ultraviolet (UV) light or ozone before being distributed to tanks. Prophylactic measures are implemented prior to the stocking of larvae and throughout the rearing process to prevent disease outbreaks.

When wild crablets are introduced into grow-out ponds, they are often not screened for bacteria or viruses. The most common diseases affecting crab culture include white spot syndrome virus (WSSV) vibriosis, and more recently, *Hematodinium*, a dinoflagellate parasite that has been associated with high mortality rates. Proper pond preparation before stocking is crucial and should include disinfection of the pond and elimination of unwanted organisms.

RESEARCH AND INNOVATION

Although foundational technologies have been commercially developed for all phases of crab culture, ongoing refinements are continually implemented to enhance the profitability and sustainability of crab production. The Science and Technology (S&T) Road Map established by PCAARRD under the Department of Science and Technology (DOST) is outlined in Table 2. This road map is revisited annually. Research and development efforts accomplished over the years have been detailed by Quinitio *et al.* (2017). Recent innovations in mangrove crab culture include the following genetic and genomic applications (The Mangrove Crab Technical Committee 2018, 2021; Romana-Eguia *et al*., 2019):

- Crabifier: Identifying the three common *Scylla* species in the country poses a challenge, particularly when wild crabs have a carapace width of less than 3 cm, as morphological differences are not discernible at this size (Vince Cruz-Abeledo *et al*., 2018). Farmers often stock crabs even smaller than 3 cm. To address this

TABLE 2
Philippines mangrove crab PCAARRD-DOST Science and Technology (S&T) Road Map from 2022–2028

Present situation	Strategic R&D	R&D results utilization	Policy research and advocacy	Capacity building and governance	S&T goals
• Inadequate supply of broodstock and seedstock. • Lack of suitable commercial diets for broodstock and practical diets for grow-out phase. • Low production/ yield due to low survival rates caused by cannibalism and diseases.	• Mangrove crab genomics (Phase 2) • Enhancement of crab broodstock. • Application of exogenous metabolites in improving soft-shell crab production. • Molecular detection of pathogens in mangrove crabs. • Interspecific-hybridization and triploid induction of mangrove crabs for improved performance traits. • Enhancement of seed production techniques for *Scylla olivacea*. • Genomics application in mangrove crab aquaculture. • Postharvest (utilization of waste products).	Rollout/pre-commercialization/ commercialization of the following: • Crabifier. • Mangrove crab fattening. • Establishment of more hatcheries and nurseries. • Development of feeds. • Probiotic-based hatchery techniques. • Detection kit for *Hematodinium*. • Nanomaterials from crab shells.	• Impact assessment (IA) on developed mangrove crab hatchery technologies. • Assessment report of the different programs/projects subjected to IA studies.	• Hatchery and nursery facilities enhancement/ upgrading. • Seminar/training on the ff: - Use of Crabifier. - Crab fattening. - Use of the improved hatchery, nursery and grow-out technologies.	• Sustainable crab production. • Increased survival rate in hatchery (> 10%), nursery (≥ 80%) and grow-out (60–70%).

issue, a tool combining genetic and imaging methods has been developed and is now available for use in the field. This ensures that the species purchased or stock are the preferred ones.

- CrabMAP: This tool generates temperature vulnerability maps for key local areas where mangrove crabs are cultivated. The results are crucial for developing climate-smart aquaculture practices in crab farming.
- CrabADAPT: This application provides insights into the genetic adaptability of mangrove crab populations exposed to varying temperature ranges and anomalies. It is based on gene expression patterns observed across populations subjected to different thermal profiles.
- CrabMOLT: This refers to the optimal combinations of salinity and temperature that facilitate crab moulting. These genetically-based technologies will undergo further validation in collaboration with farmers to enhance their effectiveness and applicability.

Selective breeding programs aimed at enhancing several beneficial traits have been initiated by SEAFDEC/AQD, resulting in crabs that are up to the third generation free of WSSV from three founding populations (Quinitio and Huervana, 2018). In selective breeding, crabs may exhibit favourable responses to selection after two or three generations, necessitating the introduction of a new batch of stock for continued genetic improvement. While traits associated with enhanced growth can be significantly improved through selective breeding, it is essential to ensure that selection proceeds only to the generation where genetic diversity, as indicated by the number of alleles, does not decline drastically. Maintaining genetic diversity is crucial for the long-term sustainability and resilience of crab populations.

Several research efforts have been identified to deal with the issue on lack of suitable commercial diets. The development of immunostimulants and growth promoting feeds – which may also increase tolerance to disease and improve survival and may eliminate the use of antibiotics – have been identified. All these efforts are towards the accomplishment of the S&T goals for sustainable production and increased survival in all phases of mangrove crab culture.

Results of the various research investigations can only give meaningful outcomes when farmers learn and apply the advances through training. This also shows the Philippines' strength in facilitating this, as several such trainings have been done.

MARKET INFORMATION

Market-sized crabs from culture ponds and from the wild are sold to wholesalers (brokers/middlemen) or consolidators, who then transport them to their destinations for export or local consumption, including restaurants and hotels (Figure 10). Crabs that do not go through wholesalers or consolidators are sold directly to local markets, restaurants, exporters and importers.

Large-scale pond owners typically have shorter trading routes compared to small-scale farmers, as they possess the means and capabilities to transport their crabs directly. This allows them to engage in direct transactions with traders and exporters. In contrast, small-scale farmers often face longer trading routes since their products pass through brokers and middlemen before reaching buying stations. Some brokers sell crabs directly in local public markets, while many small-scale farmers opt to sell their crabs directly to consumers within their communities to minimize logistics costs.

Crabs that are rejected for the export market – such as those with missing claws or limbs, undersized crabs and lean specimens – are typically redirected to local markets or to buyers involved in fattening practices.

Transportation, handling and import fees add to the cost of crabs as they are transported from the farm to the consumers. Crab price is based on the species, season, size/weight, sex, maturity, completeness of claws and limbs, and general quality of the crabs. The crabs that pass the export quality grades are sent to or picked-up by the exporters. Upon arrival at the exporters' area, the crabs are purged, cleaned, and sorted again based on the classification. The crabs are repacked in polystyrene boxes with ventilation holes.

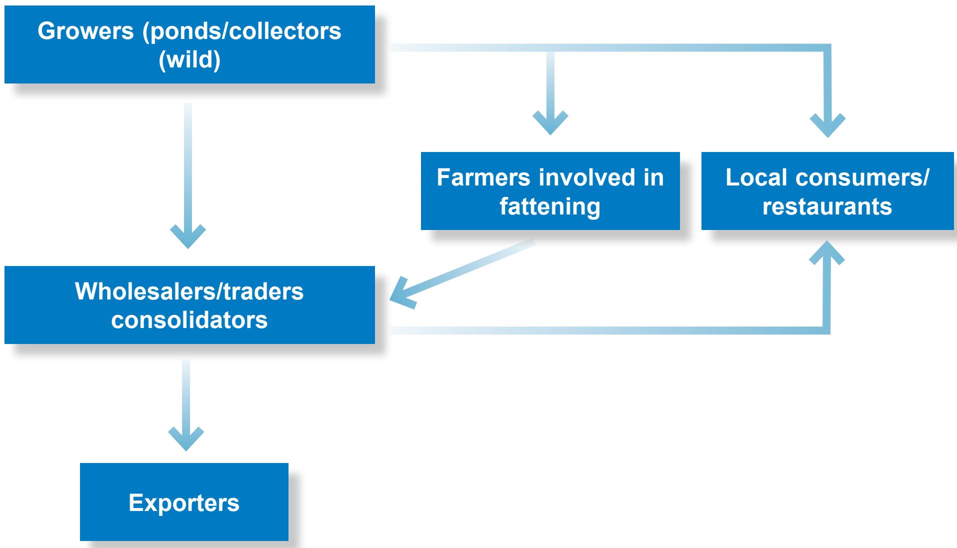
Live crabs are exported to several countries, including China, China Hong Kong SAR, Taiwan Province of China, Singapore and Malaysia. Before the COVID-19 pandemic, there were at least 16 registered exporters of mangrove crabs operating in Metro Manila (The Mangrove Crab Technical Committee 2018, 2021). The demand for exports remains consistently high, particularly towards the end of the year leading up to the Chinese New Year and during the summer months. During peak season, the price for premium crabs ranges from PHP 800–1 600/kg (or about USD 14–29/kg).

The market forms of crabs are the following:

- Live crabs – most of the exported crabs are live and classified into crabs with all body parts intact or crabs with lacking claws. Crabs without claws fetch a lower price.
- Crab claws – claws taken from live crabs or voluntarily removed by crabs are sold separately (Figure 11).
- Soft-shell crabs – newly moulted crabs with sizes ranging from 80–150 g each are frozen.

The Bureau of Agriculture and Fisheries Standards (BAFS) of the Philippine Department of Agriculture, in collaboration with relevant government and research agencies, academia and stakeholders developed the Philippine National Standard (PNS) for live, fresh chilled and fresh frozen mangrove crabs (product standard), soft-shell crabs (product standard), chilled or frozen crabs (code of practice) and Code of Good Aquaculture Practices for shrimps and crabs (BAFS, 2022). These PNS describe the food safety and quality requirements for market-size mangrove crabs.

FIGURE 10
Market channel for mangrove crabs



MAJOR ISSUES AND CHALLENGES FACING THE INDUSTRY

In addition to the issues outlined in the roadmap (Table 2), the crab industry in the country faces several other challenges, including the following:

- Mortality at megalopa stage – The moult death syndrome or mortality of megalopa is due to the difficulty of zoea 5 to completely moult to megalopa. High mortalities are also observed in megalopa approaching the crab instar stage.
- Cannibalism – Cannibalism especially during the nursery phase when crabs frequently moult is a persistent issue. Several strategies to reduce cannibalism have been applied including the incorporation of tryptophan in the diet (Laranja *et al*., 2010), removal or trimming of chelipeds (Quinitio and Estepa, 2011), use of different types and quantities of shelters, stocking density manipulation and different feed formulations (The Mangrove Crab Technical Committee 2018, 2021; Quinitio, Estepa and Huervana, 2018).
- Lack of commercial feed – Low cost and practical diets specifically formulated for mangrove crabs. Pilot testing of the formulated feeds for nursery and grow-out phase in commercial setting needs to be continued to ensure its economic feasibility. At present, only one feed company is producing formulated feed for growing the crabs in ponds.
- Diseases – Disease outbreaks leading to mass mortality are a significant challenge in crab farming. During the hatchery phase, common causes of mortality in eggs and larvae include bacterial infections such as vibriosis, fungal infections (e.g., *Lagenidium* spp. and *Haliphthoros* spp.), and infestations by ciliates like *Zoothamnium*, *Epistylis* and *Vorticella*. In the nursery phase, no serious disease issues are currently observed. However, in the grow-out phase, crabs can become infected with white spot syndrome virus (WSSV), luminescent bacteria, and dinoflagellate parasites like *Hematodinium*, which can lead to severe mortality events.
- Lack of standardization for classifying market size crabs – One of the major challenges in the crab industry is the absence of a uniform standard for classifying market-size crabs. Currently, size and quality classifications can vary between traders, exporters, and regions, leading to inconsistencies in pricing. In some cases,

FIGURE 11
Detached mangrove crab claws sold in the market

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traders or exporters intentionally downgrade the classification of crabs to pay crab growers less than the actual value of their produce. Establishing clear and enforceable grading systems for size and quality would help ensure transparency, fair pricing, and trust between farmers, traders, and exporters.

CONCLUSION

The results of past R&D efforts have been successfully integrated into existing technologies, leading to improved crab production. Notable achievements include survival rates of over 10 percent from zoea 1 to crab instar 1, more than 70 percent survival in the nursery phase, and about 50 percent in the grow-out phase. These improvements have contributed to more efficient and sustainable crab farming practices.

Recently, however, crab growers have faced significant challenges, with high mortalities among sub-adult and adult crabs, making it difficult to harvest the necessary volume for export. This issue has also impacted hatchery operators, who rely on broodstock from grow-out ponds, collectors and traders. Many crab broodstock die within a week of arrival at the hatchery, leading to poor reproductive performance, low zoeae production, and declining hatchery success. The scarcity of mature crabs has driven prices to unprecedented levels.

To address these challenges, it is critical to continue and expand the selective breeding programme for mangrove crabs initiated by SEAFDEC/AQD. This programme aims to develop high-quality, disease-free stocks with better growth rates and higher disease tolerance, which would improve overall yields. Although mangrove crabs are not particularly difficult to breed, their cannibalistic behaviour necessitates adequate facilities for successful breeding.

The selective breeding programme is multidisciplinary, involving geneticists, aquaculturists and disease experts, and requires substantial funding support from the government and stakeholders who stand to benefit from this long-term initiative. The programme demands larger facilities and the expertise of multiple disciplines, but the investment would contribute to a more resilient and productive crab farming industry.

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Status of mud crab industry in Myanmar

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ABSTRACT

The mud crab industry in Myanmar has undergone rapid commercialization in the past decade, growing by about 40 percent and generating USD 77.4 million in export revenue in the period 2020–2021. As a result, mud crabs are currently the single most important fishery export product from Myanmar. This growth was in a large part driven by the proliferation of soft-shell crab aquaculture and this value-added product can be sold for up to six times the price of live mud crabs. Myanmar also implemented several new national standards for aquaculture to conform with international food safety requirements. These measures elevated the overall safety and quality for exported seafood products, and supported export authorization to several new markets, notably in the European Union (EU). Expansion of the mud crab industry has created many new job opportunities in non-urban and economically marginalized areas of Myanmar. Soft-shell crab farming sees a high participation rate among women in rural communities. The mud crab industry evidently has a huge positive impact on economic development and improving livelihoods, but has come at the cost of overexploiting this natural resource. At present, depletion of wild stocks due to unmitigated overfishing and loss of natural habitat poses significant risks to the sustainability of this industry (Figure 1). Addressing this issue, technical proof-of-concept for mud crab hatcheries is being established in Myanmar, although the next steps will need to focus on upscaling and commercial feasibility. There are also opportunities to expand on existing community-based conservation and resource

FIGURE 1
SWOT analysis of the mud crab industry in Myanmar

STRENGTHS

- Market leadership in soft-shell crab production by volume
- Food safety and high product quality is recognized by the international market

WEAKNESSES

- High mortality in soft-shell crab farming systems
- Weak domestic logistics network leads to high mortality of live crabs during transport

S W
O T

OPPORTUNITIES

- Adopting sustainable practices (e.g. hatchery, conservation, pelleted feed)
- Innovations to improve farming efficiency
- Increase robustness of domestic transport chain (e.g. temperature-controlled trucks, better planning, improved communication)

THREATS

- Depletion of wild stock from unmitigated overfishing and loss of natural habitat
- Climate change resulting in irregular rainfall or more severe natural disasters (especially tropical cyclones)

management efforts. Additionally, improvements to industry practices are needed to minimize crab mortality rates during transportation and aquaculture, by strengthening the domestic supply chain and innovating in aquaculture technologies, respectively. Overall, there is a sizeable opportunity by investing in the future of this industry, provided there is a clear roadmap and commitment towards sustainability.

INTRODUCTION

Species of commercial crabs

Mud crabs are a commercially significant fishery resource in Myanmar, wherein the four closely-related species, *Scylla serrata*, *Scylla olivacea*, *Scylla paramamosain* and *Scylla tranquebarica* have been identified. Although the species are not distinguished in the commercial setting, studies point to different mud crab populations across the three main tracts of mangroves in Myanmar: Rakhine State, Ayeyarwady Region and Tanintharyi Region. *S. olivacea* is the main species in Myanmar and, along with *S. paramamosain*, are found starting from the Ayeyarwady Delta and going towards southern Myanmar in the Tanintharyi Region (Thein *et al*., 2015; Segura-Garcia *et al*., 2018; Salagrama and Phyo, 2020). *S. serrata* is less common in Myanmar but has been reported to be abundant in northern Rakhine State (Mar, 2023) whereas *S. tranquebarica* is very rare. Among the other crab species of commercial importance, blue swimmer crabs (*Portunus pelagicus*) are readily available but is mostly consumed within the domestic market. Spanner crabs (*Ranina ranina*) are available from October–December and are mostly exported to Taiwan Province of China and China, with some quantity going to Japan. Other swimming crabs – including the three-spot swimming crab (*Portunus sanguinolentus*), crucifix crab (*Charybdis feriatus*) and marbled crab (*Charybdis variegata*) – collectively contribute less than 10 percent of the crab catch and are highly seasonal (Macintosh, 2015).

Status of wild crab resources

The wild stock of mud crabs in Myanmar has been in steady decline over the past decades, driven by the rapid commercialization of the mud crab industry, increased fishing pressure, mangrove deforestation, and the widespread capture of immature and ovigerous ("berried") females. Despite the lack of data on wild stock levels, it is widely accepted that mud crabs are an overexploited resource, where more than 134 million crabs are collected from the wild annually (Thura Swiss, 2021). Loss of habitat is also an important cause for declining wild stock. In a country where most households still rely on traditional stoves for cooking, harvesting of fuelwood from mangroves is an important driver for deforestation (Feurer, Gritten and Than, 2018). Moreover, the conversion of mangrove forests for commercial use (such as rice fields, aquaculture ponds and salt pans) is also an important factor contributing to its decline. Consequently, mangrove cover in Myanmar has been receding at a rate of approximately 4 percent each year, which cumulatively led to a net decline of 52 percent between 1996 and 2016 (Alban *et al*., 2020). According to the most recent Forest Resource Assessment in 2020, only 453 250 ha of mangrove area remains in Myanmar (FAO, 2020). Additionally, mud crab populations are vulnerable to the effects of tropical cyclones. Cyclones in Myanmar typically coincide with the mud crab breeding season of April–May, which has historically been linked to shortages during what otherwise should be the peak season of June–September, presumably due to the disrupted breeding cycle. Most recently, the Category 5 tropical cyclone *Mocha*, which made landfall in Rakhine during May 2023, corresponded with a sharp decline in mud crab supply (DMG, 2023). Thus, anecdotal evidence points to the susceptibility of the mud crab breeding cycle to natural disasters, which could become more pronounced with climate change.

Conservation and management of wild crab resources

The Myanmar Department of Fisheries (DoF) under the Ministry of Agriculture, Livestock and Irrigation (MOALI) is the government agency responsible for the management and conservation of fishery resources. The DoF's authority over freshwater and brackish water bodies, including the estuaries and mudflats wherein mud crabs are captured, is defined within the Freshwater Fisheries Law (1991). However, decentralization under the New Constitution (2008) allows each state or region to draft their own freshwater fisheries legislation, thereby providing the flexibility to implement practices suited to each region and setting up opportunities for co-management between the authorities and resource users. To date, only Rakhine State and Ayeyarwady Region have effectively implemented new fisheries laws (Tezzo *et al*., 2018). Furthermore, the Forest Law (2018) and Conservation of Biodiversity and Protected Areas Law (2018), administrated by the Forest Department, prescribes the management of aquatic resources categorized as wild animals, designation of Protected Areas, and penalties for fishing in reserved forests including the mangroves. Mud crab fishers are required to have trapping licenses and pay fees to the Forest Department for the right to fish in the mangroves; and collectors need licenses to engage in the trading of crabs and are subject to fees payable to the DoF township officer based on their sales amount (Robalino, Russell and Soewarno, 2019).

To prevent the capture of immature crabs before they have had a chance to reproduce, the DoF Directive No. 9/94 issued under the Freshwater Fisheries Law (1991), prevents the sale, storage, and transportation of mud crabs with a carapace width of less than 8.15 cm, which is about the length of a disposable cigarette lighter as an easy guide for fishers (Imbach, 2022). However, although there are no written directives that indicate the size limit by weight, the DoF has on occasions implemented a minimum legal size at 100 g. Based on limited information, it seems that this regulation is narrowly applied to the export of live mud crabs (DoF, 2012; personal communication). This regulation is challenging to enforce because of the economic importance of mud crab industry and especially the fact that mud crab capture is an important livelihood activity for many vulnerable coastal communities. For example, a recent survey of crab fishers in Rakhine showed that 72 percent of respondents depend on mud crab capture for more than half of their total household income (García, 2021). The mud crab industry is also an important source of job opportunities in non-urban and economically marginalized areas, particularly for women, who have a high level of participation on-soft-shell crab farms engaging in feeding and post-harvest activities such as processing and marketing (Thura Swiss, 2021).

Interestingly, the DoF had reported its activities on confiscating and releasing undersized crabs up until 2012, but thereafter this regulation was likely relaxed by the authorities to facilitate the growth of the mud crab industry. However, following what seemed to be a "commercial extinction" of mud crabs with alarmingly diminished stocks in 2018 (Hosch, Belton and Johnstone, 2021), the importance of sustainability became more apparent to industry stakeholders. In 2019, the Myanmar Fishery Federation (MFF), the main non-government organization representing the private fisheries sector including the Myanmar Crab Entrepreneurs Association, pledged to reinstate the export ban on undersized crabs less than 100 g (MBT, 2019a). At present, it is unclear whether this restriction is still in place.

Notwithstanding the status of this regulation, there is low awareness among local fishers with regards to the restrictions on undersized crabs (Helvetas, 2019; Imbach, 2022). Notably, in a recent survey conducted in Mon State and Bago Region (near the Ayeyarwady Region), almost two-thirds of interviewed crab fishers responded that they did not know of any regulations for the capture of mud crabs, and that fewer than one in five fishers consistently release undersized crabs (Imbach, 2022). Among the respondents who were aware of the regulation, the majority indicated that it relates to a minimum weight instead of size, but there were significant discrepancies about the actual legal threshold. Furthermore, an examination of sales invoices from village-level crab collectors in the Bago Region showed that between one- and two-thirds of total catches consist of undersized crabs (Wynn *et al*., 2019). The Tanintharyi Region is an interesting exception wherein fishers routinely release undersized crabs. It is not clear how this practice came to be adopted by the locals, but it may be a beneficial outcome from the significant mangrove conservation activism in the region.

In addition to the limited restriction on undersized crabs, regional authorities have put in place closed seasons that were variously reported as the month of March, May or September (Niras Consult IP, 2018). Although industry experience over the past 30 years together with corroborating reports collectively suggest that the main breeding season for mud crabs in Myanmar falls in the months of April and May, there may be regional differences. For example, in southern areas of Mon State, berried mud crabs are said to be most abundant in March, which corresponds with the closed season in the Ayeyarwady Delta (Imbach, 2022). In the Bago Region and northern Mon, however, peak catches of ovigerous female crabs were reported by fishers to be between September and November. Therefore, a regional approach to implementing closed seasons may be more effective, though more research is needed to better understand the local peak breeding periods. During the rest of the year, there are no limitations to the number of crabs that the fishers can catch, including ovigerous females (Robalino, Russell and Soewarno, 2019). Although there is some awareness of the negative effects of catching female crabs, in practice less than 7 percent of fishers release ovigerous females (Imbach, 2022), almost certainly because of the premium on egg-bearing crabs in the Chinese live crab market.

Additionally, several no-catch zones for crabs have been designated by the DoF, including 12 Protected Areas for mud crab scattered along the Myanmar coastline comprising about 850 ha (DoF, 2017), and a 200 ha crab conservation area in Mon State supported by the Gulf of Mottama Project (Helvetas, 2019). Several other resource management strategies have been explored in Myanmar, although none to date have gained widespread adoption. For example, stock enhancement programmes through the release of hatchery-grown juveniles into the wild were attempted by the Yangon Technical University in 2002–2003, then again by the DoF with the support of SEAFDEC (AQD) in 2009–2010, but both were unsuccessful due to high mortality rates in the hatchery (Marius, 2013). A "crab bank" approach to protecting mud crab spawning has been described, whereby large ovigerous females sold or donated by fishers to community-managed banks are kept in floating baskets until they have released their larvae (Macintosh, 2015). However, there is no information indicating that this practice has been widely adopted.

Management and regulation of mud crab aquaculture

The aquaculture sector in Myanmar is also managed by the DoF as defined by the Law relating to Aquaculture (1989). Under this legislation, aquaculture activities and the use of aquaculture lands or fishery areas are subject to the issuance of licenses and leases granted by the DoF. However, small, single-pond aquaculture ponds operated by families for family consumption are exempted from the need to obtain such licenses. The DoF may also designate aquaculture lands from agricultural and virgin lands, barring any conflicts with other land use regulations including the Land Nationalization Act (1953) and Farmland Law (2012), and Vacant, Fallow and Virgin (VFV) Land Management Law (2023) (Tezzo *et al*., 2018). To limit its environmental impact, aquaculture facilities also need to comply with regulations set forth in the Environmental Conservation Law (2012) and Environmental Conservation Rules (2014), which are overseen by the Environmental Conservation Department.

As part of the country's commitment to the sustainable development of its aquaculture and fisheries sector, the DoF collaborated with the German development agency, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), to implement the Myanmar Sustainable Aquaculture Programme (MYSAP) in 2017, which includes developing a National Standard on Good Aquaculture Practices (Myanmar GAqP). The standard outlines best practices for hatchery, nursery and grow-out operations as it relates to food safety, fish health and welfare, as well as socioeconomic and environmental aspects. To enable a more widespread recognition and acceptance in the international markets in the Association of Southeast Asian Nations (ASEAN) member states, China, as well as other countries, the standard was developed to have commonalities with the Global GAP Aquaculture Standard and the range of standards of the Aquaculture Stewardship Council (ASC). Entities engaging in the export of fishery products need to be GAqP certified to comply with the Directive No. 8/2018 (Technical Regulations for Export and Import Fishery Products) under the Marine Fisheries Law (1990) (Tint, 2019). Several other directives issued under the Marine Fisheries Law sets guidelines in ensuring food safety and quality, including hygiene control and health requirements during food production, and restrictions on the use of additives, pesticides and antibiotics. Furthermore, to meet EU requirements on food safety and quality, the DoF implemented a National Residues Monitoring Plan (NRMP) in 2014–2015, in which establishments intending to export to the EU will need to undergo routine laboratory testing and monitoring for veterinary medical products and environmental contaminants in their fishery products (Mar, 2018). In 2018, regulatory approval was granted to select companies and soft-shell crab products were exported to the EU for the first time. At present, the DoF is continuing to promulgate GAqP and NRMP standards across the nation's aquaculture sector. Overall, the above highlights several key policies in Myanmar as it relates to the operation of aquaculture facilities but is by no means an exhaustive representation of all the regulation that may also be applicable. It is clear, however, that the country has made strides in recent years to raise its industry standards to conform with international food safety requirements.

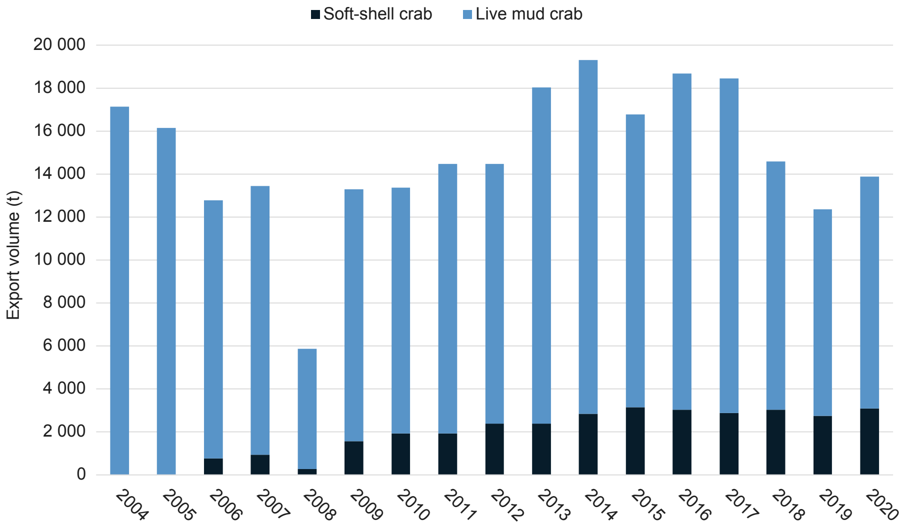
MUD CRAB INDUSTRY STATUS

Production status

In Myanmar, mud crabs are available year-round, but peak catches occur generally around the monsoon season between June to September, whereas the lowest catches occur around the dry season from February to May. The DoF started publishing fishery statistics for live mud crabs and soft-shell crabs since 2004 and 2006, respectively. Whereas the export volume for live mud crabs has generally been flat over the past decade, soft-shell crab exports saw a dramatic increase of more than 300 percent between the start of reporting to the most recent data available (Figure 2). Notably, the significant drop in export volume in 2008 can be attributed to cyclone *Nargis*, which was one of the deadliest tropical cyclones to have ever been recorded globally. It is evident that the live mud crab export volume consistently outstrips that of soft-shell crabs in a roughly 80:20 ratio, and this pattern is expected to hold since soft-shell crabs are a niche and premium seafood product. At the height of crab production around 2014 and 2015, 16 471 t of live crabs were exported from Myanmar, as compared to 3 151 t of soft-shell crabs. While it is difficult to gauge domestic consumption, an expert estimated that about half of the soft-shell crabs produced in Myanmar are sold to the local retail market, hotels and restaurants.

Mud crabs represent one of the most economically important fishery resources in Myanmar, which accounted for USD 77.4 million in exports between 2020–2021 and took the number one spot in terms of export value for fish and fishery

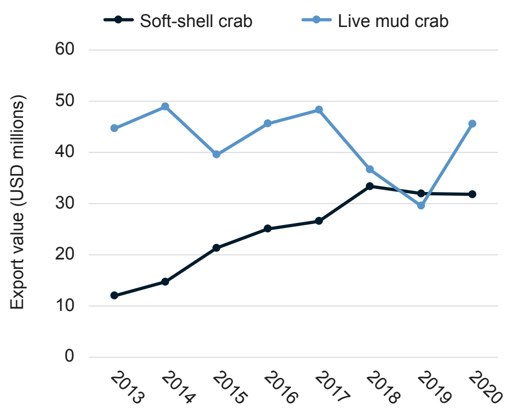
FIGURE 2
Myanmar mud crab export volume from 2004 to 2020



Source: Fishery Statistics. Annual yearbooks. Ministry of Agriculture, Livestock and Irrigation, Department of Fisheries, Republic of the Union of Myanmar.

products (Figure 3). For comparison, the next most exported fishery products that year were ribbon fish (USD 55.0 million), fish meal (USD 53.1 million) and rohu (USD 46.4 million) (DoF, 2021). The total export value for live mud crabs seems to be on a slight downtrend in recent years, possibly as more people make the switch to soft-shell crab farming to capitalize on better profit margins and quicker turnaround time. Additionally, soft-shell crab farming is more accessible than ever before. For example, the plastic baskets for soft-shell crab production used to be imported from Thailand, which can be cost prohibitive to farmers, but now there are at least three manufacturers in Yangon that can supply this material at more affordable prices. Even though the export volume for soft-shell crabs is dwarfed by that of live mud crabs, soft-shell crabs have recently been closing the gap in terms of export value. Of note, the value

FIGURE 3
Myanmar mud crab export value between 2013 to 2020



Export value (USD millions)			
Year	Live mud crab	Soft-shell crab	Total mud crabs
2013	44.7	12.0	56.7
2014	48.9	14.7	63.6
2015	39.6	21.3	60.9
2016	45.6	25.1	70.7
2017	48.3	26.6	74.8
2018	36.6	33.4	70.0
2019	29.5	31.9	61.5
2020	45.6	31.8	77.4

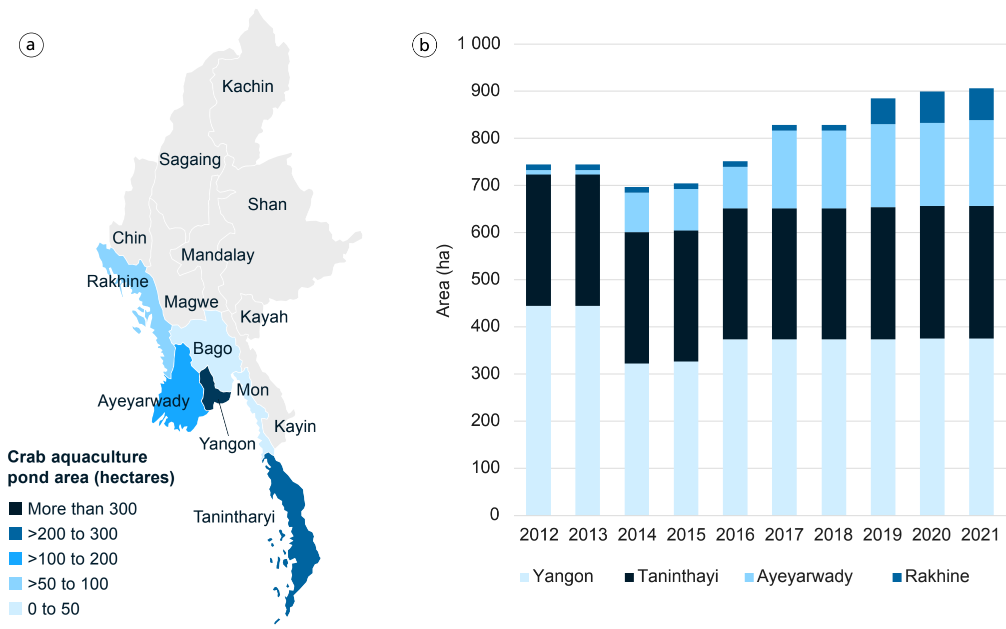
Source: Fishery Statistics. Annual yearbooks. Ministry of Agriculture, Livestock and Irrigation, Department of Fisheries, Republic of the Union of Myanmar.

of soft-shell crab exports briefly surpassed that of live mud crabs in 2019 due to the pandemic-related border closures negatively impacting China exports, which has since rebounded. Remarkably, whereas soft-shell crabs account for only 22 percent of the total mud crab export volume, it disproportionately contributes to 41 percent of the export value of mud crabs. Therefore, there is a clear opportunity in shifting towards the production of value-added soft-shell crabs to increase earning potential and create more jobs in the aquaculture sector.

Farming areas

Based on the most current DoF fishery statistics, there are more than 900 ha of pond area dedicated to mud crab aquaculture in Myanmar (DoF, 2021). The largest mud crab farming areas in Myanmar are in the Yangon Region, followed by Tanintharyi Region, Ayeyarwady Region, then Rakhine State (Figure 4). Mud crab aquaculture in Myanmar is dominated by soft-shell production, which is carried out by large-scale operations that can involve up to 500 workers per farm, whereas crab fattening or grow-out is mostly practised by individual crab fishers and collectors. Since small ponds used for subsistence purposes are not required to be registered with the DoF, the above statistic is likely representative of aquaculture ponds used for soft-shell crab farming. The first soft-shell crab farm was reported to have started in 2000 in Myeik – the largest city in the Tanintharyi Region, which borders Thailand – and it is thought that the practice was adopted from other soft-shell crab farms that were already established in Ranong (Thailand) at the time. Currently there are at least three main farms in Myeik, the largest of which is Kaung Kaung Aquaculture Co Ltd (established 2002) which has 89 ha in pond surface across 33 ponds, and with a maximum stocking quantity of over 1 million pieces of mud crabs. Soft-shell crab farming eventually spread to the Yangon Region in 2008, which expanded to five farms that are all located within an aquaculture

FIGURE 4
Mud crab aquaculture pond area in Myanmar
(a) Farm area in different States; (b) Production from 2012 to 2021



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Fishery Statistics. Annual yearbooks. Ministry of Agriculture, Livestock and Irrigation, Department of Fisheries, Republic of the Union of Myanmar.

designated zone in Kyauktan Township (Figure 5). The largest and longest-standing soft-shell crab farm in this region is SG Crabs World Ltd (established 2008), whose aquaculture operation spans 146 ha of pond surface across 20 ponds. Observing the commercial success of soft-shell farming in the Tanintharyi and Yangon Regions, there was rapid proliferation of small- to mid-sized farms that are clustered in Labutta, a town in the Ayeyarwady Region, and along the coastal areas of northern and central Rakhine primarily in Thandwe, Sittwe, and Kyaukpyu (MITV, 2022; Thu, 2022). In Labutta District there are at least nine soft-shell crab players including Texchem Marine Labutta Ltd, a Malaysian joint venture company, among two other companies and six local farmers (MBT, 2019b). Overall, soft-shell farms seem to be saturated in the Yangon, Tanintharyi and Ayeyarwady Regions, whereas Rakhine is expected to be the next area for expansion. Given that northern Rakhine is prone to tropical cyclones, building resilience to natural disasters will be especially important for the future growth of the mud crab aquaculture sector in this region.

FIGURE 5

Satellite imagery of the largest collective of soft-shell-crab aquaculture area in Myanmar

The site with 376 ha of aquaculture ponds is in Kyauktan township, about an hour's drive from Yangon. Five soft-shell crab companies are co located in this aquaculture zone wherein SG Crabs World is the largest, comprising about 40 percent of this area and with a production capacity of 60 t/month

Hatcheries, nurseries and farms

There is a well-organized network facilitating the trade of mud crabs in Myanmar, either supplying to local soft-shell crab farms or exporting live hard-shell crabs to mainly China and Thailand. Captured crabs are transported from township-level collectors to brokers or wholesalers in Yangon, which serves as an important hub for both the domestic and international market (Imbach, 2022). Mud crabs destined for the China market are usually captured in the Rakhine or Ayeyarwady regions and transported to Mandalay, which is a major trade hub for northern and central Myanmar. There, the crabs are inspected by agents from Chinese importing companies and repacked before being loaded onto a different truck bound for Muse, a border town in Shan State, and then into China's Yunnan Province for further distribution (García, 2019). There are also major crab collection centres located in Myeik where crabs are either sold to local soft-shell crab farms in the Tanintharyi Region or transported by boats or trucks to Thailand. Whereas most of the hard-shell crabs traded to China either undergo fattening or are directly consumed there, a considerable amount of the live crabs exported to Thailand support the country's soft-shell crab farms. Due to the long travel distance and lack of temperature-controlled transportation in Myanmar, it is not unusual to see 10–15 percent mortality rates under regular conditions (Marius, 2013).

In comparison to the live hard-shell crab export business, the soft-shell crab value chain has higher infrastructure and capital requirements. Given that soft-shell crabs start to harden within hours postharvest, there is a narrow window of opportunity to process and freeze the products. Therefore, processing facilities equipped with clean rooms and freezers should ideally be located nearby to the soft-shell crab farms. Larger soft-shell operations have often built processing facilities adjacent to the farms, whereas smaller operations with less financial support will opt for rudimentary facilities equipped with consumer-grade freezers or sell their live soft-shell crabs to exporters that can do the processing. As a result, there is a discernable difference in the safety standards and quality of the soft-shell crab products depending on the available facilities. Finished products are transported by refrigerated cargo trucks to Yangon Port, where is it finally exported by ocean freight to countries worldwide.

Despite several prior endeavours at mud crab hatcheries in Myanmar, there are none known to be currently in operation. Some of the earliest attempts with the goal of stock enhancement – including one by the Yangon Technological University in 2002 then again by the DoF with the support of SEAFDEC in 2009 – were terminated due to high mortality rates between the zoea fourth stage to initial megalopa stages (Marius, 2013). The most successful effort to date was led by Texchem with support from MYSAP, which achieved a 20–25 percent survival rate to the crablet stage and had produced close to 1 million crabs in the first year of operation (Fitzsimmons, 2021). Through a buyback programme, C1 crablets (around 4 mm) were supplied to local smaller-scale farms for grow-out to 70–100 g before they are sold back to the company for soft-shell production. The hatchery had started operating in 2019 but was later suspended due to the COVID-19 pandemic, deteriorating market conditions and the need to cut costs. The company has since then diverted their hatchery efforts onto barramundi (Asian seabass) with no announced plans to restart the mud crab hatchery.

AQUACULTURE PRACTICES AND SYSTEMS

Since there are no operational mud crab hatcheries at present, the methodology on broodstock management and larval rearing used in the Texchem and MYSAP programme may be considered representative of the approach used in Myanmar.

Broodstock management

Gravid *S. paramamosain* females of approximately 300–400 g each are selected from wild stocks. The level of gravidness may be visualized and evaluated by placing the specimen against a bright light source. Other selection criteria applied include vigour, complete limbs, no injury and free from shell disease manifestations. After recording the weight and carapace width, the broodstock is disinfected using formalin prior to stocking individually in bins or communally in tanks connected to a water recirculating system (RAS). Stocking containers are shaded to create a darkened environment and provided with a fine sand substrate base of at least 6 cm in depth to facilitate proper egg mass formation during spawning. The broodstock is fed daily to satiation with a variety of seafood including fish, squid, shrimp, clam, seaworm and cockle until it becomes ovigerous or berried. Throughout this period, proper husbandry is implemented to ensure hygiene and maintenance of good water quality. The berried crab may be removed from the broodstock system and stocked separately in a bin. Water exchange is conducted daily. At ambient temperatures, the newly spawned orange-coloured eggs will gradually change its coloration to brown, then black and hatch in approximately 9 days. The development of the eggs may be monitored more closely using a microscope.

Larval rearing

Hatching of the eggs usually occur in the morning. The quality of the newly hatched Z1 larvae are usually evaluated visually and may also be subjected to a formalin-based stress test to determine their overall vigour. Active larvae tend to swarm at the water surface and are highly phototactic in behaviour. Active specimens are promptly collected using a net and consolidated in a volumetrically defined container which will function as the "larvae stock". Stocking of the Z1 larvae is conducted to yield a density of 200 pieces per litre in a 500 L fiberglass tank (Figure 6a). Initial feeding is with *Artemia* umbrella stage. At approximately day-10 of the culture, the Z4 larvae are transferred into a 2 000 L fiberglass tank and powdered larval feed is included in the feeding regime. Net substrates are added into the culture tank when megalopa are formed. Crablets may be expected at approximately day-20 and are usually harvested a couple of days later (Figure 6b).

FIGURE 6
Commercial mud crab hatchery in Myanmar
(a) Larval culture tanks being stocked with newly hatched Z1 larvae; (b) Hatchery-produced C1 crablets with carapace diameters measuring about 4 mm; (c) Hard-shell crabs grown after 3 months using hatchery grown C1 crablets

©MYSAP

Hard-shell crab farming

Hatchery-produced C1 crablets are stocked extensively into mangrove ponds at densities ranging from 0.1–1 piece/m^2 depending on farmer's experience, the stocking and harvesting regime adopted, availability of feed, vegetation coverage, and shelter/refuge for the crabs. The culture area is barricaded by bunds to create a pond with a maximum depth of approximately 3 feet and is subjected to the natural tidal influences using water gates or simple polyvinyl chloride (PVC) pipes. A perimeter (net) fence may be helpful in alleviating entry of predators such as monitor lizards and otters into the culture pond. The crablets feed on various natural feeds including clams, worms and snails which are normally available within the culture pond. Supplementary feeding may be applied, if necessary. C1 crablets can reach a size of approximately 150 g in a culture period of 3–4 months, without supplementary feeding (Figure 6c). After the initial stocking, subsequent stocking may be conducted monthly while harvesting is conducted daily using crab nets. The claws of the harvested crabs are immobilized by securing them with raffia or other locally available materials and are packed into rectangular plastic baskets to facilitate transport to the soft-shell shedding farms.

Soft-shell crab production

On arriving at the soft-shell shedding farm, the plastic baskets containing the hard-shell crabs are submerged in a well-aerated brackish water flow through tank setup for approximately 30 minutes in order to help remove possible accumulated nitrogenous waste. After the "recovery" treatment, the crabs are sorted according to sizes and vigour. Undersized and inactive specimens are rejected and the selected crabs are sent to designated shedding ponds for stocking individually into boxes which are suspended on floating rafts (Figure 7a). The crabs are fed once every two days with sardines at a rate of approximately 10 percent of body weight until they moult naturally, usually within 45 days of stocking (Figure 7b and 7c). Harvesting of soft-shell crabs is conducted every three hours throughout the day or night. Harvested soft-shell crabs are placed into freshwater and are consolidated at a collection centre prior to delivery to the processing factory.

FIGURE 7

Soft-shell crab farming in Myanmar

(a) A soft-shell crab aquaculture pond in the Tanintharyi Region with floating rafts carrying plastic baskets that each contain individual crabs; (b) *S. olivacea* specimen in its hard-shell form prior to stocking into plastic baskets for shedding compared to (c) a newly moulted crab after harvest

MUD CRAB HEALTH AND DISEASE MANAGEMENT

During the hatchery phase, gravid females selected for broodstock should display vigour, no injuries and a clean exoskeleton (without signs of shell diseases and ectoparasites). Each specimen is subjected to formalin immersion at 150 ppm for 30 minutes prior to stocking into a bacterial and seaweed-based RAS broodstock maintenance system at the hatchery. At the larval-rearing phase, culture water of 30 ppt is reconstituted using brine and tap water at the hatchery. The "reconstituted seawater" is normally disinfected via chlorination and/or ozonation. Water quality during larval-rearing is maintained using a combination of green-water and water-exchange regimes. If necessary, formalin may be applied to control fungal and ectoparasitic infestations. At the grow-out phase, mortality starts to increase within a week if the water salinity drops to 0 ppt. This phenomenon is especially significant at upstream shedding sites in Myanmar during the monsoon season. Shell-fouling may also be observed during this period. Otherwise, no disease outbreaks have been observed during soft-shell crab production, likely because there is little time for the crabs to become infected with new parasites and pathogens during the short holding time. Nonetheless, the impact of viral diseases in blue crab shedding facilities has recently come into focus (Coates and Rowley, 2022), which highlights the need for more research into potential diseases in high-density crab farming conditions in Myanmar.

MARKET INFORMATION

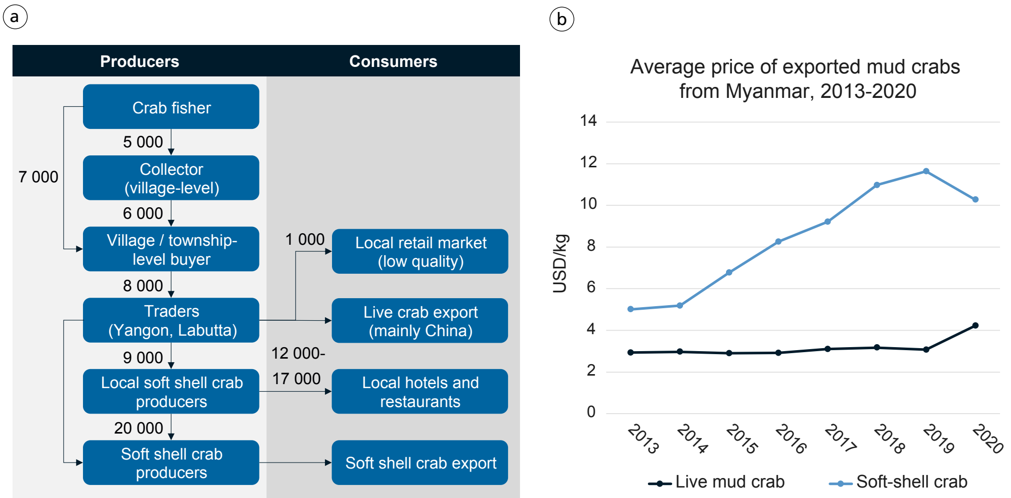
Major markets for hard-shell and soft-shell mud crabs

The mud crab market is largely segmented between hard-shell and soft-shell crabs. For hard-shells, the overwhelming majority are sold live to China and to a much lesser extent to Thailand. According to DoF statistics, 94 percent of exported live crabs are to China and the rest to Thailand (DoF, 2012). For soft-shell crabs, the United States of America is the single largest market which by itself accounts for 30–40 percent of soft-shell crab exports from Myanmar. The strong demand in the United States of America can mostly be attributed to the popularity of soft-shell crabs in Japanese cuisine and the general increase in the number of Japanese restaurants, which has been steadily growing by 4–5 percent each year (IBISWorld, 2020). Asia-Pacific also represents a significant market for soft-shell crabs, collectively accounting for 50–60 percent of exports from Myanmar. Within this geography, demand is highest in China, Hong Kong SAR followed by Australia, Taiwan Province of China, the Republic of Korea and Malaysia. Because Myanmar companies only recently received EU export authorization for aquaculture products in 2018, the European market for Myanmar soft-shell crabs is still nascent, accounting for less than 10 percent of exports.

Product prices

According to a survey conducted in 2019, mud crabs captured by fishers can be sold for between MMK 5 000–7 000/kg (Myanmar kyats) to crab collectors or township-level buyers, which are then sold for around MMK 8 000/kg to traders located at the main trade hubs such as Yangon (Figure 8a) (Robalino, Russell and Soewarno, 2019). From here, typically the larger crabs are selected for the live mud crab market whereas the smaller crabs would be supplied to soft-shell crab farms at around MMK 9 000/kg. It should be noted that the price of live mud crabs can fluctuate considerably depending on the landing quantity, which is the lowest (and most expensive) during the dry season, or demand (e.g. high consumption in China during lunar new year). The average price of exported live mud crabs over the past 10 years has been relatively flat, between USD 2–4/kg (Figure 8b). In comparison, soft-shell crab prices saw tremendous growth between 2015 to 2020, from USD 5.20 to 11.60/kg which equates to a 124 percent increase. Due to soft-shell crabs being a highend seafood that is primarily consumed in restaurant settings, it is a food product that is sensitive to discretionary consumer spending. Consequently, soft-shell crab prices have recently been on the decline due to a global market slowdown but is expected to rebound as the economy recovers. Over the long-term, however, prices for mud crabs can be expected to gradually increase with diminishing wild stock, unless more sustainable practices are implemented.

FIGURE 8
Mud crab prices in Myanmar
(a) Reference prices for mud crabs at each step of the value chain; (b) average prices of mud crabs exported from Myanmar between 2013 to 2020



Note: Above prices are denoted as Myanmar Kyats (MMK) per kg.

Source:
(a) Adapted from Robalino, J.J., Russell, A.J.M. & Soewarno, N. 2019. Myanmar Ayeyarwady Delta: Bio-based value chain analysis for sustainable mangrove restoration. Seoul, The Global Green Growth Institute.
(b) Fishery Statistics. Annual yearbooks. Ministry of Agriculture, Livestock and Irrigation, Department of Fisheries, Republic of the Union of Myanmar.

MAJOR ISSUES, PROBLEMS AND CHALLENGES FACING THE MUD CRAB INDUSTRY

Given the current state of mud crab overexploitation and loss of natural habitat, the risk of depleting the wild stock poses the most important long-term threat to this industry. Expansion of conservation and resource management efforts may lead to incremental benefits, but it is especially important to raise awareness and educate stakeholders to yield full benefit. It is apparent from the several survey studies that poor dissemination of information is an important barrier towards adoption of sustainable practices; and in more extreme cases, these practices are often abandoned when at odds with more immediate needs to support basic livelihoods. Therefore, prescribing more general restrictions on fishing activities (e.g. mandating the release of ovigerous females) will likely not be effective. Given that the farming system for mud crabs has mostly remained the same since its inception in Myanmar, technological innovations are long overdue. In this regard, the advancements of the shrimp industry could be a useful case study towards building the development roadmap for mud crab aquaculture, such as closing off the life cycle through the development of hatcheries and transitioning to pelleted feeds. Fortunately, the incentive is already there, as several of the main soft-shell crab producers in Myanmar have expressed interest in mud crab hatcheries. While the Texchem/MYSAP hatchery programme seems to have achieved technical proof-of-concept, the cost-effectiveness of hatchery-produced crabs compared to wild-caught crabs will be the key driver of industry adoption. One of the challenges of hatchery-derived crabs is the immense pond area needed for grow-out to mitigate cannibalism issues and relatively few grow-out operations in Myanmar. It is most likely that using the ponds for low density mud crab grow-out incurs a high opportunity cost versus engaging in high-value soft-shell crab farming or other, more intensive forms of aquaculture. Mud crab polyculture with tilapia, for example, is a potential solution but it is not a prevalent practice in Myanmar. Alternatively, hatchery-derived crabs could be stocked into private leasable fishery areas or better yet, existing Community Forests which are mangrove areas designated by legal land-use agreements and management plans between communities and the Myanmar Forest Department (Critchley and Kyaw, 2023). The use of natural crab feed (e.g. sardines and trash fish) could also become a constraint on sustainability. To address this issue, pelleted feeds like those currently used in the shrimp industry could be adapted for mud crabs. Alternatively, guppy fish, crickets and the pupae of the black soldier fly could also be sustainable feeds for crablets and crabs.

The high mortality rates of mud crabs incurred during transport and during aquaculture highlights areas of unmet need for innovations to increase the robustness of the domestic transportation network and to improve farming efficiency. At present, around 10–15 percent of crabs are expected to perish while in transit and an additional 30 percent mortality rate can be expected during farming, which creates a tremendous amount of wastage. Therefore, strategies to reduce crab mortality would inadvertently reduce the fishing pressure to achieve the same level of product output. The use of temperature-controlled or even insulated cargo trucks are obvious albeit capital-intensive solutions, but many other aspects of modern cold chain solutions could apply. On the aquaculture side, the causes of the mortality issues are unfortunately still not clearly understood. One of the first steps will be to conduct a retrospective analysis on industry mud crab aquaculture data to generate leading hypotheses on the cause of high crab mortality. Depending on those findings, possible solutions could include:

- integration of seaweed-based or plant-based recirculating system as a simple and cost-effective approach to maintaining good water quality;
- novel basket designs conducive to mud crab survival; and
- incorporation of a mud substrate (likely as a source of vital minerals) to help promote crab survival at low-salinity conditions during periods of high rainfall, and so forth.

CONCLUSION

The mud crab industry in Myanmar has seen rapid development over the years and notably carved out a competitive niche for soft-shell crabs in the global market. The implementation of national standards such as the GAqP and NRMP has helped to elevate the overall safety and quality of its exported crab products, which is currently recognized by many international buyers. While the success of this industry was dependent on the collective effort of the various government, industry, and non-profit stakeholders, it is important to recognize the endowment of rich fishery resources that has enabled this economic growth. Therefore, there is a critical need to secure the long-term future of this industry by ensuring the sustainability of the mud crab supply. There is still a long road towards achieving sustainability for mud crabs in Myanmar, but the many potential solutions support an optimistic outlook.

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Mud crab aquaculture industry in Thailand

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ABSTRACT

Mud crabs have become one of the target species for aquaculture in Thailand due to their high market demand. In 2021, the wild catch of mud crab reached 2 871 t, valued at Thai baht (THB) 641.4 million (USD 18.0 million). The three dominant species are *Scylla olivacea*, followed by *Scylla paramamosain* and *Scylla tranquebarica*. The production of farmed mud crabs increased sharply from 1 321 t in 2018 to 3 479 t in 2021 and 2 882 t in 2022. The values also rose accordingly, from THB 487 million (USD 13.6 million) in 2018 to THB 1 054 million (USD 29.5 million) in 2021 and THB 956 million (USD 26.8million) in 2022. Initially, *S. olivacea* was the main farmed species when farmers were still relying on wild seeds, but there is now increased focus on stocking farmed seeds of *S. paramamosain*. Recent success in the development of systems and techniques for the consistent production of broodstock in captivity has overcome the bottlenecks of insufficient and low-quality seed supply in Thailand. Regular seed production by hatcheries, coupled with strong government policies, have encouraged more farmers to be involved in mud crab aquaculture. Two common methods of grow-out farms are monoculture and polyculture systems. In 2022, there were 5 266 registered farms covering an area of 51 726 rai or (8 276 ha), with the largest area located in the middle region of the Gulf of Thailand. Major challenges facing the Thai mud crab aquaculture industry include quality broodstock; inadequate seed supply and high price; suitable farming systems and low survival rate; feed and feeding; and seasonal price fluctuations. However, it is believed that creating and connecting sustainable supply chains, promoting strategic research and development, consistent support from the government, as well as involving more farmers and stakeholders are the key success factors for the sustainable expansion and development of mud crab aquaculture in Thailand.

INTRODUCTION

With a coastal area spanning 2 614 km along the Gulf of Thailand and Andaman Sea, marine crabs are essential fishery and aquaculture commodities with high market demand. Two main groups of marine crabs are highly valued: mud crabs (*Scylla* spp.) and blue swimmer crabs (*Portunus pelagicus*). Four mud crab species are reported, namely *S. paramamosain*, *S. tranquebarica*, *S. olivacea* and *S. serrata*. The natural mud crab populations in Thailand's mangrove ecosystem are largely dominated by *S. olivacea* (Pradissan, 2006; Sodsuk, 2006), followed by *S. paramamosain* and *S. tranquebarica*. However, *S. serrata* is seldom found in Thai waters.

The total production of all crab species, including both wild catch and farm output, in 2021 was 49 043 t valued at THB 9 145 million or USD 256 million (DoF, 2022). Of this, 45 561 t or THB 8 090 million (USD 226.5 million) were from capture fisheries,

TABLE 1
Total crab production and value from capture fisheries and aquaculture in Thailand (2012–2022)

Crab species	Total crab catch (1 000 t)									
	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Blue swimmer crab	33.5	25.7	23.9	22.4	31.2	28.9	26.4	40.0	35.9	36.2
Mud crab spp.	2.9	2.2	1.6	1.5	0.5	0.4	1.6	3.0	3.1	6.4
Other crab spp.	4.2	3.4	2.8	3.0	4.4	6.6	6.0	9.6	8.3	6.4
Total	**40.6**	**31.3**	**28.3**	**26.9**	**36.1**	**35.9**	**43.0**	**52.6**	**47.3**	**49.0**
	Total value (THB million*)									
Blue swimmer crab	4 185	3 562	3 671	3 793	5 453	4 980	5 398	8 034	7 769	6 762
Mud crab spp.	424	323	267	221	107	74	551	949	1 538	1 697
Other crab spp.	183	146	120	226	389	652	827	1 035	1 125	685
Total	**4 792**	**4 030**	**4 059**	**4 241**	**5 949**	**5 707**	**6 777**	**10 019**	**9 893**	**9 145**

* THB 1 = USD 0.028

Source: DoF, 2013–2022. Fishery statistics of Thailand. Bangkok, Department of Fisheries, Ministry of Agriculture and Cooperatives.

while 3 482 t or THB 1 055 million (USD 29.5 million) were from aquaculture (Table 1). Most of the production of blue swimmer crab (*P. pelagicus*) came from wild catch due to the lack of commercial farms (Suppapan *et al*., 2023), except for a few farms in the eastern region of Thailand, such as Samut Sakorn province. They are either consumed in local market or exported as crab meat to other countries. The catch of *P. pelagicus* increased from 33 464 t in 2012 (DoF, 2014) to 36 245 t in 2021 or 1.97 percent of total fish landings in Thailand, valued at THB 6 763 million or USD 189.4 million (DoF, 2022). The catch of mud crabs (*Scylla* spp.) from the wild population in Thailand has slightly decreased from 2 905 t in 2012 (DoF, 2014) to 2 871 t in 2021, accounting for 0.35 percent of the total fish landings and valued at THB 641 million or USD 18.0 million (DoF, 2022).

Mud crab (*Puu Tha Le* or *Puu Dam* in Thai language) has been cultured in Thailand for many decades, using the traditional culture method of collecting small crabs from the wild and keeping them in the ponds for fattening purposes. The first module of mud crab culture was introduced at the Faculty of Science and Technology, Prince of Songkla University (PSU), Thailand, in 1988. In recent years, mud crabs have emerged as a promising aquaculture species in Thailand, driven by high demand, economic viability, and strong potential for aquaculture development, particularly in the numerous abandoned shrimp farms. The Department of Fisheries (DoF) developed a strategy to support mud crab aquaculture, by targeting mud crab production of 5 000 t in 2023. Remarkably, production exceeded expectations in 2021, reaching over 6 000 t or 3 400 t from aquaculture and 2 800 t from wild catch. More than six research centres under the DoF are actively developing farming techniques and producing crablets to meet the demand from crab farmers. The government policy, known as "*Kaset Plaeng Yai*" or large agriculture plot, includes mud crab farming as one of the target species. Moreover, the Department of Marine and Coastal Resources (DMCR) has supported the culture of mud crab in some degraded community mangrove forests, silviculture, to increase productivity and support livelihoods of fisherfolks (Sakapan and Temram, 2011; Sermthong, 2012).

STATUS AND MANAGEMENT OF WILD RESOURCES

Although the wild catch of mud crab has been reported for many years, biological information of the wild stock is scarce in Thailand. Several measures have been introduced to manage mud crab fisheries and aquaculture, especially to meet international obligations regarding their conservation and management. The implementation of the Royal Ordinance on Fisheries BE 2558 (2015) has led to changes in the management practices of Thai laws and regulations regarding fisheries activities. This includes the prohibition of certain destructive fishing gears that are harmful to fish fingerlings and crabs, such as foldable traps or elongated collapsible traps (*Ai Ngo*), set bag nets (*Rua Sai Man*), bamboo traps, push nets and trawlers.

Increasing mud crab populations in their natural habitat by releasing crablets is an important objective of the Department of Fisheries, and this activity is being conducted regularly in many coastal provinces. Additionally, several measures for the conservation of mangrove habitats in the country indirectly contribute to the conservation management of mud crab resources.

MANAGEMENT AND REGULATION OF MUD CRAB AQUACULTURE

All aquaculture practices, including mud crab farming, must be carried out within designated aquaculture zones, as outlined by the Provincial Fisheries Committee under Section 77 of the Royal Ordinance on Fisheries BE 2558 (2015). Farmers are required to meet several conditions, including notifying the relevant authorities about their aquaculture activities, providing details on the origins of the aquatic animals stocked, using approved feeds and chemicals, and adhering to guidelines for managing effluent water and solid waste. They must also implement procedures to prevent water leaks from aquaculture areas and take any further measures necessary to protect the environment, consumer safety, or neighbouring enterprises.

INDUSTRY STATUS

Wild catch landings

The wild catch production of mud crab has fluctuated since 2012, starting at 2 905 t, declining to only 282 t in 2018, and rising again to 2 871 t in 2021 (Table 2). The values ranged from THB 424.1 million (USD 11.9 million) in 2012 to THB 64.2 million (USD 180 million) in 2018 and THB 641.4 million (USD 18.0 million) in 2021. The crabs were caught from both the Gulf of Thailand and Andaman Sea, with some variation in catch between these two areas. Although not directly recorded, it is estimated, based on personal observations from various markets, that more than 90 percent of mud crabs caught were *S. olivacea*, with some contributions from *S. paramamosain* and *S. tranquebarica*.

TABLE 2

Wild catch landings and value of mud crabs in Thailand from 2012–2021

Year	Total		Gulf of Thailand		Andaman Sea	
	Catch (t)	Value (THB 1 000)*	Catch (t)	Value (THB 1 000)	Catch (t)	Value (THB 1 000)
2012	2 905	424 166	2 185	344 123	720	80 043
2013	2 152	322 671	921	178 326	1 231	144 345
2014	1 633	267 099	657	106 670	976	160 429
2015	1 495	221 650	820	135 584	675	86 066
2016	539	107 059	230	44 354	309	62 705
2017	413	74 876	163	29 182	250	45 694
2018	282	64 231	145	32 078	137	32 153
2019	1 332	333 013	949	237 195	383	95 818
2020	484	121 361	203	51 126	281	70 235
2021	2 871	641 412	1 289	353 139	1 582	288 273

*THB 1 = USD 0.028

Source: DoF, 2013–2022. Fishery statistics of Thailand. Bangkok, Department of Fisheries, Ministry of Agriculture and Cooperatives.

Farming areas

For fisheries management purposes, the coastal area of Thailand is divided into five zones, covering all coastal regions of the country. In 2022, a total of 5 266 mud crab farms were registered in Thailand, covering an area of 51 726 rai or 8 276 ha (Table 3). The largest number of registered mud crab farms is 3 546, in coastal zone 4, the middle region of the Gulf of Thailand (Table 4). Nakhon Si Thammarat province, situated in this zone, is the major crab farming province with 3 453 registered farms. The area, once a major shrimp producing area, has since been converted to mud crab farms. Coastal zone 2 is the second largest mud crab farming area, with a total of 946 registered farms. The provinces of Samut Songkhram and Samut Prakarn are the second- and third-largest provinces for mud crab farming in Thailand. However, the second-largest production and value of mud crabs were from Ranong province, situated on the Andaman coast.

TABLE 3
Production of farmed mud crabs in Thailand from 2018–2022

Mud crab	Year				
	2018	2019	2020	2021	2022
No. of farms	2 879	3 211	4 854	5 551	5 266
Farming areas (rai)	21 119	26 185	44 738	51 326	51 726
Production (t)	1 321	1 712	2 555	3 479	2 882
Production value (THB million)*	487	616	876	1 054	956
Average price (THB/kg)	369	359	342	303	336

*THB 1 = USD 0.028

Source: DoF, 2019–2023. Fishery statistics of Thailand. Bangkok, Department of Fisheries, Ministry of Agriculture and Cooperatives.

TABLE 4
Production area of mud crab farming in Thailand in 2022

Area/province	No. of farm	Area (rai*)	Production (t)	Value (THB 1 000)
Coastal Zone 1	**107**	**826.9**	**67.9**	**23 661**
Trat	21	220.2	19.4	7 312
Chantaburi	83	597.2	46.9	15 789
Rayong	2	9.5	1.6	560
Coastal Zone 2	**946**	**30 832**	**347.9**	**124 341**
Chachoengsao	12	259.5	6.1	2 550
Samut Prakarn	246	5 603.2	112.9	41 758
Bangkok	24	584.9	5.2	1 935
Samut Sakhon	251	6 553.7	88.5	22 181
Samut Songkhram	284	13 445.5	127.4	53 520
Phetchaburi	129	4 389.2	7.8	2 396
Coastal Zone 3	**449**	**3 435.6**	**162.7**	**60 225**
Prachuap Khiri Khan	213	2 062.2	51.6	20 020
Chumphon	25	175.2	13.1	5 202
Surat Thani	211	1 198.1	98.0	35 002
Coastal Zone 4	**3 546**	**16 091.7**	**1 395**	**493 788**
Nakhon Si Thammarat	3 453	15 663.8	1 357.8	478 949
Songkhla	85	366.2	31.1	12 515
Pattani	8	61.7	6.4	2 324

TABLE 4 (CONTINUED)

Area/province	No. of farm	Area (rai*)	Production (t)	Value (THB 1 000)
Coastal Zone 5	**218**	**539.9**	**908.1**	**253 714**
Ranong	67	222.0	811.4	226 367
Phangnga	12	12.4	14.7	4 070
Krabi	25	53.5	10.1	2 672
Trang	29	81.7	10.5	2 938
Satun	85	170.2	61.5	17 666
Total	**5 266**	**51 726**	**2 882**	**955 731**

*1 rai = 0.16 ha

Source: DoF. 2023. *Statistics of sea crabs culture survey 2022*. Report No. 11/2023. Bangkok, Fisheries Development and Planning Division, Department of Fisheries, Ministry of Agriculture and Cooperatives.

Currently, only two private hatcheries, located in the provinces of Nakhon Si Thammarat and Satun, are in operation. One additional hatchery in Krabi province intermittently switches between shrimp and crab farming. Most farmers currently rely on government hatchery and farms for their seed supply. There are at least five government hatcheries producing crablets to serve crab farmers. It is expected that more shrimp hatcheries and farms will be converted to meet the growing demand for crablets.

AQUACULTURE PRACTICES AND METHODS

Broodstock management

The scarcity of berried female crabs for hatchery operations has long posed a significant challenge to the growth of Thailand's mud crab industry (Nooseng, 2015). Despite various efforts to produce broodstock, the spawning success rate remains critically low. To supplement domestic production, importing broodstock – particularly *S. paramamosain* – from neighbouring countries has emerged as an alternative for seed production. However, this comes at a considerable cost, ranging from THB 5 000 to 8 000 (USD 140–224) per broodstock. Factors contributing to the low broodstock success include failed fertilization, nutritional deficiencies, microbial infections, heavy fouling organism infestations, and environmental stressors.

Recently, the Faculty of Science and Technology at PSU successfully developed an innovative system and technique for producing gravid female crabs in recirculated systems without the need for eyestalk ablation (Figure 1). This advancement has significantly improved the consistency of high-quality broodstock supply within the country. As a result, the University now serves as a key broodstock provider to numerous government and private hatcheries. The system, developed by Hajisamae *et al.* (2022), has achieved an egg extrusion success rate of 70–80 percent within 30 days of housing. This new method is being transferred to selected government and private hatcheries and is expected to alleviate a major bottleneck in the mud crab aquaculture supply chain. With more accessible broodstock, hatcheries will be better equipped to refine nursing techniques and boost seed production for mud crab farming.

Most broodstock used in Thailand are sourced from either the wild or from farms, with wild-caught broodstock generally preferred for their higher-yield seed production. Healthy female crabs weighing 300–400 g bearing eggs at maturation stage 3 or 4 are selected and transported to the broodstock development units. These crabs are housed in various types of tanks or incubation buckets and maintained at the desired environmental conditions. Their diet primarily consists of bivalves, such as blood cockles, green mussels, or mangrove clams, as well as polychaetes.

FIGURE 1
Mud crab broodstock spawning system (a) and a berried female with intact eyestalks (b) at Prince of Songkla University, Thailand

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Broodstock that show no signs of spawning after 45 days are removed from the system. Berried females are transferred to separate tanks or buckets for egg incubation, which lasts around 9–12 days, depending on the size of the crab and ambient conditions. Water is exchanged daily at a rate of 50–70 percent, and the fertilization and development of the eggs attached to the pleopods are closely monitored under a microscope. Live food for the zoea stage is prepared in advance, timed with the anticipated hatching date, determined by observing the stages of egg development. Hatching generally occurs after midnight and continues into the early morning. Once hatching is complete, all the zoea are collected the following morning for further cultivation.

Larval rearing and nursing

In Thailand, the production of *S. paramamosain* crablets is primarily conducted by government hatcheries under the Department of Fisheries, Ministry of Agriculture and Cooperatives (e.g. the Thung Talae Forest Royal Development Study and Crab Conservation Centre in Krabi province) and by several Coastal Aquaculture Research and Development Centres located in Pattani, Songkhla, Krabi, Trang and Surat Thani provinces. Currently, only two private hatcheries, adapted from shrimp hatcheries, consistently produce crablets. Most of the mud crab nursing process occurs within these hatcheries, raising crabs from zoea 1 (Z1) to crablet 2 or 3 (C2–C3) stages before transferring them to grow-out farms. Among the government hatcheries, the Thung Talae Forest Royal Development Study and Crab Conservation Center in Krabi province, along with Wasina Farm, a private hatchery in Satun province, and the nursery centre at PSU (Figure 2), have pioneered the use of outdoor nursery ponds for rearing megalopa or crablet C1 to C2. This practice, commonly used in Viet Nam, is expected to gain broader adoption in Thailand in the near future.

More entrepreneurs are expressing their interest in mud crab hatchery business due to increasing demand for crablets in the country and the availability of farmed broodstocks. The survival rate of mud crab larvae from Z1 to C2 is about 1–15 percent.

In Thailand, two methods of larval rearing are employed for mud crabs: the two-phase method and the three-phase method.

- In the *two-phase method*, larvae are reared in a single tank until they reach the Z5 stage, after which they are transferred to another tank and nursed until they develop into crablets, ready for transfer to grow-out farms.

FIGURE 2

The mud crab hatchery operated by the Faculty of Science and Technology, Prince of Songkla University, Thailand

(a) The entrance of the hatchery at PSU; (b) mud crab larvae culture tanks; and (c) mud crab larvae culture tanks

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- The *three-phase method* begins by rearing larvae in an initial culture tank until Z3. If high larval density is observed, the larvae are moved to a second tank and nursed until they reach Z5. At the Z5 stage, they are transferred to a third tank, where they are grown until they reach the crablet stage.

Zoea stage 1 (Z1) larvae are typically reared in concrete tanks with capacities of 5–10 m^3 at a density of 50 000–100 000 zoea/m^3 (Nooseng, 2015). During the first zoea stage (zoea 1), rotifers (*Brachionus* sp.) at a density of 10–15 ind./ml remain the preferred feed. However, some research stations have replaced rotifers with *Artemia* umbrella (8-hour hatched *Artemia*) to feed zoea 1 through zoea 3. For zoea 4, *Artemia* instar or nauplii are provided at a density of 3–5 ind./ml. At this stage, formulated feeds and vitamins are also introduced.

Water management includes a 30–50 percent water change on days 3–4 of nursing, followed by alternating 20–30 percent water changes every other day. During the megalopa stage, the crabs are fed with adult or frozen *Artemia* alongside formulated feeds. Nets are introduced into the tanks to provide shelter and to reduce cannibalism among the megalopa. Calcium and magnesium are added to maintain alkalinity levels between 110–150 ppm.

Crablets are typically sold or distributed to crab farmers when they reach crablet stage C2–C3, with a carapace width of 0.5–0.9 cm, at THB 3.00–5.00 per crablet.

In addition to crablet production, some farms are involved in nursing crablets to juvenile crabs, typically reaching a size of 6–7 cm in carapace width. These juvenile crabs are reared in earthen ponds for a period of 30–45 days before being sold to nearby grow-out farms. This intermediate nursing stage has gained increasing attention from both nursery operators and grow-out farms, as it helps to accelerate the overall crab farming process. By supplying more developed juveniles, farms can reduce the time needed to reach market size, improving efficiency and profitability in mud crab production.

Hard-shell crab farming

Two commonly practised methods for mud crab grow-out farming in Thailand are monoculture and polyculture, or multitrophic culture systems. Monoculture involves farming only mud crab in ponds, typically earthen ponds modified from abandoned shrimp farms. Sizes of the pond are about 2–10 rai (0.32–1 ha) with a depth of around 1 m and salinity of 10–30 ppt (Figure 3). The two predominantly farmed species are *S. olivacea* and *S. paramamosain*, with *S. olivacea* being the major farmed species if the juveniles are sourced from the wild. Nevertheless, some farmers may stock very low proportion of *S. tranquebarica* and *S. paramamosain* together with *S. olivacea* in the same pond as they often release all species into the pond based on the availability of small-sized mud crabs or juveniles. Many farmers have begun stocking hatchery-produced *S. paramamosain* crablets, typically ranging in size from 0.5–1 cm (C2 to C3 stages), at a density of 0.5–2 crablets/m² in ponds. When stocking larger juveniles, farmers often purchase wild-caught crabs from fishers, usually around 50–100 g/crab. However, due to the decreasing availability of wild juveniles, an increasing number of

FIGURE 3
Grow-out mud crab farms in (a) Nong Cik, Pattani; (b) Prince of Songkla University, Pattani; and (c) Kuiburi, Prachap Khiri Khan

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farmers now prefer using hatchery-reared *S. paramamosain* juveniles, which offer a more consistent and reliable supply for stocking.

Juvenile crabs are typically fed trash fish or mussels for 2–3 months when stocked as juveniles, and for 4–5 months when stocked as crablets, to reach marketable sizes of 3–5 crabs/kg.

Two harvesting methods are commonly practiced: partial or selective harvesting and total harvesting (Nooseng, 2015).

- *Partial or selective harvesting* involves using collapsible traps or common crab traps to regularly capture crabs that have reached marketable size, depending on availability and market demand. In some cases, farmers may restock crablets or juvenile crabs for the next cycle while still completing the harvest of the current crop.
- *Total harvesting* is conducted by draining the pond and using rakes, hooks and scoop nets to collect crabs that have burrowed into the mud.

An alternative mud crab farming method, aquasilviculture, is promoted by the Department of Marine and Coastal Resources under the policy of "people living together with the forest." This approach integrates mud crab culture within protected mangrove forests, as seen in Pattani and Krabi provinces. While the primary focus is on mangrove conservation through community engagement, mud crab farming is practiced on a smaller scale. Typically, about 1–3 rai (0.16–0.48 ha) of mangrove area is allocated to 10–15 village members. Around 300–500 crabs, each weighing 50–100 g, are farmed in these designated areas and fed with trash fish for 2–4 months before being harvested.

In polyculture or multitrophic culture systems, farmers stock prawns (e.g. Pacific white or tiger shrimp) or seaweeds (especially *Gracilaria*) in their mud crab ponds. The density of the shrimp varies between 10 000–20 000 shrimp post-larvae/rai (62 500–125 000 post-larvae/ha). Crabs and shrimps are normally fed with trash fish or mussel as in monoculture systems, but sometimes additional shrimp pellets are provided. Shrimps can be harvested after 2 months of culture, depending on size and market demand. Seaweeds can be harvested anytime once they have grown enough to be sold. Additionally, some farmers in Chachengsao province stock mud crabs in paddy farms during the summer season while shift to rice farming in the rainy season.

Fattening farm

During harvesting, post-moult crabs and female crabs exhibiting early ovarian development stages (Stages 1 and 2) that are not ready for market are sorted and either restocked in the same pond or transferred to a separate fattening pond. Some farms specialize exclusively in fattening crabs, as this approach can yield prices that are two to three times higher than those of market-ready crabs. Currently, several fattening methods are employed, including earthen pond systems, concrete ponds, and condo-based or vertical fattening systems (Figure 4).

The earthen pond system for fattening crabs operates similarly to conventional earthen pond culture, with the key difference being the stocking of underweight males or females with early ovarian development stages (Stages 1 and 2). The crabs are typically fattened for 1–2 months until they reach the market weight for males or full ovarian development for females (Stages 3 and 4). Additionally, some farmers utilize floating plastic baskets within the pond to individually fatten crabs. The condo-based or vertical fattening system, which employs recirculating water, is a newer practice that has garnered significant interest from farmers. In this system, crabs are cultured in separate units and are generally fed once a day with low-cost fresh fish or mussels. The survival rate of crabs in this system ranges from 60–80 percent, with a production weight gain of approximately 20–30 percent. Some farmers prefer using concrete ponds for fattening, particularly for crabs that require a very short culture period and are nearly ready for sale.

FIGURE 4
Different types of mud crab fattening systems practiced in Thailand
(a) Indoor fattening system; (b) Indoor raceway fattening system; (c) Concrete pond fattening system; and (d) Outdoor fattening system

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Soft-shell crab production

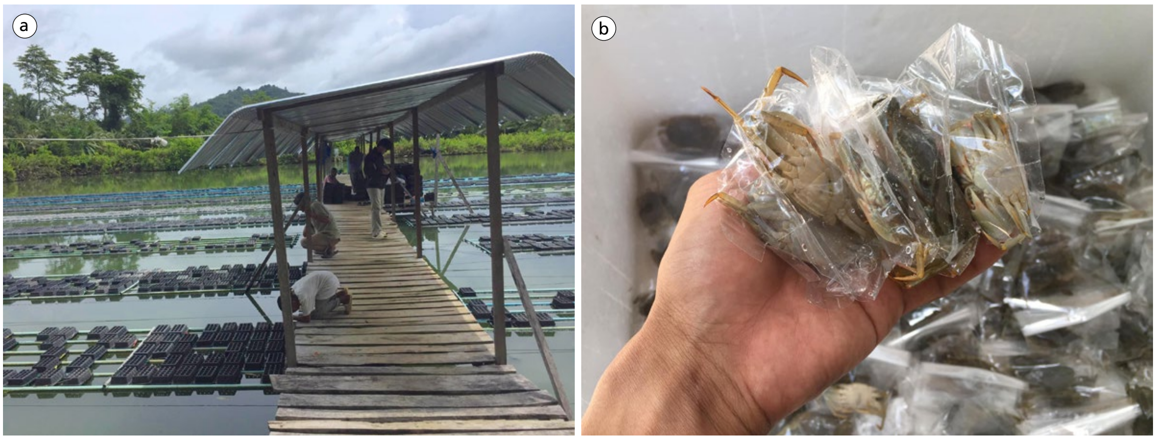
Soft-shell crab production has been a profitable business for many years, especially in the provinces of Ranong, Satul and Chumporn. Farmers typically rely on wild-caught crabs, usually consisting of 10–20 crabs/kg, as their raw material. The crabs, sometimes declawed, are stocked individually in plastic boxes placed on PVC pipe rafts until they moult and can be harvested (Figure 5). Newly moulted crabs are collected, placed under a 3–4 hour monitoring program, then placed in freshwater for 30 minutes to reduce the salt content, and then packed, frozen and sold. The main challenges for soft-shell crab production include a shortage of small crabs as raw material, labour cost (as it is a very labour-intensive business), and maintenance of the water quality in the ponds. Efforts are currently underway to address these challenges and improve soft-shell crab production. These efforts include exploring the use of farmed crabs instead of wild-caught crabs, adopting digital technology to monitor crab metamorphosis, and experimenting with vertical farming systems.

HEALTH AND DISEASE MANAGEMENT

Several diseases have been identified in mud crab farming, including incomplete moulting, bacterial shell disease, shell discoloration, limb loss, and parasitic infections.

1. *Incomplete moulting*, a condition that leads to high mortality rates, is most common in fattening farms, particularly those using the condo-based or vertical system. This problem is believed to stem from poor water quality, low temperatures and nutritional deficiencies.

FIGURE 5
View of a typical soft-shell-mud crab farm and market-ready product
(a) An example of soft-shell mud crab culture in earthen pond; and (b) Soft-shell crab products



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2. *Bacterial shell disease* is marked by significant shell damage, including necrosis, erosion and perforation. This not only diminishes the crab's market value but also heightens the risk of secondary infections, which can lead to death.
3. *Shell discoloration* presents as yellowish-brown to reddish-brown deposits on the shell. Although it may not damage the shell's structure, it can negatively impact other organs, such as the gills and eyes.
4. *Gill discoloration* is characterized by grey, brown or black discoloration of the gill arches, often caused by poor pond preparation resulting in a high organic load. This can clog the gills, causing respiratory stress and leading to death.
5. *Limb loss* involves the loss of major appendages, which can severely affect the crab's ability to feed, mate and defend itself.
6. *Parasitic infection* by stalked barnacles (*Octolasmis* spp.), particularly on the gills, may cause mortality. Barnacles may also be found around the carapace, near the inhalant aperture, at the base of the cheliped, and on the second and third maxillipeds. When present in large numbers, they compete for oxygen, especially if they cover most of the crab's respiratory surfaces (Lavilla-Pitogo and de la Peña, 2004).

RESEARCH AND INNOVATION

1. *Broodstock development*: The successful and consistent production of berried female crabs has played a crucial role in advancing the mud crab aquaculture supply chain in Thailand. This successful method has been transferred to both government hatcheries and private entrepreneurs. Furthermore, ongoing efforts are directed towards the development of improved strains of broodstock and the exploration of various factors influencing broodstock development.
2. *Hatchery and nursing systems*: With the growing availability of berried female broodstock, hatcheries can further optimize their expertise in crab nursery culture. Key factors for enhancing crablet survival rates include improving larval health, providing optimal environmental conditions, and ensuring the use of high-quality, nutritionally balanced feeds. A significant improvement in feeding strategies is the replacement of rotifers with *Artemia* umbrella or *Artemia* instar, which has shown promise in promoting better growth and survival during the early stages of development.
3. *Grow-out farm*: Grow-out farms aim to maximize profits and optimize pond usage for farmers, often incorporating polyculture with other aquatic species or

integrating crab farming into rice fields. Key strategies to improve crab survival rates include minimizing cannibalism, preventing pond escapes, controlling predation, maintaining water quality and pond substrate, and optimizing feeding practices. Farmers have also experimented with integrated multitrophic aquaculture (IMTA), combining crabs with seaweeds, fish or prawns in polyculture systems. Stocking crab seeds at sizes of 2.5–4.0 cm in earthen ponds has shown potential to increase survival rates and reduce the overall growing period.

4. *Fattening farm*: There is increasing interest in using recirculating aquaculture systems (RAS) for fattening mud crabs in condo-based vertical farming units. Researchers and farmers are exploring the adoption of automated devices to streamline management and production processes. Furthermore, efforts are underway to integrate innovative marketing strategies aimed at expanding customer awareness and enhancing the appeal of mud crab aquaculture.
5. *Soft-shell crab farm*: Overcoming the challenges in soft-shell crab production, such as the shortage of small-sized crabs and the need for skilled labour, requires the establishment of a local supply chain to provide farmed crabs for soft-shell crab farming. Additionally, the development of relevant technology to reduce the labour required during operations is considered crucial for this type of mud crab aquaculture.

MARKET INFORMATION

Major markets for hard- and soft-shell mud crabs

Although some exports have been reported, Thailand is predominantly considered a mud crab-importing country due to high domestic demand and insufficient local supply (Kaewsai, 2004). Crabs from Myanmar, Sri Lanka and Bangladesh are imported to meet this demand. The Thai mud crab industry experiences fluctuations, particularly during the period between Christmas and Chinese Lunar New Year, driven by increased demand from China. This surge in international demand can influence the domestic market, occasionally leading to exports. Despite strong global demand for mud crabs, local production remains insufficient. Additionally, there are instances of crab imports followed by re-exports to other countries. In the case of soft-shell crabs, nearly all production is consumed domestically. Average prices of crab products, from the megalopa stage to adult crabs, based on data from various markets across the country, are presented in Table 5 (DoF, 2022) and Table 6 (based on authors' estimates).

TABLE 5
Thai Department of Fisheries standard price of mud crab megalopae and crablets

Mud crab life stage and size	Price (THB/ind.) *
Megalopae	1.0
Crablet C1	1.5
Crablet C2 (0.5–0.9 cm)	3.0
Crablet (1.0–1.5 cm)	5.0
Juvenile crab (6.0–7.0 cm)	18.0–20.0

* Average market price.

THB 1 = USD 0.028

Source: DoF. 2022. Fishery statistics of Thailand 2020. Report No. 4/2022. Bangkok, Department of Fisheries, Ministry of Agriculture and Cooperatives.

TABLE 6
Average price of mud crab in Thailand in 2023

Characteristics of crab	Price (THB/kg*)	
	Low demand season	High demand season
Buffet crab (mixed crab)	140–170	160–180
Water crab or post-moult male crab (< 4 crab/kg)	160–180	180–200
Firm meat male crab (2 crab/kg)	330–400	370–420
Firm meat male crab (3 crab/kg)	280–350	300–370
Firm meat male crab (4–5 crab/kg)	200–250	230–290
Firm meat male crab (6–7 crab/kg)	150–170	170–200
Stages 1 and 2 ovarian development (3–7 crab/kg)	200–250	200–250
Full ovarian maturity (6–8 crab/kg)	350–450	400–530
Full ovarian maturity (4–5 crab/kg)	480–600	550–650
Full ovarian maturity (2–3 crab/kg)	600–700	650–800
Soft-shell crab (8–10 crab/kg)	220–240	230–270

* THB 1 = USD 0.028

MAJOR ISSUES AND CHALLENGES OF THE INDUSTRY

The mud crab aquaculture industry faces several challenges, including limited access to quality broodstock, insufficient seed supply, low survival rates during both grow-out and fattening due to cannibalism and disease outbreaks, a lack of commercially formulated feed, and seasonal price fluctuations. To address these issues, further applied research is required to produce high-quality broodstock, and ensuring the consistent production of healthy crablets. Likewise research should focus on broodstock domestication through selective breeding or a genetic improvement programme.

The high cost of crablets increases grow-out farm production expenses, reducing profitability. Expanding the number of private hatcheries is essential to enhance competition, improve crablet quality, and lower prices, which could encourage more farmers to invest in mud crab farming.

Furthermore, low survival rates during the grow-out phase diminish returns on investment, posing a major constraint for farmers. Many potential mud crab farmers are former shrimp farmers accustomed to higher returns, making it difficult to shift to mud crab farming without improved profitability. Integrating multitrophic systems or polyculture offers an opportunity to increase income by diversifying production. Establishing nursing farms to raise crab seeds from C2 to C5–C6 (3.0–7.0 cm) for stocking in earthen ponds is also necessary to strengthen the supply chain.

The absence of commercial feeds specifically formulated for mud crabs and the fluctuating availability and cost of fresh feed contribute to operational uncertainty.

Seasonal price fluctuations also create uncertainty for new farmers considering entry into the market. As Thailand remains a net importer of mud crabs, local production has yet to meet domestic demand. Establishing a stable supply chain remains the most critical challenge for Thailand's mud crab aquaculture industry.

CONCLUSION

The future sustainable expansion and success of the mud crab aquaculture industry hinges on several key factors, including the creation and connection of a sustainable supply chain, strategic research and development, robust government policy support, and the active participation of farmers and entrepreneurs. Breaking through the bottlenecks in sustainable broodstock production, successful seed production, and the establishment of private hatcheries will play a pivotal role in bridging the domestic supply chain. As more crablets become available, there is greater potential for the development of improved farming techniques, leading to higher profits from marketing hard-shell and soft-shell crabs, and potential additional income from polyculture. The contribution of strategic research and development programmes is believed to be crucial in addressing gaps in knowledge within the mud crab supply chain.

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Status of mud crab aquaculture in Singapore

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ABSTRACT

Singapore is neither an agriculture nor aquaculture country. Being a small country of about 735 km^2 in size, the country has less than 1 percent arable land for agriculture. At least 90 percent of its food, consumed by close to 6 million people, is imported from more than 115 countries. Mud crab is one of the seafood items regularly imported as it is part of the local iconic "Singapore Chilli Crab" dish. The local demand for the crab far outweighs the supply that it could get from overseas imports. About 10 t of crabs, particularly *Scylla serrata* of between 650 g and 1.5 kg/crab, are consumed daily.

The mud crab aquaculture industry is very nascent with no local commercial hatcheries or mud crab farms. Due to the decline in mud crab imports into Singapore over the years, there have been a few mud crab fattening or soft-shell crab farms set up since 2009, but none have been successful in meeting the strong local demand for the crustacean so far. However, there has been ongoing mud crab R&D activity since 2020 at a research facility set up by the Aquaculture Innovation Centre (AIC) (Figure 1). The AIC was established as a national centre in July 2019 by Enterprise Singapore under the Ministry of Trade and Industry to serve the farming needs of the local aquaculture industry. Research into mud crab spawning, hatchery and nursery as well as customized diet development for different stages of growth and health management of the species has been the focus at the AIC research farm since late 2020. The processes and technology development for mud crab aquaculture would be licensed to commercial companies interested in mud crab production be it hard-shell or soft-shell crab farming or fattening either locally or overseas. That could be a way of cultivating some self-sustenance to cope with the declining imports of mud crabs for local consumption.

FIGURE 1
Mud crab research and culture facilities at the Aquaculture Innovation Center
Experimental (a) and concrete culture (b) tanks

©Apollo Aquaculture Group/AIC

INTRODUCTION

Green mud crab (*Scylla paramamosain*), orange mud crab (*Scylla olivacea*) and purple mud crab (*Scylla tranquebarica*) are found locally, while the giant mud crab (*S. serrata*) – popularly consumed locally – is imported mainly from Sri Lanka and other overseas countries.

There is a huge demand for mud crabs particularly *S. serrata* due to its large size compared to the other species. There are no local commercial mud crab hatcheries or producing farms but at least 3–6 t of mud crabs are imported daily.

Mud crab imports

Volza's Singapore Import data indicates an average of 3 300 t of mud crab, both live and chilled, are imported by Singapore annually – or approximately 10 tonnes daily. Singapore is the second-largest importer of mud crabs in the world after China. About 18 150 shipments of imported crabs arrive each year, coming from India, Viet Nam and Sri Lanka. Based on Volza's Singapore Live Mud Crab Buyers & Importers directory, there are 188 active live mud crab importers in Singapore, importing from 122 suppliers in 77 countries (https://www.volza.com/global-trade-data/singapore-import-trade-data). On average, imports of crabs into Singapore are projected to decrease by 3.7 percent year-on-year over the same period, reaching 455 850 kg in 2026. This is a 9.7 percent decrease since 1994. In 2021, Singapore was twenty-second in the world rankings for imports, with 567 140 kg annually. Sweden topped the rankings, followed by the Republic of Korea, China and Japan.

INDUSTRY STATUS

Production status

Singapore is not an aquaculture country, but it has about 110 coastal farms with less than 20 land-based farms. As the emphasis on food security is to encourage local farmers to ramp up production of vegetables, fish and eggs to meet 30 percent of the total nutritional needs by 2030 (to reduce reliance on foreign food imports), food fish farming is viewed favourably and preferred over other species such as shrimps and crabs.

Between 2009 and 2016, there were a handful of local mud crab fattening farms using trash seafood as feed for the mud crabs. However, quite a few either ceased operation due to high production cost or relocated their operations outside Singapore. In 2021, a local start-up company started its mud crab hatchery business in Indonesia due to cheaper land and labour cost and has been successful in producing crablets for sale. Another local company is partnering with AIC to set up mud crab farming in selected mangrove site in Brunei Darussalam in 2025 with the objective of exporting mud crabs to Singapore in the future. In 2023, a local mud crab importer set up a mud crab recirculating aquaculture system for fattening "water crabs" found in the batches of imported crabs.

RESEARCH AND INNOVATION

Presently, AIC is the only centre that has been doing in-depth mud crab research (Figure 2 and Figure 3) targeting nutrition, feed and feeding, disease management, hatchery and larviculture, as well as development of smart integrated culture systems for mud crab production. Prophylactic treatment of the mud crabs using environmentally friendly sodium percarbonate and veterinary chemical has shown far better reduction in bacteria count over conventional formalin- or antibiotic-treated crabs. Spawning condition has been developed through a customized diet using pellet feeds and has been successful without the need for eye stalk ablation – a practice commonly used for induction of spawning in mud crab hatcheries. The Centre will

FIGURE 2
Feed preparation and feeding trial facilities

FIGURE 3
Mud crab pathogen screening for parasites and bacteria

continue to develop technologies for improving the health and growth performance of crablets and adult crab spawning ability, so that these could be licensed to commercial companies or farms for production. Hopefully, there will be more farmers willing to grow and produce mud crabs for commercialization or to work with agencies in mud crab conservation.

AIC's mud crab hatchery and crablet technology other than the capabilities built up in feed and feeding, health and disease management and integrated culture system, were supported by Enterprise Singapore under the Technology Adoption Programme from 2020 to 2022. An Invention Disclosure Form has been filed for the mud crab hatchery and crablet technologies. Currently, AIC is working with a local S&M enterprise to bring mud crab farming to Brunei Darussalam with the objective of exporting adult mud crabs or soft-shell crabs back to Singapore, thus providing some resilience in mud crab supply for local consumption.

MAJOR ISSUES AND CHALLENGES FACING THE INDUSTRY

Due to land and skilled manpower constraints, as well as high utility cost in Singapore, other than ensuring environmental sustainability and food safety, the challenges faced by the nascent aquaculture industry may be insurmountable. Innovation and technology development based on the "grow-more-with-less" concept, together with financial assistance and support, would be important to drive the aquaculture industry forward (https://www.sfa.gov.sg/singaporefoodstory/grow-local). Vertical farming systems with technologies that support energy efficiency as well as waste and wastewater management for intensive crab production (be it for soft-shell crab or crab fattening) may be able to pave the way for the development of the mud crab farming industry in Singapore.

CONCLUSION

It is challenging for Singapore to be a mud crab producing country as such propagation would require extensive land, skilled manpower and resources. However, Singapore through AIC can be the R&D hub for mud crab innovation and technology development. The technologies once developed could be licensed to companies interested in mud crab farming overseas or those willing to commercialize technologies or products such as diagnostic kits or vaccines developed from the mud crab R&D.

Singapore could also continue to develop technologies in mud crab hatchery with the objective of providing a sustainable supply of crablets to local farms, and extension services could be provided to them through AIC. Likewise, the establishment of a national quality mud crab broodstock and seedstock is key for the development of local mud crab industry, to enhance self-reliance on local production and reduce foreign imported mud crabs for local consumption needs.

Status of mud crab industry in Malaysia

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ABSTRACT
Malaysia's coastal waters host a diverse array of Portunidae crab species, including *Portunus pelagicus*, *Charybdis feriatus*, *Charybdis miles*, *Charybdis natator*, *Podophthalmus vigil* and *Scylla* spp. Notably, all species of mud crabs from the genus *Scylla*, except for *S. serrata*, can be found in Malaysian waters. Fish landings (captured fisheries) in Malaysia from 1990 to 2022 ranged from 0.9 to 1.3 million t, generating estimated revenues of MYR 2.6–15.3 billion (USD 0.58–3.4 billion). Over the same period, crab landings (inclusive of all harvested crab species) increased from 7 793 t in 1990 to 13 890 t in 2015 and decreased slightly to 9 475 t in 2022. All crab landing data from 1990 to 2000 are grouped together without distinguishing between species. Starting from the year 2005 to 2022, mud crab data became available, although initially categorized under "stone crab" and later as both "stone crab" and "mud crab" starting from the year 2020. Mud crab landings increased from 1 836 t in 2005 to 3 470 t in 2010, decreased slightly to 1 868 t in 2020, and increased exponentially to 8 507 t in 2022. Mud crab aquaculture production rose from 190 t in 1990 to 335 t in 2022, with revenue peaking at MYR 16 million in 2022. Despite the promising growth, mud crab aquaculture contributes only 0.07 percent of the total national mariculture production in 2022. Major challenges include the decline of wild stocks, limited aquaculture investment, and competition from imported crabs. Conservation efforts are hampered by the lack of specific policies for mud crabs, although mangrove forest protection indirectly benefits mud crabs. Restocking programmes led by local universities and governmental bodies face limitations. Enhanced research, policy development, and targeted management strategies are required to sustain Malaysia's mud crab resources and addressing the challenges effectively.

INTRODUCTION

Crab species
A variety of commercially important crab species from the family Portunidae, including *Portunus pelagicus* (Blue swimming crab), *Charybdis feriatus* (Crucifix crab), *Charybdis miles* (Soldier swimming crab), *Charybdis natator* (Ridged swimming crab), *Podophthalmus vigil* (Sentinel crab) and *Scylla* spp. inhabit the coastal waters of Malaysia. Among these, mud crabs of the genus *Scylla* hold the highest commercial value, with market prices reaching up to USD 50/kg, and are in high demand both domestically and internationally. The decline in wild catches due to overfishing and habitat destruction further heightened their importance in aquaculture. Mud crabs are found across the Western Indo-Pacific region and are classified into four species: *S. serrata, S. olivacea*, *S. tranquebarica* and *S. paramamosain*, as detailed by Keenan, Davie and Mann (1998) and Fazhan *et al.* (2021). The morphological differences among these species are important for identification purposes by farmers and fishers. All

four species of *Scylla* are highly prized for their meat, making them important resources in both fisheries and aquaculture. Over the past decade, global capture production has exceeded 20 000 t while aquaculture production has surpassed 100 000 t (FAO, 2018).

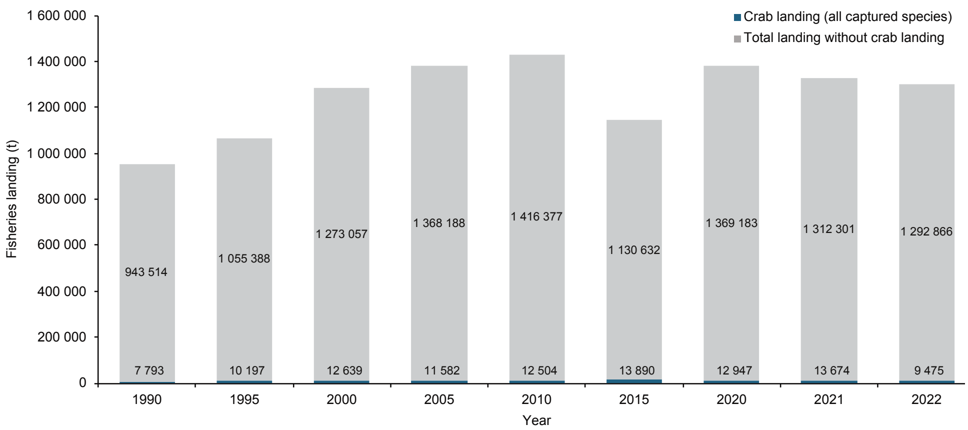
Each *Scylla* species varies significantly in size and morphology. In general, *S. serrata* is the largest, followed by *S. tranquebarica* and *S. paramamosain*, with *S. olivacea* being the smallest (Ogawa *et al*., 2012; Waiho, Fazhan and Ikhwanuddin, 2016; Fazhan *et al*., 2017b). Despite its smaller size, *S. olivacea* is known for its endurance due to its adaptability to low-salinity habitats and exposure to intertidal tides. Three of the *Scylla* species, namely *S. olivacea*, *S. tranquebarica* and *S. paramamosain* are prevalent along the coastal zones of Malaysia (Waiho, Fazhan and Ikhwanuddin, 2016). While a report by Kosuge (2001) suggested the presence of *S. serrata* in the Matang Mangrove Forest Reserve, subsequent studies by Fazhan, Waiho and Ikhwanuddin (2017a) found only two escaped specimens, indicating no viable population of this species exist in Malaysia.

Natural hybrids among *Scylla* species have been reported by Imai and Takeda (2005) in their natural habitats in Japan. Recently, Fazhan *et al*. (2021), identified four types of possible hybrids from the Sulu Sea, Malaysia, which displayed distinct morphological and morphometric variations compared to the pure species. Although hybridization trials in captivity have been successful, demonstrating that crossbreeding among all species of mud crabs is feasible (Fazhan *et al*., 2017c), the presumed hybrids found in the wild exhibited negative heterosis, being smaller than the pure species (Fazhan *et al*., 2020b). The three *Scylla* species found in Malaysia coexist in sympatry. In the Strait of Malacca and the South China Sea of Peninsular Malaysia *S. olivacea* is the predominant species, while *S. paramamosain* is more common in the Sulu Sea in East Malaysia. Seasonal shifts in species abundance have been observed, with *S. tranquebarica* being more abundant from October to February, while *S. paramamosain* from May to October (Fazhan *et al*., 2017b).

Wild stock status

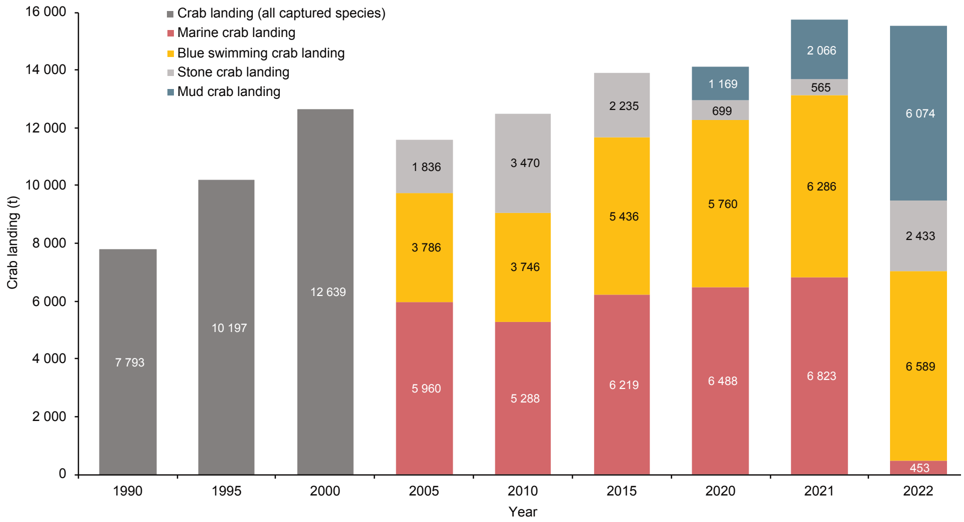
Crabs, alongside fish and other marine products, hold significant importance in Malaysian fisheries. The mud crab aquaculture sector in Malaysia primarily depends on wild stock resources. Based on the available yearly capture statistics recorded by the Department of Fisheries Malaysia, total crab landings from captured fisheries from 7 793 t in 1990 to 13 890 t in 2015 and slightly decreased to 9 475 t in 2022 (Figure 1). However, it is important to note that most data before 2020, including data on landing volume, did not specifically distinguish mud crabs at the genus level. Mud crabs were

FIGURE 1
Malaysia total fisheries and total crab landings from 1990 to 2022 (t)



Source: Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022).

FIGURE 2
Malaysia crab landing according to species from 1990 to 2022 (t)



Note: All crabs were designated only as "crab" in 1990 to 2000. Both "stone crab" and "mud crab" were used to represent *Scylla* spp. since 2005 and 2020, respectively, as data were collected based on states and different local names of mud crabs exists for *Scylla* spp.

Source: Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022).

categorized, together with other captured crab species as "crab" from 1990 to 2000, as "stone crab" ("ketam batu") from 2005 to 2015, and as both "stone crab" and "mud crab" ("ketam nipah") from 2020 to 2022. According to Figure 2, the first recorded mud crab landing in 2005 was 1 836 t. By 2010, the landing increased to 3 470 t before decreasing to 2 235 t in 2015. A further decline was recorded in 2020, with landings dropping to 1 868 t, when both "stone crab" and "mud crab" categories referred to the mud crab genus *Scylla*. However, in 2022, the demand for mud crabs in Malaysia rebounded, leading to an increase in mud crab landings to 8 507 t. While this indicates a positive trend for mud crab fisheries in recent years, there is currently no reliable data to comprehensively assess the status of wild mud crab stocks in Malaysia. Therefore, there is a need for in-depth studies and targeted management strategies to ensure the sustainability of wild mud crab populations in Malaysian waters.

Conservation and management of wild resources

Mud crab fisheries not only play a crucial role in supporting coastal communities that depend on these resources for their livelihoods, but also contribute to the small-scale aquaculture industry, especially in the production of soft-shell crabs, hard-shell crabs, and berried female crabs. Despite the importance of mud crabs, there is currently no specific governmental policy focused solely on the conservation and management of wild mud crab resources. However, existing regulations related to mangrove forests, which are crucial habitats for mud crabs, indirectly support the sustainability of these resources. Mangrove forest reserves in Malaysia are generally managed under different regulations depending on the region. In Peninsular Malaysia, forest management is governed by the National Forestry Act 1984 (Amendment 1993) in line with the Peninsular Malaysia Forestry Policy 2020. In East Malaysia, the forest is governed by the two states, Sabah and Sarawak. Sabah Forestry Department oversees forest management, harvest control, and royalty payments, guided by the Forest Enactment 1968, Forest Rules 1969, Forest (Timber) Enactment 2015, and the Sabah Forest Policy 2018. Meanwhile, in Sarawak, the Sarawak Forestry Department is responsible for forest administration and resource management, operating under the Forest Ordinance 2015, Forest Regulations, and the Sarawak Forest Policy 2019.

Malaysia has a total of 668 967 ha of mangrove forests, with 378 175 ha in Sabah, 173 792 ha in Sarawak, and 117 000 ha in Peninsular Malaysia. Of these mangrove forests, 70 percent are designated as protected areas. The mangrove reserves in Malaysia are spread across several states, namely Johor state – Tanjung Piai National Park; Kedah state – Sungai Merbok Mangrove Forest Reserve; Perak state – Matang Mangrove Forest Reserve; Sabah state – Kudat Mangrove Reserve, Teluk Marudu Mangrove Reserve, Kuala Maruap Forest Reserve; and Sarawak state – Sarawak Mangrove Forest Reserves. These protected areas are important habitats of mud crab. Mangrove forests offer critical ecosystem aspects that support the life cycle of mud crabs, including nursery grounds, feeding habitats and shelter.

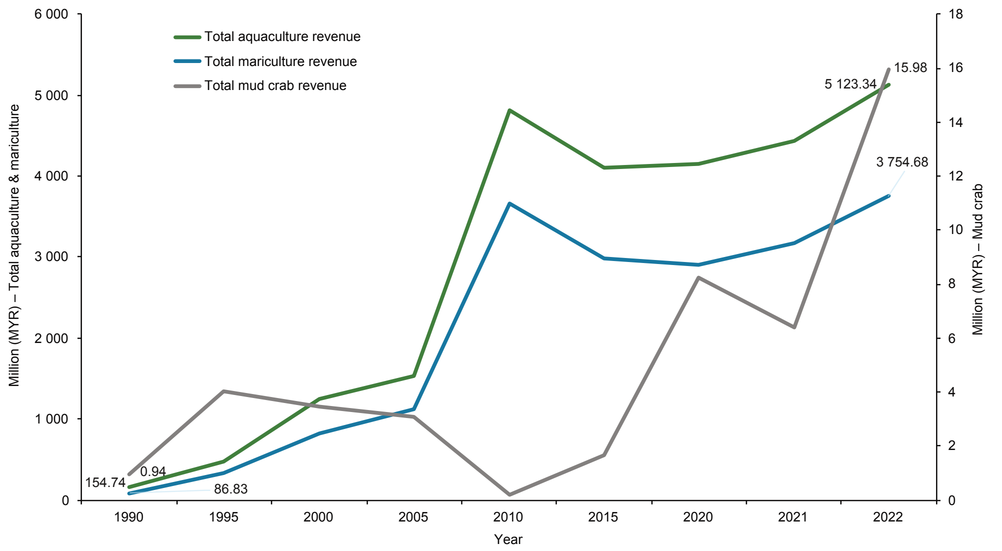
However, to further support mud crab fisheries and aquaculture in Malaysia, there is a need for policies specific to mud crabs that would ensure their long-term exploitation and promote aquaculture development. Some examples include regulations and policies regarding minimum landing size, sex-based trading, seasonal fishery regulation, and refugia. At present, conservation and management of the wild resources are mainly driven by local universities, with frequent restocking programmes carried out by the Universiti Malaysia Terengganu in Peninsular Malaysia and the Universiti Malaysia Sabah in East Malaysia. By building on the nation-wide mangrove management programme, Malaysia can ensure the continued viability and sustainability of mud crab resources for future generations.

INDUSTRY STATUS

Aquaculture production status

Malaysia, rich in aquatic resources such as fish, shrimp, crabs and shellfish, recorded an increasing aquaculture (inclusive of freshwater, brackish, and marine cultures) revenue from MYR 155 million to MYR 5 billion from 1990 to 2022 (Figure 3) (Department of Fisheries Malaysia, 1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022). The total mariculture (only brackish and marine cultures) revenue followed the same trend, peaked at MYR 3.8 billion in 2022, representing approximately 73 percent of the total aquaculture revenue (Figure 3). The increase in total aquaculture and mariculture

FIGURE 3
Total aquaculture (fresh, brackish and marine), mariculture (only brackish and marine), and mud crab production revenues from 1990 to 2022 (MYR billion)



Source: Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022).

revenues reflects the exponential growth in production volumes. A nearly 1,000 percent increase in production volume for both aquaculture and mariculture was recorded in 2022 compared to 1990 (Table 1).

Comparatively, mud crab production in Malaysia has fluctuated over the years, starting at 190 t in 1990, peaking at 623 t in 1995, and dropping to its lowest point of 12 t in 2010 before gradually recovering to 334 t in 2022 (Table 1). Nonetheless, due to the increase in market prices, total mud crab revenue grew from MYR 936 thousand in 1990 to MYR 4 million in 1995, when production was at its highest, and peaked at around MYR 16 million in 2022 (Figure 3).

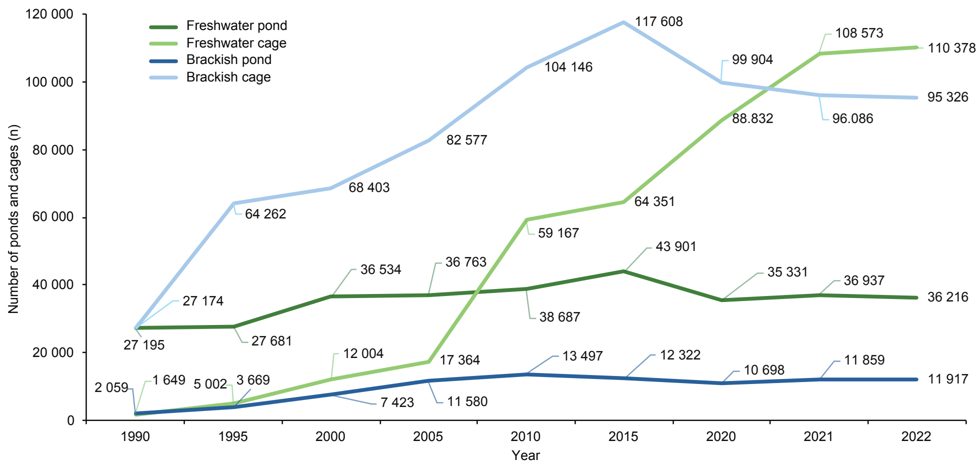
TABLE 1
Total aquaculture, mariculture and mud crab production in Malaysia from 1990 to 2022 (t)

Year	Total aquaculture production (t)	Total mariculture production (t)	Mud crab production (t)
1990	52 303	42 614	190
1995	132 742	114 249	623
2000	167 894	117 206	211
2005	207 220	145 213	222
2010	580 778	425 380	12
2015	506 276	394 320	61
2020	400 018	302 807	210
2021	417 188	311 284	206
2022	573 683	457 814	335

Source: Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022).

The farming of mud crabs is often associated with brackish water culture systems, either in ponds, cages, or tanks. Based on Figure 4, the usage of freshwater ponds rose relatively at a slower rate compared to the usage of brackish water ponds and cages, and freshwater cages in supporting Malaysia's aquaculture production. Specifically, the number of ponds rose from 27 195 freshwater ponds in 1990 to 36 216 freshwater ponds in 2022, a mere 33 percent increase in the number of ponds in a span of 32 years. Comparatively, within the same time span, the number of brackish cages, brackish

FIGURE 4
Number of freshwater and brackish water ponds and cages used for aquaculture practices in Malaysia from 1990 to 2022



Source: Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022).

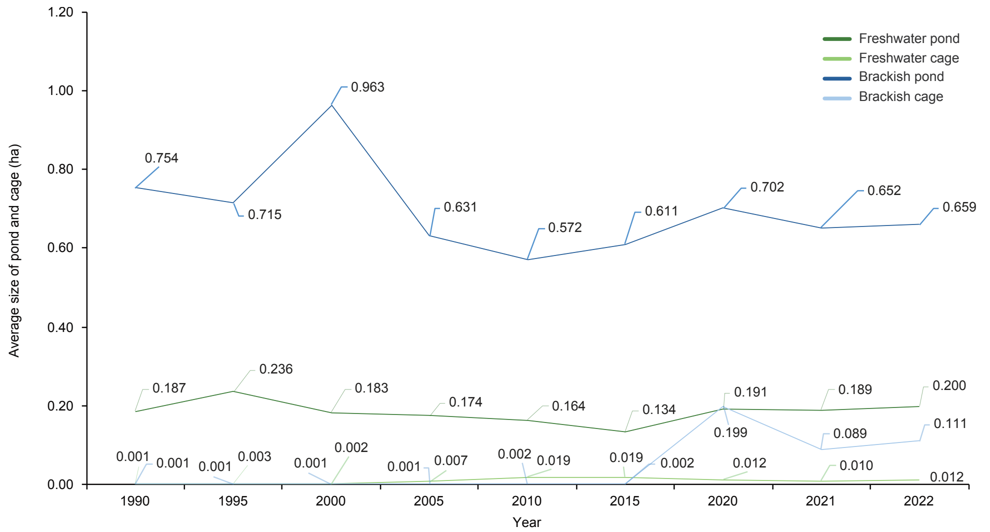
ponds, and freshwater cages recorded exponential increases of 251 percent, 479 percent, and 6 594 percent (Figure 4).

Based on data from the Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022), significant growth in the use of brackish and freshwater aquaculture ponds and cages area (ha) from 1990 to 2022 was recorded. Brackish pond areas increased from 1 552 ha in 1990 to 7 858 ha in 2022, while brackish cage areas grew substantially from about 24 ha in 1990 to 10 620 ha by 2022, especially after 2010. Freshwater pond areas also expanded, from 5 089 ha in 1990 to 7 226 ha in 2022, while freshwater cage areas rose from 2.14 ha in 1990 to 1 280 ha in 2022, with notable increases after 2005. These trends reflect the growing scale of aquaculture operations, with both pond and cage areas increasing over time to accommodate higher production capacities.

In general, the average size of brackish and freshwater ponds are consistently larger than the average size of brackish and freshwater cages throughout 1990 to 2022, with the exception of brackish cages being averagely slightly larger than the average size of freshwater ponds (Figure 5). Averagely, among freshwater and brackish ponds and cages, brackish ponds are the most favored culture systems among farmers in Malaysia, with a consistent range of 0.572 to 0.963 ha/pond. Among cage culture systems, brackish cage culture increased in average size starting from 2015, ranging from 0.089 to 0.199 ha/cage during 2020 to 2022.

FIGURE 5

Average size of ponds and cages used in aquaculture in Malaysia from 1990 to 2022

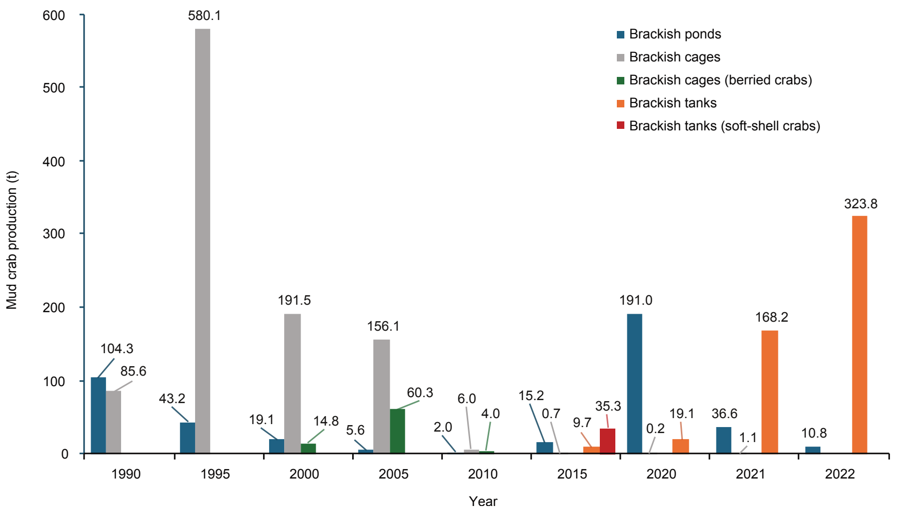


Note: The average size of ponds and cages is calculated by dividing the total size (ha) by the total number of ponds or cages in a specific year.

Source: Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022).

The trend of mud crab production in Malaysia shows substantial fluctuations over the period 1990–2022 (Figure 6; Table 1). In 1990, a moderate production of 190 t was recorded, with outputs from brackish pond and brackish cage cultures of 104 t and 86 t, respectively. In 1995, mud crab production spiked to 623 t, driven largely by a significant increase in cage production. This was followed by a decline in 2000, with total production falling to 225 t due to a sharp drop in both pond and cage production. Notably, berried crabs were first reported to be cultured in brackish cages in 2000. From 2005 to 2010, production remained relatively low. In 2005, production was 222 t, then decreased further to 12 t in 2010, with a marked reduction in both pond and cage systems, and small-scale berried crab production. However, from 2015 onward, there

FIGURE 6
Total aquaculture production of mud crabs in ponds, cages and tanks in Malaysia from 1990 to 2022 (t)



Source: Department of Fisheries Malaysia (1990, 1995, 2000, 2006, 2010, 2015, 2020, 2021, 2022).

was a noticeable change. In 2015, total production rose to 61 t, supported partially by the production of soft-shell crabs (35 t) and normal crab fattening (10 t) in tanks. The upward trend continued in 2020, with mud crab production increasing to 210 t, slightly decreasing to 206 t in 2021, and peaking at 335 t in 2022. Interestingly, there was an obvious shift in primary mud crab production methods. Brackish pond culture declined rapidly from 191 t in 2020 to only 11 t in 2022, while brackish tank culture gained preference, increasing from 19 t in 2020 to 324 t in 2022 (Figure 6).

AQUACULTURE PRACTICES AND METHODS

Mud crab aquaculture in Malaysia remains a relatively small industry compared to other cultured marine species such as shrimps, owing to the abundance of wild stock populations and competitive prices of imported mud crabs. The primary culture activities involve crab fattening and soft-shell crab production, both are often carried out by small-scale farmers as supplementary income sources rather than as full-scale commercial ventures. Consequently, there is a noticeable absence of comprehensive and reliable data on the industry's overall size and economic impact.

Broodstock management

Broodstock are sourced either from the wild or from farms. In general, the essential characteristics of broodstock includes physically active, absence of any external parasites, possess intact appendages, weigh 300–350 g, and have nearly mature ovaries. These broodstock are housed in one tonne tanks, supplied with a bottom layer of fine sand (< 70 µm), approximately 10–15 cm deep, and the addition of shelter in the form of PVC pipes (Fazhan *et al.,* 2022). The stocking density for the broodstock is maintained at 2–3 ind./m^2. The water in the tanks is carefully regulated at a temperature range of 28–32 °C, salinity range of 30–35 ppt, and a pH maintained at 8.0–8.5. Continuous aeration is crucial during the culture period to ensure the water remains oxygenated.

Maintaining the highest level of water quality is essential during broodstock culture. The water level in the tank should be maintained at 30–40 cm, and a complete or partial (50%) water exchange performed daily to remove any feed residue or faeces. Alternatively, recirculating aquaculture system (RAS) can be applied to reduce the frequency of water exchanges. The fine sand at the bottom of the tank is also thoroughly cleaned every 3 days to ensure a healthy environment for the broodstock. Since broodstock typically spawn at night or in the early morning, and the eggs need time to harden, it is advised that water exchanges be conducted after 08:00 to avoid disrupting the spawning process. Broodstock are fed a nutrient-rich diet consisting of clams, blood cockles, squid and fish to help promote gonad development and improve egg quality (Azra & Ikhwanuddin, 2016). Feeding is carried out daily after the water exchange.

Broodstock with well-developed gonads will naturally begin to spawn within 2–3 weeks after being introduced into the pond or tank. If spawning does not occur within one month, the broodstock should be replaced. Although eyestalk ablation can induce gonadal maturation and hasten the egg extrusion process, it is not recommended and not practised in most hatcheries in Malaysia due to ethical concerns. After spawning, females are transferred to individual holding tanks to allow better control of the water quality and minimize stress. These tanks, with a capacity of 1 t, are set up two days prior to the transfer. The tank is filled to 70 percent of its capacity with treated water, which is chlorinated and then dechlorinated using sodium thiosulfate. Additionally, ethylenediaminetetraacetic acid (EDTA) is added at a concentration of 0.02 g/L to further treat the water, and the alkalinity is adjusted to 120–140 ppm using sodium bicarbonate before the female crab is introduced. Healthy embryonic development is indicated by berried females carrying dense egg masses. During this period, it is important to maintain a water temperature of 28–32 °C and salinity of 30–35 ppt to prevent shedding of the egg and ensure proper development. As the embryos develop, the colour of the egg mass changes progressively, starting from orange and transitioning to light yellow, then grey, dark brown and finally black. Under optimal conditions of 28–32 °C, the eggs typically hatch after 10–12 days of incubation.

Larval rearing

Once the larvae hatch, they are transferred immediately. The larvae are disinfected by immersing them in a 200-ppm formalin solution for 10 seconds, after which they are placed in tanks of 1–2 t at a density of 50 000–100 000 larvae per tank. The larvae remain in these tanks throughout the nursery phase until they reach the crablet stage (C1–C5) and can be sold to commercial crab nurseries or released back to the wild for restocking.

The feeding schedule for crab larvae is carefully planned to meet their nutritional needs at each stage of their development. During the Zoea 1 (Z1) stage, the larvae are initially fed microalgae or *Artemia* instar, supplemented with formulated feed. As they advance to the Z2, Z3 and Z4 stages, their diet shifts to include *Artemia* nauplii, along with formulated feeds provided at various times throughout the day. By the time the larvae reach the Z5 stage, their diet is diversified to incorporate both *Artemia* biomass and formulated feed, ensuring they receive a well-balanced nutrition. This dietary regimen continues into the megalopa stage. Finally, during the crablet C1 to C4 stages, the larvae's diet is further enriched by adding chopped fish or squid along with the formulated feed, providing a more varied and nutrient-rich diet. The feeding routine is structured to occur three times daily in early morning, midday, and early evening across all stages – except during the C1 to C4 stages, where the midday feeding is omitted. This organized feeding plan is vital for promoting the larvae's growth, optimizing their health, and ensuring their survival as they progress through various developmental stages (Waiho *et al*., 2018).

RESEARCH AND INNOVATION

Mud crab aquaculture development and innovation are critical research areas in Malaysia, driven by the country's commitment to enhancing food security and supporting the aquaculture industry. At the national level, numerous research grants support ongoing mud crab projects. Key areas of focus include optimizing broodstock rearing processes to ensure a higher yield of healthy mud crabs that are capable of producing high quality larvae in huge quantity. Additionally, universities and the Department of Fisheries Malaysia are working to improve larvae rearing techniques to enhance larvae survival rates through better nutrition, environmental control and disease management. Periodic assessments of wild mud crab populations by the Department of Fisheries Malaysia and universities in various regions further ensure the sustainable exploitation of mud crab resources in Malaysia.

The role of marine species, including mud crabs, as a viable protein source is highlighted in the Malaysian Government's latest food security policy (MAFS, 2023), as well as the National Agrofood Policy 2021–2030 (MAFS, 2021) in both fisheries and aquaculture. Additionally, to emphasize the importance of sustainable aquaculture and the role of crustaceans in national food security, especially high-value species such as mud crabs, the Ministry of Higher Education Malaysia designated the Institute of Tropical Aquaculture and Fisheries (AKUATROP) at Universiti Malaysia Terengganu as a Higher Institution Center of Excellence for shellfish research, focusing primarily on sustainable production of mud crabs and tiger shrimps to cater for the nation's development needs. This designation underscores the government's commitment to advancing research and development in mud crab aquaculture.

MARKET INFORMATION

Major markets for hard- and soft-shell mud crabs

Mud crabs are highly priced crustaceans, with berried female mud crabs and large males fetching the highest price in the market. Due to the high demand for mud crabs in Malaysia, mud crabs are increasingly being imported from other countries, particularly from Indonesia, Sri Lanka and Viet Nam. While most imports are for local consumption, some are transited for export to China, Hong Kong SAR, Singapore and Taiwan Province of China.

In Malaysia, local mud crabs are categorized by size and grade: AA (≥ 500 g/crab, priced at MYR 55–250/kg), A (250–499 g/crab, MYR 45–55/kg), B (200–249 g/crab, MYR 25–45/kg), C (100–199 g/crab, MYR 20–35/kg) and D (< 100 g/crab, MYR 10–25/kg). The price of mud crabs is also dependent on the availability of supply in the specific geographical location. The mud crab market is diverse, with distinct size and sex classes commanding different prices. Large mud crabs often fetch higher prices in larger cities, with ovigerous female crabs commanding premium prices due to their perceived quality and taste. Generally, in restaurants, ordinary mud crabs are priced at MYR 160/kg while good quality crabs are about MYR 250/kg. However, during festive seasons like Eid Fitri, Eid Adha, Lunar Chinese New Year and Christmas, prices can exceed MYR 250/kg due to limited supply and heightened consumer demand.

Recently, there is a growing demand for soft-shell crabs in Malaysia due to their high price range (MYR 60–80 per kg). Consequently, some crab fishermen would temporarily culture juvenile-sized crabs and harvest them immediately after moulting. These small-scale soft-shell crab industries, however, are often temporary as they depend fully on the availability of (1) juvenile crabs from the wild, and (2) space and equipment for soft-shell crab culture.

MAJOR ISSUES AND CHALLENGES FACING THE INDUSTRY

Mud crab production in Malaysia is still relying on wild-caught and imported mud crab resources. While fattening and hard-shell farming were once popular, both culture activities have declined, according to the data from the Department of Fisheries, Malaysia. Mud crab nurseries capable of producing crablets are still in trial phase, primarily led by universities and a few private aquaculture companies. However, owing to the abundance of mud crab resources, the low prices of imported crabs, and the complex skills and knowledge needed to culture mud crabs, aquaculture companies are reluctant to invest in large-scale mud crab farming in Malaysia.

In the aquaculture industry, crabs are known carriers of diseases that could also affect shrimps, making them unsuitable for polyculture with shrimps. Additionally, consumer perception is also a significant factor impeding the expansion of mud crab aquaculture in Malaysia, as most Malaysians prefer marine crabs such as blue swimmer crabs, over mud crabs. Some Muslims avoid mud crabs because they live both in water and on land, which conflicts with the concept of halal. Additionally, the presence of sacculinid parasites – specifically rhizocephalan *Sacculina beauforti* in East Malaysia (Waiho *et al*., 2017) – poses a significant threat to the culture of the mud crab *S. olivacea* (Fazhan *et al*., 2018). This parasite is highly prevalent among *S. olivacea* and can severely impact their health. Infected crabs experience disruptions in their physiological processes, including the prevention of moulting and damage to the gonads, which impedes both their growth and reproduction (Fazhan *et al*., 2020a).

CONCLUSION

The status of crab fisheries and aquaculture in Malaysia highlights both the importance and the challenges of managing these crucial resources. Crabs, particularly those from the genus *Scylla*, represent a significant economic contributor to the fishery sectors of Malaysia, driven by their high market value and increasing demand. The increasing mud crab revenue from MYR 936 000 in 1990 to MYR 16 million in 2022 demonstrates a growing industry with substantial economic impact. Despite these positive trends, the mud crab fishery and aquaculture sectors are facing a series of interrelated issues that threaten their sustainability.

Firstly, the decline in wild crab populations, exacerbated by overfishing and habitat degradation, is a pressing concern. The observed decrease in wild catches, despite the overall increase in landings, suggests that wild stocks are being depleted faster than they can replenish. Secondly, the aquaculture sector, although expanding, remains underdeveloped relative to its potential. Mud crab farming constitutes a small fraction of total mariculture production, at only 0.07 percent of the total output in 2022. The sector's growth is hindered by inadequate infrastructure and technical skills, limited investment, and competition from imported crabs. The transition from traditional fishing to a more structured aquaculture system is complicated by these constraints, necessitating improvements in farming practices, technology and investment.

Moreover, the indirect benefits derived from policies protecting mangrove ecosystems are crucial but insufficient. Mangroves play a vital role as nurseries and habitats for juvenile crabs, making their conservation essential for sustaining crab populations. However, targeted regulations and management strategies specifically addressing crab fisheries and aquaculture are lacking.

Current efforts, including restocking programmes and research by local universities, are important but need to be supported by comprehensive data and integrated into broader conservation and management frameworks. While the crab fisheries sector in Malaysia demonstrates considerable economic potential, its long-term sustainability is threatened by overfishing, habitat degradation and underdeveloped aquaculture practices. To ensure the viability of these resources, it is imperative to implement effective management strategies that balance harvesting with conservation. Enhancing aquaculture infrastructure, investing in research and innovation, and developing specific policies for crab fisheries will be crucial for addressing these challenges. Strengthening conservation efforts for mangrove ecosystems and supporting restocking initiatives will further contribute to the resilience of crab populations. A holistic approach combining sustainable practices, scientific research, and robust policy frameworks is essential for securing the future of Malaysia's crab fisheries and aquaculture industries, ultimately benefiting local communities and ensuring food security.

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Mud crab aquaculture situation in Japan

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ABSTRACT
Three mud crab species – *Scylla paramamosain*, *Scylla serrata* and *Scylla olivacea* – are distributed along the shores of Japan. *S. paramamosain* is dominant in temperate zones, *S. serrata* in subtropical regions, while *S. olivacea* is a less common species. The Fisheries Research and Education Agency (FRA) has played a central role in the development of seed production techniques adapted from those developed for the Japanese swimming crab, *Portunus trituberculatus*. Large-scale release trials have been conducted in the past. However, large-scale stocking initiatives by the FRA were discontinued in 2014, leaving only small-scale stocking efforts currently managed by local fisheries authorities. Comprehensive data on mud crab fishery in Japan is still scarce, and systematic stock assessment is lacking. Although there are no regulations specific to the harvesting of mud crabs, the Fisheries Act and several laws prohibit the use of crab traps by unlicensed persons, particularly within protected areas such as Ishigaki Island. In addition, the Food Hygiene Act prohibits the use of formalin or antimicrobials in the production of seed intended for human consumption. Mud crab is considered a luxury seafood product in Japan. Imported soft-shell and live crabs are often served in restaurants in Tokyo, highlighting the inadequacy of the domestic production in meeting the local demand. Large-scale aquaculture is considered challenging in Japan due to the high costs associated with electricity, labour and feed, as well as the limited availability of suitable land. As a result, FRA has shifted its research focus to small-scale aquaculture as a more practical and sustainable approach to address these economic and environmental constraints.

INTRODUCTION

Crab species
Three crab species, *S. paramamosain*, *S. serrata* and *S. olivacea*, are distributed along the coast of Japan (Figure 1) (Oshiro, 1988; Oshiro and Imai, 2003; Sakaji and Fuseya, 2015). *S. paramamosain* is typically found in inner bays within temperate zones, with the primary fishing areas being Lake Hamana and Urado Bay (Yamakawa, 1978; Hamasaki and Kitada, 2008; Hamasaki *et al*., 2011). Notably, this species has also been found in colder regions, including the Sea of Japan (Motoh and Nagasawa, 2007) and Matsushima Bay (Yagura, 2021). *S. serrata* is mainly found in the subtropical regions of the Ryukyu Archipelago (Oshiro, 1988). *S. olivacea* is less common in Japan (Ogawa *et al*., 2011, 2012). As a result, both *S. paramamosain* and *S. serrata* are important local fisheries, supporting regional economies and livelihoods (Obata *et al*., 2006; Hamasaki *et al*., 2011).

Previous research on seed production and release of mud crabs in Japan has primarily focused on *S. paramamosain* and *S. serrata*. Other important crab species include the Japanese swimming crab (*P. trituberculatus*), blue swimmer crab (*Portunus pelagicus*), Japanese mitten crab (*Eriocheir japonica*), snow crab (*Chionoecetes opilio*), horsehair

FIGURE 1
Distribution of the mud crab species in Japan
The distribution of *Scylla paramamosain* extends south of Chiba Prefecture (CH) along the Pacific coast and south of the Ariake Sea (AR) in the East China Sea. Notable localities for this species include Hamamatsu City (HM) and Kochi City (KC). *Scylla serrata* is predominantly found around the islands of Okinawa (OK) and Ishigaki (IS). The rarer *S. paramamosain* is primarily detected in Matsushima City (MS) and Kaga City (KG).

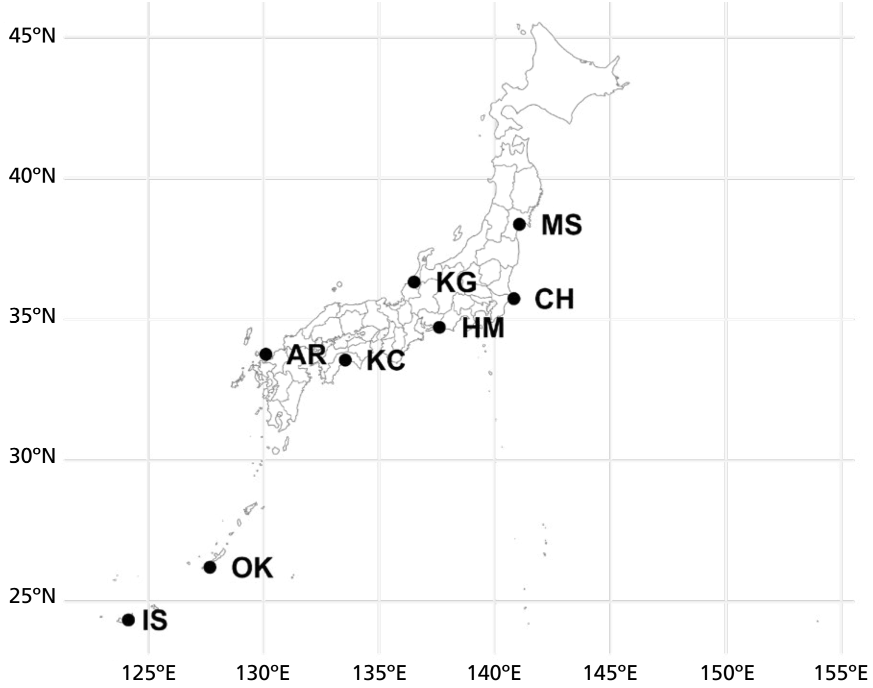

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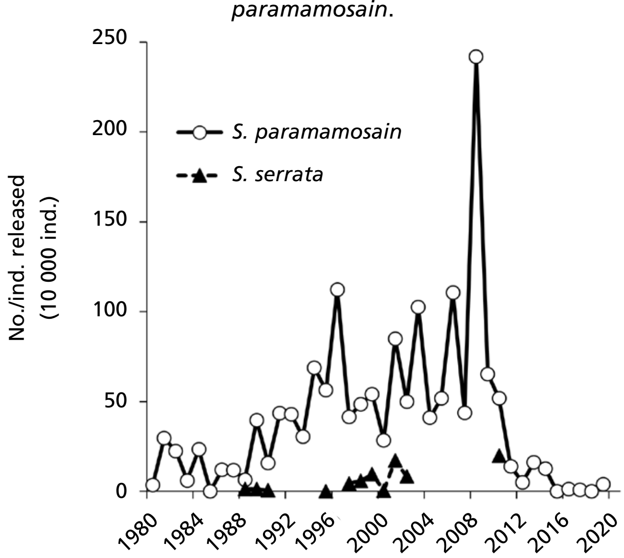
FIGURE 2
Numbers of hatchery-raised *Scylla* spp. crablets released in Japan
The Japan Sea Farming Association (JSFA) developed mud crab seed production technology and conducted restocking activities until 2014. Currently, the Shizuoka Prefectural Research Institute of Fishery is the sole organization conducting small-scale release trials of *Scylla paramamosain*.



crab (*Erimacrus isenbeckii*) and red king crab (*Paralithodes camtschaticus*). Seed production methods have been developed for these species, with release programmes conducted for *P. trituberculatus*, *P. pelagicus* and *E. isenbeckii*. The production techniques for mud crabs in Japan have been adapted from methods originally developed for cultivating the Japanese swimming crab. However, it is important to note that FRA's large-scale stocking efforts were discontinued in 2014 (Figure 2). Currently, stocking operations are minimal, with annual releases limited to tens of thousands of *S. paramamosain*.

Wild stock status

Comprehensive catch data for mud crabs are limited, highlighting the localized and restricted nature of their populations. This lack of information is further compounded by the absence of systematic stock assessments, which are crucial for understanding the health of the mud crab stocks and sustainability of the fishery.

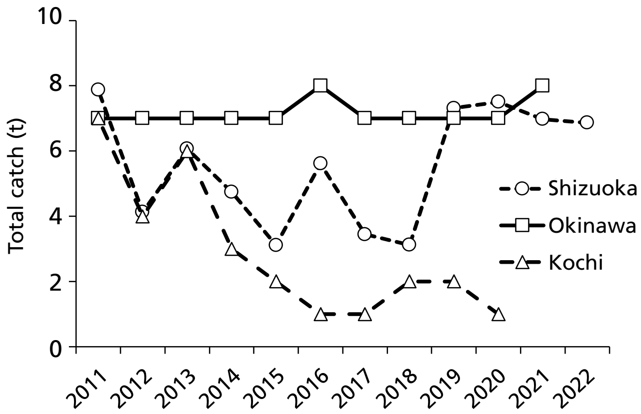
CONSERVATION AND MANAGEMENT OF WILD RESOURCES

Currently, there are no specific regulations in Japan governing the fishery of mud crabs. The Fisheries Act (Japan Fishery Act, 1949) imposes restrictions on the use of crab traps and gill nets in various regions, particularly for individuals without a valid fishing license.

A notable example is Ishigaki Island, recognized as a vital habitat for mud crabs. This island features a protected marine area that underscores the significance of conserving its aquatic ecosystems. Within this protected zone, fishing of certain aquatic species is strictly prohibited to maintain the delicate balance of the ecosystem and safeguard the habitats of mud crabs and other marine organisms. Strengthening regulations and management measures in such critical areas could further enhance the protection of these species and their environments.

FIGURE 3
Landing volumes of all crab species in Japan from 2011–2023

In Shizuoka, catches are predominantly *Scylla paramamosain*. In Kochi and Okinawa, data combine *Portunus trituberculatus* and *Portunus pelagicus*, with the latter species being dominant, while *Scylla* spp. are less abundant in both regions.



INDUSTRY STATUS

Production status

Currently, comprehensive data and information on aquaculture production for mud crabs in Japan are lacking (Figure 3). However, small-scale aquaculture efforts are ongoing, primarily in Okinawa Prefecture. In Lake Hamana, the catch of wild *S. paramamosain* is estimated at approximately 6 t/year. In Kochi Prefecture, the combined annual catch of *P. trituberculatus* and *P. pelagicus* is about 8 t, with *P. pelagicus* being the dominant species. In Okinawa Prefecture, *S. serrata* is classified as a portunid crab, and the combined catch with *P. pelagicus* is approximately 7 t/year (Ministry of Agriculture, Forestry and Fisheries, 2015–2022).

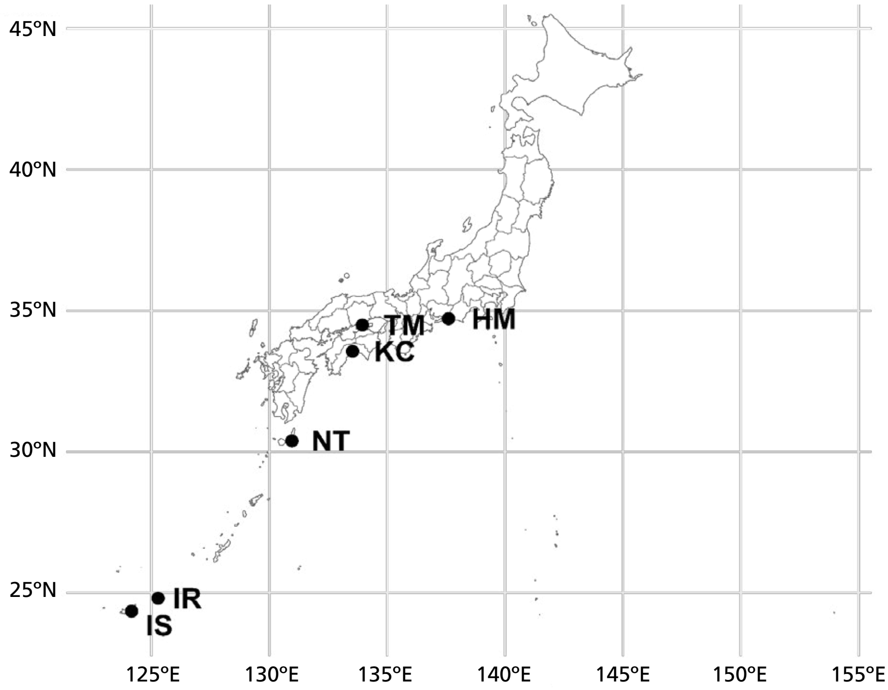
Farming areas

Small-scale aquaculture is currently being conducted on Irabu Island, part of Miyakojima City in Okinawa Prefecture. In addition to this, aquaculture trials have been attempted in Tamano City (Okayama Prefecture), Nakatane City (Kagoshima Prefecture) and Lake Hamana in Hamamatsu City (Shizuoka Prefecture). Unfortunately, these trials have not yielded positive results (Figure 4). The challenges faced in these regions highlight the need for further research and development to optimize aquaculture practices for mud crabs, potentially leading to more sustainable and productive operations in the future.

Hatcheries, nurseries and farms

For *S. paramamosain*, the seed supply was previously provided by the FRA's Tamano Station, which ceased operations in 2017. However, the Shizuoka Prefectural Research Institute of Fishery continues to play a vital role in seed production, annually producing tens of thousands of *S. paramamosain* crablets and releasing them into Lake Hamana.

FIGURE 4
Locations of mud crab seed production facilities and aquaculture trials in Japan
Seed production for *Scylla serrata* took place at the Yaeyama Station, Ishigaki Island (IS). *Scylla paramamosain* is currently produced at the Shizuoka Prefectural Research Institute of Fishery, Hamamatsu City (HM), following the closure of the Tamano Station (TM). Small-scale farming of natural *S. serrata* seedlings is done on Irabu Islands (IR). Past efforts to culture imported *Scylla olivacea* in Nakatane City (NT) were unsuccessful. Release experiments for *S. paramamosain* took place in Hamamatsu (HM) and Kochi City (KC), while *S. serrata* was trialed in Ishigaki City (IS) and Iriomote Island.



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The FRA's Yaeyama Station successfully developed seed production technology for *S. serrata*. However, efforts to implement mass production were constrained by recurrent disease outbreaks. Although the Fisheries Research and Education Agency has since ceased large-scale seedling releases, the Yaeyama Station continues to produce a limited number of seedlings for small-scale aquaculture research on *S. serrata* (Figure 4).

Additionally, the Food Sanitation Act (Japan Food Sanitation Act, 1947) prohibits the use of formalin or unauthorized antimicrobials in the seed production of any aquatic species intended for human consumption.

AQUACULTURE PRACTICE AND METHODS

Broodstock management

Non-ovigerous female crabs are procured and maintained in tanks with continuous water flow and a sandy substratum. Typically, these tanks are double-bottomed, segregating the feeding area to avert sand contamination and inhibit the formation of a reduction layer. The primary diet consists of Asari clams (*Ruditapes philippinarum*) and Antarctic krill (*Euphausia superba*). After spawning, the crabs are moved to tanks without sand while maintaining continuous water flow. One day prior to hatching, the crabs are transferred to incubation tanks, where the development of the eggs is meticulously monitored.

Larval rearing

Larvae stocking densities ranged between 10–50 ind./L in tanks with capacities of 50–200 m^3. At the Yaeyama Station, mud crab zoea are cultivated in 500 L tanks with a density of 20 ind./L. During the early zoea stages, nutritionally enriched S-type rotifers are provided at concentrations of 20–40 ind./ml. From the Z2 stage onward, enriched *Artemia* is introduced and densities of 0.5–2.0 ind./ml. Additionally, phytoplankton species, including *Nannochloropsis* and diatoms, are added daily as a dietary supplement.

HEALTH AND DISEASE MANAGEMENT

Mass mortality due to necrosis: When producing *S. serrata* crablets bacterial necrotic diseases are commonly observed. A systematic survey has identified several causative organisms, with *Aquimarina hainanensis* being notable (Midorikawa *et al*., 2020). While treatment with sodium nifurstyrenate can prevent the disease, its application in aquaculture seedlings is restricted by law. Consequently, research has shifted towards biological control methods (Dan and Hamasaki, 2015).

Moult death syndrome: This phenomenon is observed during the metamorphosis from Z5 to megalopa, leading to moulting failure and subsequent mortality (Dan and Hamasaki, 2011).

Bacterial shell disease: This condition is predominantly observed in older crab specimen, and to date, no preventive measures exist (Lavilla-Pitogo and de la Peña, 2004).

RESEARCH AND INNOVATION

Research on the thermal adaptation of Japanese mud crab populations has revealed that *S. paramamosain* exhibits remarkable adaptability to lower water temperatures typical of temperate regions in Japan. This species demonstrates a greater tolerance to these cooler conditions compared to *S. serrata*, allowing it to thrive in environments where the latter species may struggle.

As global warming leads to rising sea temperatures, changes in the species composition and geographical distribution of mud crabs in Japan are anticipated. The increasing temperatures may favour the expansion of *S. paramamosain* into areas that were previously too cool for optimal growth, while *S. serrata*, being less adaptable to temperature fluctuations, may experience population declines or shifts in its distribution range. This shift could have implications on local ecosystems, fisheries, and on the overall biodiversity of marine habitats.

Moreover, the adaptability of *S. paramamosain* to varying thermal conditions may open new opportunities for aquaculture in Japan. As traditional species face challenges associated with climate change, *S. paramamosain* could become a more viable option for sustainable fisheries and aquaculture practices.

Understanding the adaptive mechanisms of these species is essential for the development of effective management strategies. Ongoing research is necessary to monitor the impacts of climate change on mud crab populations and to implement measures that ensure the sustainability of both aquaculture and wild fisheries in the face of shifting environmental conditions (Sanda *et al*., 2022).

MARKET INFORMATION

Product prices

Within its catchment area, *S. paramamosain* is considered a premium local delicacy, with market prices occasionally reaching JPY 6 500/kg (approximately USD 43/kg) (Okinawa Prefectural Federation of Fisheries Cooperatives, 2024). This high value

TABLE 1
Changes in average landing prices for *Scylla serrata* and the more abundant, lower-priced *Portunus pelagicus* at major fish markets in Okinawa over the past decade

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022
Price (USD/kg)	10.3	13.8	14.9	16.62	15.8	16.3	12.8	17.1	21.2
Amount (kg)	3 858	5 102	5 187	4 564	3 450	3 316	2 591	3 570	4 605

Source: Okinawa Prefectural Federation of Fisheries Cooperatives. 2024. Shikyoujouho: Okinawa Uminchu Uoichiba. (Market information 2011–2021). [Accessed on 20 November 2024]. https://www.okinawa-fish.jp/.

reflects both its culinary significance and the growing demand for fresh, locally sourced crabs.

In metropolitan areas, particularly Tokyo, some restaurants offer imported soft-shell crabs, catering to the growing consumer demand. Additionally, high-end restaurants also procure and serve imported live crabs, which are priced significantly higher due to their perceived superior quality and freshness.

Despite the popularity of mud crabs, the domestic catch in Japan is insufficient to meet the local market demand. As a result, Japan relies on imports to supplement local supplies. Landing prices in major fishing markets on Okinawa-Jima Island have increased in recent years, indicating a rising demand for crabs (Table 1) (Okinawa Prefectural Federation of Fisheries Cooperatives, 2024). However, it is important to note that the data does not differentiate between *S. serrata* and *P. pelagicus*. The latter species is typically harvested in greater quantities and is associated with a lower market price.

This discrepancy highlights the need for accurate data collection and market analysis to better understand the dynamics of crab fisheries in Japan. Improved knowledge of species-specific trends could help stakeholders adapt to changing market demands and enhance the sustainability of crab fisheries, ensuring that both local and imported crabs can coexist in the marketplace while meeting consumer preferences.

MAJOR ISSUES AND CHALLENGES FACING THE INDUSTRY

In the Japanese context, the costs associated with feed, electricity and labour are significantly higher than in many other countries. Additionally, there is a shortage of areas suitable for aquaculture development. The accessibility of hatchery-produced mud crablets is limited, and reliance on natural seed resources poses challenges regarding both sustainability and catchability.

As a result, implementing large-scale aquaculture remains a challenge, prompting the Fisheries Research and Education Agency to prioritize research on small-scale aquaculture initiatives.

Moreover, the limited availability of facilities for artificial crablet production is compounded by a notable shortage of trained and skilled technicians in seed production. This gap underscores the urgent need to transfer seed production techniques and train the next generation of technicians. Addressing these issues will be critical for enhancing aquaculture sustainability and productivity in Japan.

CONCLUSION

In Japan, there is a growing demand for premium local aquatic food products among both domestic consumers and tourists. Although large-scale aquaculture production faces challenges related to technological limitations and high production costs, small-scale land-based aquaculture presents a promising opportunity that necessitates ongoing technological advancements. Additionally, the effects of global warming are expected to drive mud crabs northward, potentially expanding their distribution within Japan and enhancing their market presence.

However, it is a general concern that the number of skilled technicians in mud crab seed production, particularly within organizations like the FRA, is currently declining. Urgent action is required to address this issue, especially through the training and development of new professionals in the field. Ensuring a steady pipeline of skilled technicians is crucial for maintaining sustainable aquaculture practices and meeting the increasing demand for high-quality aquatic products.

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Domestication and selective breeding of mud crabs

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ABSTRACT

Mud crabs or mangrove crabs, *Scylla* spp., are among the top ten commercially important aquaculture commodities in the Philippines. However, commercial mud crab production remains dependent on wild-sourced seedstock which may soon be depleted if conservation and adequate management schemes are not strictly implemented and technologies for hatchery-based seed production are not applied. As such, there is a need to promote and adopt science-based technologies in crab domestication, as well as traditional and advanced selective breeding methods, to ensure the continuous propagation of quality seedstock that can supply the increasing demand of the crab industry. This technical paper discusses some of the updates in *Scylla serrata* domestication, broodstock development and selective breeding research in the Philippines.

INTRODUCTION

In 2020, world aquaculture production of mud crabs *S. serrata* and *Scylla paramamosain* registered at 248 800 t and 159 400 t, respectively. Production of these two species jointly contributed only 3.6 percent to the total global aquaculture production of eight major crustacean species (FAO, 2022). In the Philippines, aquaculture production of mud crabs (*Scylla* spp.) was reported at 23 112 t in 2021 – a slight increase of 11.3 percent from the previous year. This commodity, farmed in brackish water ponds, marine fish pens and cages, ranked sixth among the top ten aquaculture commodities produced in that year according to the Philippine Statistics Authority (DA-BFAR, 2021).

A lack of crab seedstock for aquaculture has been addressed partly by the local promotion of crab breeding and hatchery technology by the Philippine Council for Agriculture, Aquatic and Natural Resources, Research and Development (PCAARRD), under the Department of Science and Technology (DOST). Funds were allocated for the establishment of hatcheries under the project on "Adoption of improved commercial-scale mangrove crab hatchery-nursery system" in several parts of the country to encourage artificial production of seedstock. In addition to this, nursery rearing areas have been set up by the Department of Agriculture-Bureau of Fisheries and Aquatic Resources (DA-BFAR) in key collection sites in the Philippines. This programme started in 2022 when DA-BFAR turned over 12 mangrove crab nursery sites to fishers in the province of Catanduanes which has long been known as the crab capital of the Philippines (DA-BFAR, 2024).

Basic technologies on the broodstock management and seed production of *Scylla* spp. were first developed in the late 1990s (Quinitio, Parado-Estepa and Alava, 1999; Quinitio *et al*., 2001). Since 2011, following advancements in breeding and seed production technologies and the successful domestication of captive *S. serrata* crab broodstock, hatchery-reared seedstock has been utilized, albeit in limited quantities (Quinitio *et al*., 2011).

MUD CRAB AS FARMED SPECIES

Mud crabs are considered an economically important portunid species in small-scale coastal fisheries and aquaculture (Liew, Yong and Lim, 2024). Although local mud crab production has been steadily increasing, the need to further boost farm output is a response to the increasing commercial demand for this species for both domestic consumption and international trade. Three mud crab species, *S. serrata*, *Scylla olivacea* and *Scylla tranquebarica*, have been traded locally, but the preferred species is *S. serrata* as it is larger, less aggressive and has a wide natural distribution in the Western Indo-Pacific region (Quinitio *et al*., 2015).

Apart from the establishment of crab hatcheries, the local government units in areas where crablets are naturally sourced are implementing municipal ordinance that prohibits the collection and trading of ≤ 3 cm crablets outside the municipality of origin (Quinitio *et al*., 2015). In 2020, Fisheries Administrative Order No. 264, was issued by DA-BFAR (2020) that regulates the catching, possession, transport and trading of crablets, juveniles and gravid *Scylla* spp. for nationwide implementation. This ordinance has indirectly helped promote the expansion and use of hatchery-produced crab seedstock.

The Philippine mud crab aquaculture industry has significant growth potential, contingent on a reliable supply of hatchery-produced seedstock. Addressing this gap is challenging; however, with strict enforcement of crab-catching regulations, the establishment of additional hatcheries that maintain high-quality broodstock for larval production, and the adoption of optimal breeding and seed production technologies, the demand for local crab seedstock could be sustainably met.

BROODSTOCK DEVELOPMENT

When initiating a domestication program, several key information elements are essential: the source and quality of broodstock; an understanding of the optimal conditions for broodstock maturation; production and grow-out of crablets (hatchery and nursery); and comprehensive requirements for nutrition, health and environmental management, including water quality standards. These aspects were thoroughly defined when initiatives for the domestication, broodstock development, and management of *S. serrata* were undertaken in 2011, drawing on years of prior research and technological validation (Quinitio *et al.,* 2001; Quinitio and Parado-Estepa, 2008).

The technologies have been further refined and field-tested beyond the domestication research. With these improvements it has been easier to maintain the domesticated crab stocks as hatchery-produced seedstock are being continually produced. One of several important mud crab research projects is the development of a technique for evaluating the quality of newly hatched mud crab larvae based on survivability from stress tests (Quinitio, de la Cruz-Huervana and Parado-Estepa, 2018; Quinitio, Parado-Estepa and de la Cruz-Huervana, 2018). This trait, along with an assessment of the stock's genetic background, could be valuable for screening high-quality broodstock. Such a screening protocol is important, as studies have shown that the quality of crab larvae may positively correlate with performance at later stages, such as the megalopa and early juvenile phases (Quinitio, de la Cruz-Huervana and Parado-Estepa, 2018).

Breeders are normally sourced from the wild. However, should a facility rear potential crab broodstock from wild-sourced crab juveniles, one concern is knowing if the seedstock is the preferred species. Many fishers who collect crabs use traditional identification methods such as those based on morphological traits. Differentiation of the three species, especially in the early crab stages, using a dichotomous key remains challenging given some ambiguous morphological characteristics. Vince Cruz-

Abeledo, (2016) attributes these to morphological aberrations and has studied the use of both image analysis comparing frontal lobe spine shapes using a software called SHAPE (Vince Cruz-Abeledo, Ting and Lagman, 2018) and validating species identity using molecular markers such as ITS-1 and 16S rDNA markers with 97.8 percent accuracy. This method of identifying species at the crab instar and juvenile stages in the wild is especially valuable for ensuring that the correct species of seedstock are reared in nursery and grow-out enclosures for commercial production. Additionally, it aids in selecting suitable individuals for broodstock development.

In addition to the genetic quality of crab broodstock, a critical factor in their development and management is a well-defined nutritional regimen. Nutritional interventions are primarily focused on dietary enhancements to support maturation and optimize reproductive performance, as nutrition significantly influences ovarian development in crabs. Beyond improving the quality of berried females, feeding breeders with optimized diets also enhances larval quality, contributing to overall seedstock viability (Pattiasina *et al*., 2016).

Azra and Ikhwanuddin (2015) have done an extensive review of available literatures on maturation diets in *Scylla* broodstock. Crab broodstock diets were developed based on their requirement for high amounts of lipids, fatty acids and protein as these are needed for the maturation and breeding processes. Such nutrients are best provided for by a mix of natural diet or feed and artificial diets from fish meal and other feed ingredients. On the other hand, it has been proven that feeding broodstock natural diets, composed of mussel meat, squid and low value fish, can improve the quality of the eggs and larvae (Millamena and Quinitio, 2000). The major concern in using natural diets in maintaining broodstock is proper water quality management since excessive use of the feeds may pollute and cause the deterioration of the rearing water in broodstock tanks (Azra and Ikhwanuddin, 2015).

An essential aspect of broodstock development and management, particularly when crab breeders are ready for spawning, is the preparation of spawning tanks with specific provisions. These include appropriate substrates, such as a base layer of gravel or pebbles topped with sand, sand-filtered water, sufficient aeration, and artificial shelters to minimize aggression among breeders within the same tank (Azra and Ikhwanuddin, 2015).

A study on the "Optimization of temperature for *S. serrata* broodstock in a recirculating system with a polychaete-assisted biofilter" (Mercedes Pates, personal communication, 2023) is being implemented in Mindanao State University, Iligan Institute of Technology, to enhance broodstock performance in captivity. The setup features a recirculating aquaculture system (RAS) incorporating adult polychaetes, supported by sand biofilters at a density of 200 g/m² (Figure 1). Additionally, the reproductive performance of broodstock held at temperatures of 27, 30 and 33°C in the RAS will be evaluated for stress response using molecular markers. Findings on the optimal temperature achieved with the polychaete-assisted sand filter system can then be readily adopted by hatchery operators.

FIGURE 1
Recirculating water system with the use of polychaetae assisted sand biofilters for mud crab broodstock maintenance

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DOMESTICATION AND SELECTIVE BREEDING

Domestication

To successfully produce seedstock from captive crab breeders, it is essential to comprehend the species' life cycle, reproductive biology, and the husbandry technologies needed at each developmental phase—from zoea to crab instar to juvenile and ultimately to adulthood. This involves controlling the life cycle, manipulating breeding processes, and completing the life cycle while managing each stage of development under captive conditions. Once commercial quantities of the crabs are produced, one can then claim that domestication has been achieved. The Aquaculture Department of the Southeast Asian Fisheries Development Center (SEAFDEC/AQD) was able to close the life cycle of the three *Scylla* species (*S. serrata*, *S. tranquebarica*, and *S. olivacea*). *S. serrata*, as the priority species of interest at SEAFDEC/AQD, was intensively studied as its life cycle in captivity was completed after 9 months (Quinitio *et al.*, 2001; 2011).

Domestication refers to the process of breeding, caring for, and feeding wild species under controlled management, with the primary goal of food production, as exemplified by the domestication of various aquatic species (Duarte, Marba and Holmer, 2007; Hedgecock, 2012). Before breeding and rearing crabs in captivity, the caught individuals undergo health checks for pathogens and receive treatment as necessary during a quarantine period. Domestication is broadly defined as the process by which a population of animals adapts to captive conditions through genetic changes that occur over generations and environmentally induced developmental events that recur within each generation (Price, 1984; Price, 2002). Liao and Huang (2000) further define domestication in aquaculture as the complete control of an organism's life cycle and the manipulation of breeding in captivity, including the organism's readiness to spawn once domesticated. In the context of domestication as a prerequisite for selective breeding, Friedman *et al.* (2022) define domestication in aquatic species as achieved when the species exhibits the first outcomes of selective breeding. If no such outcomes are observed, a species is considered domesticated only after three successive generations or reproductive cycles under controlled conditions. However, Teletchea (2021) noted that this criterion of three successive cycles is somewhat arbitrary and that domestication can be interpreted in various ways by different scientists.

Quinitio *et al.* (2011) reported the successful domestication of *S. serrata* at SEAFDEC/AQD, having produced three successive generations of disease-free captive mud crab stocks. In this study, founder stocks were sourced from four locations: Cagayan, Camarines, Samar, and Surigao (Figure 2). To facilitate domestication, the genetic quality of each stock was assessed and compared using molecular markers to analyse genetic diversity indices. This genetic analysis is essential when resources for DNA-based assessments are available and is highly recommended for planning a selective breeding programme.

During the domestication process, evaluation of the four stocks with microsatellite DNA markers revealed no significant differences in genetic variability, with mean expected heterozygosity ranging from 0.812 to 0.860 (Romana Eguia *et al.*, 2009; Quinitio *et al.*, 2011). However, only three of the original five microsatellite DNA markers yielded interpretable results via GeneScan at the time of analysis. Understanding the levels of genetic diversity is crucial for determining suitability for domestication and subsequent selective breeding. Low heterozygosity levels would indicate a risk of inbreeding, regardless of whether the stocks were sourced from natural habitats.

If the breeding programme advances towards selective breeding with a structured artificial selection scheme, it is important to continuously monitor the genetic diversity of the stocks used in breeding crosses over generations. This monitoring helps assess any declines in genetic variability, which may later necessitate a reassessment of the selection scheme, a replacement of stocks for further domestication, or the adoption of more advanced selection strategies, such as genomic selection.

Given the increasing affordability and accessibility of DNA analysis and gene sequencing services, incorporating genetic marker systems for pedigree analysis in selective breeding programmes can significantly enhance the efficiency and profitability of the aquaculture industry in general, and the crab production industry in particular (Friedman *et al*., 2022).

FIGURE 2

Map of the Philippines showing the sources of *Scylla serrata* in Cagayan (brown star), Camarines Norte (blue star), Samar (gray star) and Surigao (red star) as founder populations

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Map from ©Dreamstime

Selective breeding

The information obtained from the initial studies on the domestication programme was used as basis for the succeeding selective breeding programme of SEAFDEC/AQD which aimed to evaluate the response of crabs to selection based on desired traits (e.g. fast growth, resistant to diseases); evaluate the reproductive performance of crabs that were subjected to selection; and monitor genetic changes and minimize inbreeding.

Adult crabs from wild stocks from Surigao and Camarines Norte were used as the founder stocks. After the founder stocks (P_0) from Surigao and Camarines Norte had spawned, newly hatched larvae were evaluated for quality. Quinitio, de la Cruz-Huervana and Parado-Estepa (2018) developed a method to assess the quality of newly hatched mud crab larvae by exposure to 40 mg/L formalin (37 percent) for 3 hours. The 37 percent formalin solution was used to enable hatchery operators to easily adopt the quality assessment method. Good quality larvae could then be evaluated based on larval survival in a post-formalin stress test. Only good quality larvae were reared in the hatchery. Thereafter, hatchery-produced crablets (day 23–25 from zoea 1) were reared in net cages installed in nursery ponds at the brackish water station of SEAFDEC/AQD for 1–2 months or until they had attained a carapace width 2–6 cm. Selection was done and the juveniles were further cultured in earthen grow-out ponds (Figure 3). Some of the Surigao and Camarines Norte (P_1) crab populations from the founder farmed types were used for disease challenge tests (see Figure 4 for the selective breeding scheme) while the rest of the crablets or juveniles were stocked in brackish water ponds for the growth evaluation trials (see Figure 5 for the selection scheme).

Second-generation (F_2) families from Surigao were produced after 11–12 months from the zoea 1 stage (Figure 6). The results indicated that producing multiple generations of mud crab in captivity is feasible, provided there are no constraints on the availability of rearing enclosures. Throughout the breeding process, the crabs remained free from white spot syndrome virus (WSSV) from the founder stocks to both the F_1 and F_2 generations. WSSV challenge tests revealed that several farmed types from Camarines Norte exhibited the highest resistance to the virus.

FIGURE 3

Brackish water ponds used for growing mud crab juveniles to market size

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FIGURE 4

Selective breeding scheme (mass selection) for disease resistance in mangrove crab *Scylla serrata*

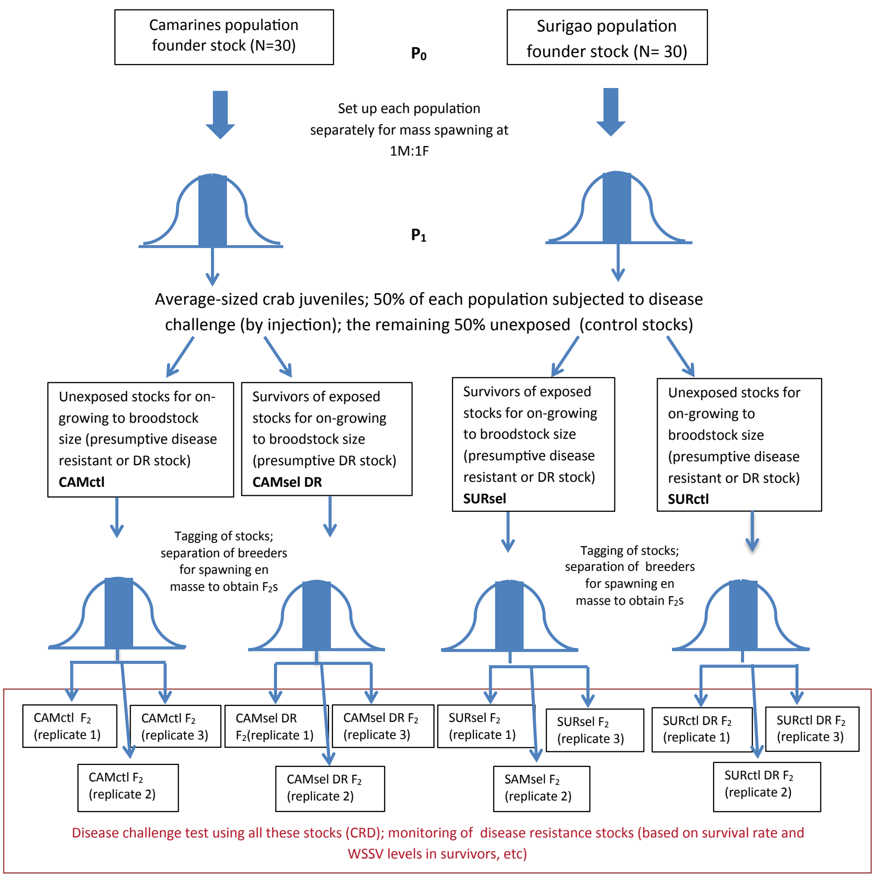
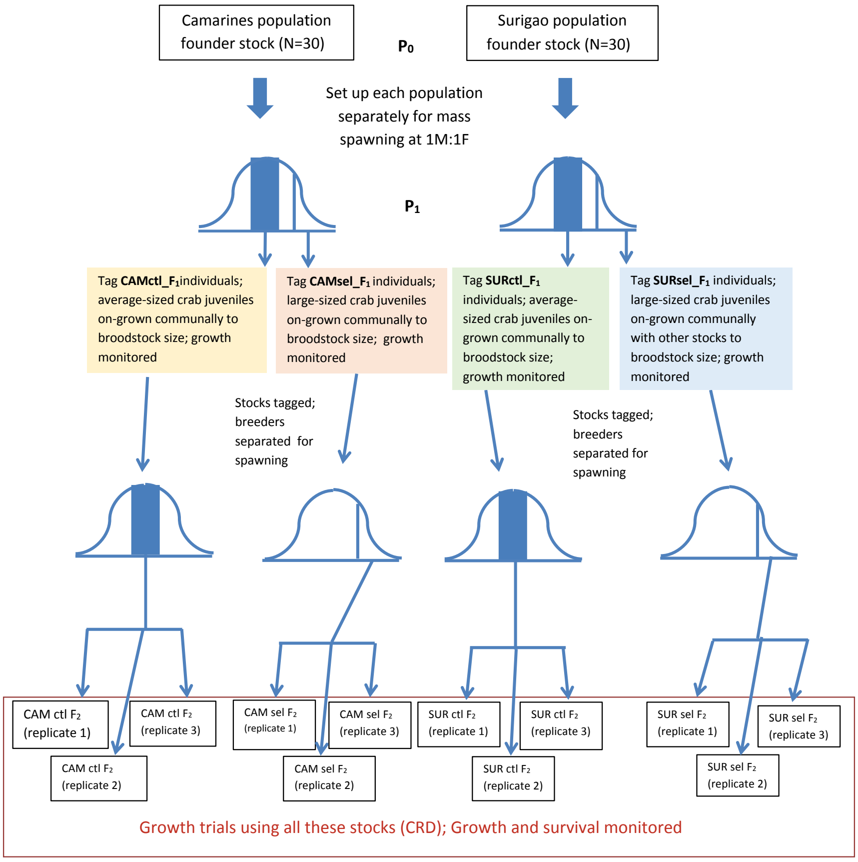


FIGURE 5
Selective breeding scheme (mass selection) for enhanced growth in mangrove crab *Scylla serrata*



Interestingly, there was no apparent correlation between growth and breeding efficiency traits. While the number of zoeae per female improved up to the second generation, no clear trend emerged regarding overall breeding traits. However, the average duration from spawning to hatching decreased across generations. Therefore, it is recommended that a separate selection programme be implemented specifically targeting breeding efficiency as an improved trait.

Crabs utilized in selective breeding may respond well to selection after two or three generations; following this, a new batch of stocks should be introduced for genetic enhancement. Although traits associated with good growth may be enhanced through a selective breeding programme, selection should continue only until genetic diversity levels, measured by the number of alleles, are not drastically reduced.

The preliminary results were promising, demonstrating the successful production of three generations of mud crabs free from

FIGURE 6
Adult mud crabs produced following a selective breeding programme lasting 11–12 months

pathogens, such as viruses, which could be transmitted to successive generations (Quinitio, Huervana and Eguia, 2018). Unfortunately, the initiative had to be discontinued due to limited funding and a shortage of available experts to continue working on the project.

Aquaculture commodities such as tilapia, salmon, and shrimp have undergone genetic improvement through conventional quantitative genetic methods, including mass selection, combined family selection, and within-family selection. The choice of selection method for aquatic species depends on the heritability of the traits being considered. For instance, economically important species like oysters have been selectively bred using ploidy manipulation, resulting in the production of triploid oysters that grow faster than their diploid counterparts.

Crustaceans, particularly shrimp, have been extensively studied due to the urgent need to address viral diseases that impact growth, survival and marketability. Major players in the shrimp industry have focused on developing genetically superior seedstock by creating specific pathogen-free (SPF) and specific pathogen-resistant (SPR) shrimp. This approach often involves conventional and marker-assisted selection over multiple generations (sometimes as many as 30 generations) targeting traits such as disease resistance, fast growth, and high fecundity (see https://www.shrimpimprovement.com/).

In contrast, while mud crabs are also susceptible to viral pathogens, the selective breeding and production of disease-resistant stocks have yet to be thoroughly investigated. Currently, efforts have primarily focused on the early detection and screening of stocks for viral pathogens, leading to the exclusion of infected individuals from use as broodstock or seedstock.

With recent advancements in genetic technologies, developing superior quality crab broodstock can possibly be achieved in a shorter period. Genome editing technologies such as CRISPR/Cas9 can be readily used to edit out genes, which may then lead to the development of quality aquaculture stocks such as those that are disease resistant, as has been done for salmon, carp, catfish, oyster, tilapia, etc. (Gratacap *et al*., 2019).

With the advent of more advanced techniques such as marker-assisted selection, routine genotyping by sequencing (Robledo *et al*., 2017) and genome editing, improving the economically important traits of several aquaculture species (including *Scylla* spp.) may be achieved more efficiently and in a shorter period.

To date, preliminary studies have been done to identify stocks that could possess better traits. One example is a local study on crab stocks obtained from three known collection sites with varying climate profiles, namely: Cagayan, Bicol and Bataan. Mud crabs from these three sites were compared for heat stress response via transcriptome profiling and it was noted that there was a population-specific response of *S. serrata* to temperature variation and that crab stocks from Cagayan had broad heat tolerance and high capacity for acclimation (Shrestha *et al*., 2021). Such results could serve as a foundation for selecting crab stocks for use in selective breeding, particularly in response to the increasing need for heat-tolerant crabs due to the challenges posed by climate change. Meanwhile, another project funded by the Department of Science and Technology (DOST) aims to generate a transcriptome profile of *S. serrata* in response to WSSV infection. Once published, the findings from this study will elucidate the molecular and genetic mechanisms underlying the resistance, or lack thereof, of *S. serrata* crabs to WSSV. This information could later inform the identification of individuals or stocks suitable for selective breeding for WSSV disease resistance (R. Ravago Gotanco, personal communication, 2023).

CONCLUSION

In light of the above, it is crucial for current and prospective mud crab hatchery operators and grow-out farmers to thoroughly understand the various requirements and protocols associated with mud crab domestication before embarking on selective breeding schemes aimed at producing superior quality stocks. A primary consideration is ensuring that the wild-sourced mud crabs used for breeding and rearing in captivity are free from pathogens that could lead to diseases, ultimately jeopardizing farm yields.

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Domestication and the future of genetically improved mud crabs

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ABSTRACT

Genetic improvement in aquaculture involves the use of genetic and molecular principles in the selection of desirable traits. Although mud crab production is still heavily relying on wild caught fishery, the recent advancement in its molecular aspects have provided a basis for domestication and genetic improvement. However, most molecular characterization research on mud crabs have revolved around *Scylla paramamosain*, owing to its abundance and popularity in Asia, especially China. To date, the chromosome-level high-quality reference genome of mud crab (*S. paramamosain*) has been uncovered, revealing a total size of 1.21 giga base pairs with contig N50 of 11.45 mega base pairs and scaffold N50 of 23.61 mega base pairs. Also uncovered were female-specific single nucleotide polymorphism (SNP) markers that could be useful in sex determination and guide mud crab monosex production. The high-density linkage maps of *S. paramamosain* provided valuable information on the chromosome linkage groups, especially in the mapping of quantitative trait loci (QTLs) related to desirable traits, including sex on chromosome 6. Meanwhile, a total of 84 QTLs of 26 growth traits were mapped using F2 genetic map, of which 21 QTLs were exclusively found on chromosome 6. Interestingly, the growth trait-related SNPs and QTLs showed significant association with sex traits. The sex determination system of mud crab, *S. paramamosain*, is postulated to be ZW/ZZ based on the results of female-specific SNP loci and high-density linkage maps. Additionally, a 40K liquid SNP chip with genotyping calling rate (97.02 percent) and polymorphic SNP rate (89.19 percent) for *S. paramamosain* has been developed for genome selection and subsequent growth trait prediction. A new strain of *S. paramamosain* with higher growth rate has been developed via continuous artificial selection. Additionally, two hybrid farmed types from cross between *S. paramamosain* and *Scylla serrata*, with obvious advantages in growth rate and resistance to *Vibrio parahaemolyticus*, were produced.

INTRODUCTION

Mud crabs primarily distributed throughout the Western Indo-Pacific region are capable of surviving in a wide range of salinity. It has become an economically significant mariculture species globally and a popular seafood item in Southeast Asian countries (Le Vay, Ut and Walton, 2007). Mud crab farming has been practiced for over 100 years in China and in the past 30 years across Asia (Keenan and Blackshaw, 1999; Williams and Primavera, 2001). However, production remains insufficient to meet the growing demand from consumers, resulting in consistently high market prices. Furthermore, current mud crab farming heavily relies on wild-sourced seed stock with finite and unreliable supply, hindering expansion due to limited access to hatchery-reared seed (Le Vay, 2001; Walton *et al*., 2006).

Genome sequences play a crucial role in elucidating fundamental aspects of organism evolution and enable the identification of genes involved in various adaptations in animals (Zhang *et al*., 2019; Gutekunst *et al*., 2018). Despite the existence of several genome maps in shrimps and crabs (Zhang *et al*., 2019; Tang *et al*., 2020; Tang *et al*., 2021; Zhao *et al*., 2021), the current genomic data available for Decapoda is insufficient to facilitate comprehensive genomic studies, which impedes our understanding of developmental processes, reproductive strategies, and nutritional intake within this ancient yet highly successful lineage.

Sex-determination mechanisms of animals are remarkably diverse and complicated, and they attract considerable interest in research due to their significant implication in both theory and practice. Among crustaceans, several crab species, including *Guinusia dentipes*, *Eriocheir japonicus* and *Hemigrapsus sanguineus* have an XY/XX sex-determination system based on karyotype studies (Niiyama, 1937, 1938; Lécher, Defaye and Noel, 1995). Importantly, studies on the genetic basis of sex-determination mechanism are the foundation for the future development of sex manipulation biotechnologies, including monosex population, especially in species with significant sexual dimorphism. So far, the sex determination mechanism remains unclear in most aquaculture crustacean species, which has obviously limited its potential application in the aquaculture sector.

An accurate and comprehensive genetic linkage map is the cornerstone for genomic and genetic studies, as well as the selective breeding of a species. Hitherto, due to the capacity for quantifying the extent of recombination, linkage disequilibrium, and chromosomal rearrangements across populations, genetic linkage mapping has become an excellent and essential tool in genome assembly, comparative genomics, and quantitative trait locus (QTL) mapping. With the advantage of the genetic linkage map, the QTLs related to desirable traits were identified and applied to molecular breeding and marker-assisted selection in aquaculture. In decapod crustaceans, however, because of their high number of chromosomes, progress on the construction of high-density linkage maps is slow and difficult.

Furthermore, compared with other aquatic species, genetic improvement of mud crabs is still in its infancy. Therefore, it is critical to speed up the genetic improvement of mud crabs. Genomic selection (GS) and genome-wide association studies (GWAS) have been widely implemented to accelerate the genetic improvement of important economic traits. Finding efficient and reliable high-throughput genotyping tools is the premise and basis of implementing GS and GWAS on mud crabs.

WHOLE GENOME SEQUENCING AND ASSEMBLY

To date, two reference genomes of mud crabs have been completed (Zhao *et al*., 2021; Zhang *et al*., 2024). The latest *S. paramamosain* genome revealed by Hongyu Ma and his research team has a size of 1.21 giga base pairs with contig N50 of 11.45 mega base pairs and scaffold N50 of 23.61 mega base pairs, mapped using a combination of Nanopore ultra-long, HiFi and Hi-C sequencing. In comparison, the N50 of the sequences obtained here is approximately five times that achieved in the previous genome assembly (N50 < 200 kilo base pairs) (Zhao *et al*., 2021), indicating a significant improvement in the published *S. paramamosain* genome. The contigs were further cut and anchored to 49 pseudochromosomes. The genome contains 206 695 simple sequence repeats and 345 610 tandem repeats. A total of 33 662 protein-coding genes were predicted. Compared with Chinese mitten crab and marbled crayfish (Cui *et al*., 2021b; Gutekunst *et al*., 2018), coding genes are comparatively more abundant in *S. paramamosain*. The average coding sequence length of mud crab protein-coding genes was similar to that of Chinese mitten crab *Eriocheir sinensis* (Song *et al*., 2016) and shrimp *Litopenaeus vannamei* (Zhang *et al*., 2019), but longer than that of swimming crab, *Portunus trituberculatus* (Tang *et al*., 2020). Comparisons of gene number and protein length indicated the mud crabs had a better quality of gene models than the other two crabs (*E. sinensis* and *P. trituberculatus*), suggesting a useful resource for further comparative studies and a more comprehensive understanding of genomic characteristics in mud crab.

In *S. paramamosain*, 1 545 gene families are expanded, while 2 671 are contracted. The expanded genes are significantly enriched in development-related pathways, including betalain biosynthesis, ubiquitin-mediated proteolysis, circadian entrainment, neurotrophin signaling, adrenergic signaling in cardiomyocytes, longevity-regulating pathways, MAPK signaling and autophagy. On the other hand, the contracted gene families were mainly annotated for nutritional metabolism, including carbon metabolism, propanoate metabolism, glyoxylate and dicarboxylate metabolism, microbial metabolism in diverse environments, biosynthesis of secondary metabolites, carbon fixation pathways in prokaryotes, methane metabolism, pyruvate metabolism, and glycolysis and gluconeogenesis, indicating that there have been alterations in nutrition intake during the process of evolution.

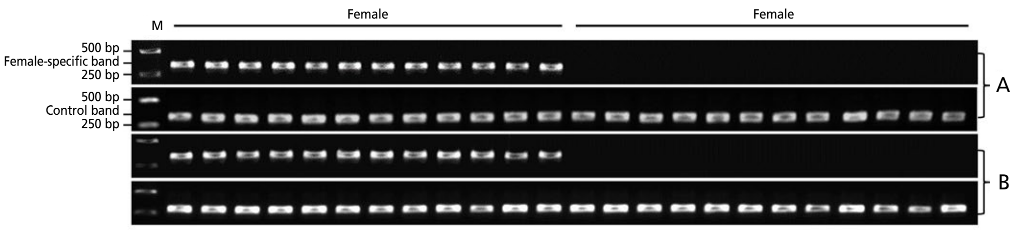
SEX DETERMINATION BASED ON SEX-SPECIFIC MARKER IDENTIFICATION, GENETIC MAP CONSTRUCTION AND QTL MAPPING

Sex-specific markers in *S. paramamosain* were identified, and subsequently provide insights into the species' sex determination mechanism and serves as a guide to the future establishment of sex control technology (Waiho *et al*., 2019). After restriction site associated DNA sequencing and sequence comparison, 12 SNP loci were identified being heterozygous in all females, but homozygous in all males, indicating that the sex determination system in *S. paramamosain* is WZ/ZZ, with females being heterogametic. These SNP markers were then successfully validated by polymerase chain reaction (PCR) assay and sequencing using an additional 195 samples (106 females and 89 males). Furthermore, a PCR-based genetic sex identification method was successfully developed (Figure 1). A total of 96 specimens (48 females and 48 males) were used to determine the accuracy and precision of the PCR-based genetic sex identification method. The results showed a 100 percent accuracy for identification of genetic sex of *S. paramamosain*.

FIGURE 1

Agarose gel separation of PCR amplification products with female-specific and control primers in 24 female and 24 male *Scylla paramamosain* from a full-sib family cultured in a pond at Shantou, China

Female-specific band (320 base pairs): PCR products amplified with the female-specific primer (SPFS); Control band (282 base pairs): PCR products amplified with control primer (SPC); M: marker; A: the agarose gel electrophoresis results for 12 females and 12 males. B: the agarose gel electrophoresis results for another 12 females and 12 males



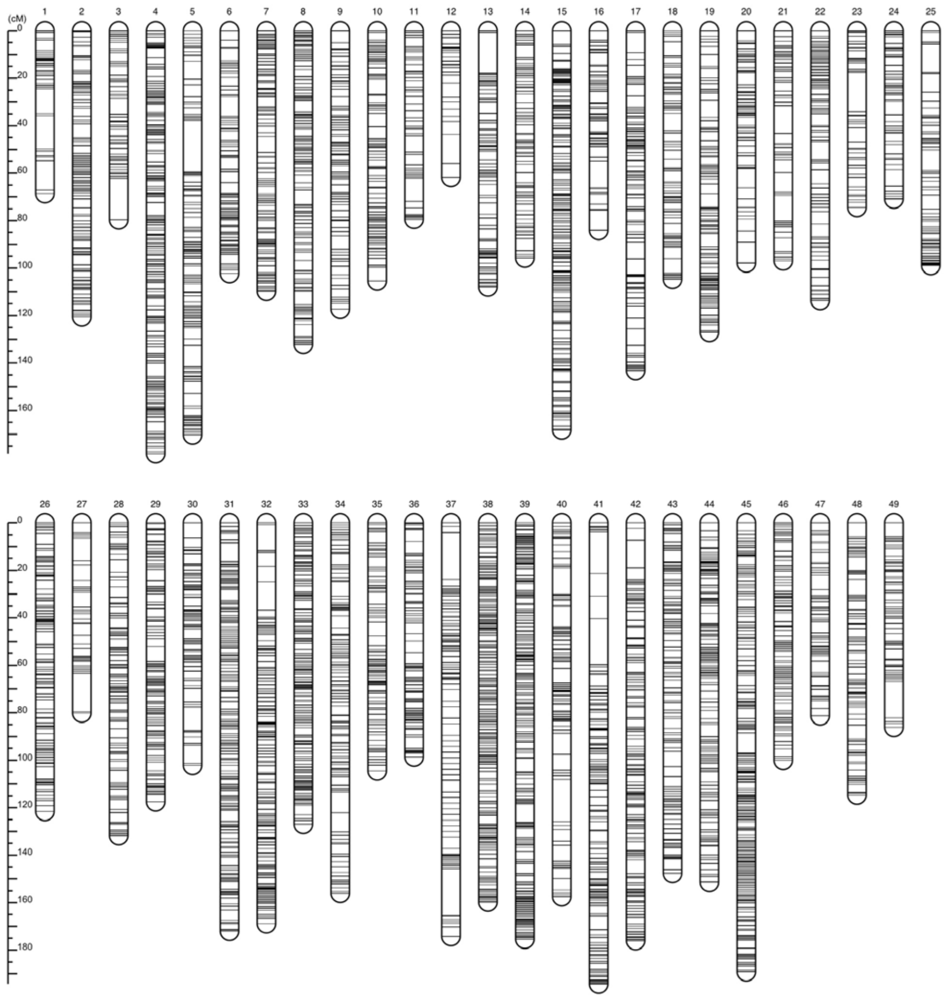
Source: Shi, X., Waiho, K., Li, X., Ikhwanuddin, M., Miao, G., Lin, F., Zhang, Y., Li, S., Zheng, H., Liu, W., Aweya, J.J., Azmie, G., Baylon, J.C., Quinitio, E.T. & Ma, H. 2018. Female-specific SNP markers provide insights into a WZ/ZZ sex determination system for mud crabs Scylla paramamosain, *S. tranquebarica* and *S. serrata* with a rapid method for genetic sex identification. *BMC Genomics*, 19: 981.

A total of four different kinds of genetic maps were published (Ma *et al*., 2016; Waiho *et al*., 2019; Zhao *et al*., 2019; Cui *et al*., 2021a). In Waiho *et al*. (2019), a genetic linkage map containing 49 linkage groups (LGs) with 16 701 markers were constructed for F_1 generation with a high 99.95 percent individual integrity value (Figure 2). Quantitative trait loci for phenotypic sex traits were exclusively found on LG32, with 516 markers distributed in two QTL regions and covered approximately 86.72 percent of the 168.88 centimorgan (cM) LG length. After linkage analysis, a sex-averaged consensus genetic linkage map of hybrid *Scylla* (*S. serrata* ♀ × *S. paramamosain* ♂) containing 49 LGs with 5 574 markers was constructed with a high 99.97 percent individual integrity value, spanning a total distance of 4318.54 cM with an average marker interval of 0.78 cM. The 100 markers linked to phenotypic sex were exclusively found on LG12, which were distributed in three QTL regions and covered approximately 70.42 percent of the 68.88 cM LG length.

A high-resolution genetic map for the F_2 generation of *S. paramamosain* was constructed with a total of 17 899 SNPs, clustering into 49 LGs. QTL analysis indicated that pseudo-chromosome 6 (LG 6) was linked to phenotypic sex, in which 414 SNPs were distributed in one QTL region and covered 98.186 cM LG length, annotated by

FIGURE 2
The genetic linkage maps of *Scylla paramamosain* based on F_1 family

(a) Sex-averaged



Source: Waiho, K., Shi, X., Fazhan, H., Li, S., Zhang, Y., Zheng, H., Liu, W., Fang, S., Ikhwanuddin, M. & Ma, H. 2019. High-density genetic linkage maps provide novel insights into ZW/ZZ sex determination system and growth performance in mud crab (*Scylla paramamosain*). Frontiers in Genetics, 10: 298.

717 genes. All 49 linkage groups have good collinearity with the genome chromosome. The results showed that 84 QTLs were associated with 26 growth-related traits, of which 21 QTLs were exclusively found on pseudo-chromosome 6 (LG 6). Additionally, the genes and SNPs related to growth traits were found. Thirteen candidate genes were identified from the QTLs on LG 6. Interestingly, the SNP markers and QTLs which showed significant association with growth-related traits (body weight, carapace length, and carapace width) were also significantly associated with sex-specific traits.

Using the univariate model, GWAS was performed for sexual phenotypes in F_2 offspring and wild *S. paramamosain* population, respectively. Results showed that these significant SNPs were mainly located on chromosome 6. The most significant SNPs in F_2 offspring and wild-sourced *S. paramamosain* population were located at base pair 19 158 157 and base pair 35 457 053 positions of chromosome 6, respectively. Five candidate genes associated with sexual phenotypes were identified and annotated, including SLC28A3, AMFR, UBXN1, FRS3 and HIST1H1B. Collinearity analysis of the sex determination region between high-density genetic linkage maps and chromosome-level reference genome was carried out. Results showed that the sequences of the sex-determining region (SDR) from QTL mapping were mapped to chromosome 6 of the reference genome. The Spearman's correlation coefficient ranged from 0.950 to 0.985 between the SDR and chromosome 6 in purebred *S. paramamosain*, which indicated high collinearity of the genetic and physical maps. But Spearman's correlation coefficient between the SDR and chromosome 6 was very low in hybrid mud crabs (*S. serrata* ♀ × *S. paramamosain* ♂), which indicated that chromosome recombination maybe exists in interspecific hybridization of mud crabs (*Scylla* spp.). In general, chromosome 6 may be the sex chromosome of *S. paramamosain*.

GENOME SELECTION TECHNOLOGY BASED ON LIQUID CHIP

To carry out genome selection, a 40K SNP array was developed for the mud crab. The number of SNPs range from 9 071 to 696 216 on each chromosome, with an average SNP density of 1.74 to 21.06 SNPs/Kb. The large gap regions were mainly in the middle or tail of the chromosomes, which may overlap with centromeric or telomeric regions. The individual calling rate, SNP number, SNP missing rate, minor allele frequency, and heterozygosity rate of the 40K SNP array were analyzed using 11 wild mud crabs. The results showed that the average individual calling rate was 97.02 percent, ranging from 78.41 percent to 98.15 percent. The minor allele frequency (MAF) values of SNPs ranged from 0 to 0.5, and 92.70 percent of loci had values greater than 0.05. The number of SNPs with a missing rate less than 0.1 was 36 240, comprising 89.81 percent of all SNPs. The number of SNPs with a heterozygosity rate less than 0.5 was 35 989, being 89.19 percent of all SNPs. All the data showed that the 40K SNP array should be sufficient to obtain high-quality genotype data for genetic studies. The prediction accuracy and unbiasedness values for four growth traits were evaluated by using different GS models with the 40K SNP array in the F_2 population. The results showed that the prediction accuracies of GS for body weight (BW), body height (BH), carapace length (CL) and carapace width (CW) were 0.218, 0.136, 0.180, and 0.202, respectively. However, the unbiased values ranged from 0.398 to 0.804, indicating that the genomic breeding values were biased estimates of breeding value due to the small population sizes. In general, the 40K SNP array will be a valuable tool for genomic selection in mud crab.

PROGRESS IN NEW VARIETY DEVELOPMENT THROUGH SELECTIVE AND HYBRID TECHNOLOGIES

In recent years, a new farmed type of *S. paramamosain* named "*Dongfang No. 1*" was developed by grouping breeding technology with a rapid growth rate. Meanwhile, a new farmed type of *S. paramamosain* has been developed by continuous artificial selection, which showed a faster growth rate than a natural wild specimen. In addition, the interspecific artificial hybridization technique was established between *S. paramamosain* and *S. serrata*, and two hybrid farmed types (*S. serrata* ♀ × *S. paramamosain* ♂; *S. serrata* ♂ × *S. paramamosain* ♀) were obtained. The culture assay showed that the two hybrid farmed type crabs had significant growth advantages than *S. paramamosain* and *S. serrata*. Further, scientists tested the effect of *Vibrio parahaemolyticus* on the hybrids crabs, with the results showing that the survival rate of the hybrids was significantly higher than that of wild *S. paramamosain*, indicating that the hybrid crabs possess a stronger antibacterial capability.

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Broodstock management for mud crab

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ABSTRACT

Inconsistent production of good quality broodstock for hatchery is the bottleneck of the mud crab aquaculture industry. This paper describes *Scylla* spp. broodstock management, with special reference to *Scylla paramamosain*. The broodstock production facilities include tanks for the initial treatment of broodstock, spawning tanks with appropriate sand substrate and incubation tanks. For this system, water salinity of 32–35 psu, pH of 7.5–8.5, alkalinity of 120–180 mg/L, dissolved oxygen of 4.7–5.6 mg/L, ammonia of < 0.25 mg/L and temperature of 27–29 °C are maintained. Wild gravid female crabs of 200–400 g with mature ovaries, preferably at stage 4, are selected as broodstock. They are fed natural diets including fish, mussel meat, squid, bivalves and shrimps. Once spawning occurs, the crabs are immediately transferred to the incubation tank for the incubation of fertilized eggs and the hatching of zoeae. The average cost of production of berried broodstock for *S. paramamosain* is approximately USD 45/crab. Additionally, some problems and challenges in the production of quality broodstock are highlighted. It is expected that this report can serve as a reference for the effective production and management of mud crab broodstock.

INTRODUCTION

The main challenges and bottlenecks in the development of the mud crab industry are the inconsistency in broodstock performance and the unpredictability of larval quality and survival (Waiho *et al*., 2018). The limited production of quality berried females in captivity reflects the inconsistent and insufficient production of *Scylla* seed worldwide, as the development of mud crab seed production is closely linked with broodstock selection and management (Azra and Ikhwanuddin, 2016). In many countries, mud crab hatchery technology is still in the development stage, hence few reports on broodstock development and breeding programmes. Thus, the majority of crab farms rely heavily on wild seed, and this puts tremendous pressure on the already decreasing natural mud crab populations due to potential anthropogenic factors such as overfishing and utilization of small-sized crabs (Ikhwanuddin *et al*., 2011; Waiho *et al*., 2015; Viswanathan *et al*., 2019).

The lack of readily available berried females or spawners in the hatchery has greatly affected seed production in many countries, including in Thailand (Nooseng, 2015). There have been several efforts conducted to produce quality broodstock or ovigerous females, but the rate of spawning success has been very low and often inconsistent. To meet the demand for larvae in hatcheries, government agencies often resorted to importing ovigerous females, particularly *S. paramamosain*, from neighbouring countries. The import of ovigerous females was perceived as a better alternative, with higher success rate, compared to relying on locally sourced broodstock. The import of mud crab broodstock has been practised for many years now although the cost is high (approximately USD 150–220/broodstock). Moreover, some farmers directly import crablets to stock into their farms to address the shortage of domestic seed supply. Failed fertilization, nutritional deficiency, microbial infection, heavy infestation with fouling organisms, and environmental stress are among the major causes preventing the successful production of ovigerous broodstock.

Generally, the production of gravid female crab as broodstock in captivity worldwide often involves eyestalk ablation to induce ovarian maturation and shorten spawning process (Quinitio and Parado-Estepa, 2008; Tran, 2017). However, this technique may increase the risk of infection if it is badly managed. Recently, the Mud Crab Learning Centre (MCLC) at Faculty of Science and Technology, Prince of Songkla University (MCLC@PSU) in Thailand, has successfully developed a technique for producing gravid female mud crabs, *S. paramamosain*, in recirculated water system without eyestalk ablation (Hajisamae *et al.,* 2022). Consequently, the supply of quality broodstock in the country has become more consistent and MCLC@PSU has become the first domestic broodstock-producing centre that supplies hatcheries in Thailand. The success rate of egg extrusion by mature crabs sourced from the ponds or wild is 70–80 percent after holding the adult crab for an average of 25 days in a system developed by Hajisamae *et al.* (2022). This new system has been disseminated to some government-run and private hatcheries. This recent development is expected to resolve the bottleneck in the mud crab aquaculture supply chain in the near future.

BROODSTOCK FACILITY SETUP

Essential for successful larval production are proper nutrition and suitable water conditions in the management of broodstock (Shelley and Lovatelli, 2011). The main broodstock facilities include tanks for the initial treatment of incoming broodstock, tanks for holding broodstock or spawning tanks, and incubation tanks. Temperature control is also placed in the system to control diurnal variation of water temperature. Precise control of temperature is required for the incubation and hatching of eggs. Utilizing immersion heaters is possible but the devices need to be protected not to be damaged by the crabs or placed in the treatment unit of the recirculating water system. Maintaining mud crab broodstock in low-light conditions appears to minimize stress levels, which in turn leads to better reproductive performance (Shelley and Lovatelli, 2011). To establish a lowlight regime, the broodstock facility for *S. paramamosain* at the MCLC@PSU is equipped with a dark plastic curtain at the entrance of the building (Figure 1). Furthermore, studies have shown that maintaining light conditions at 0.2–5.0 lux above the water surface in spawning tanks is optimal for broodstock (Hajisamae *et al*., 2022).

Spawning tank

The spawning facility should provide suitable environmental conditions to induce normal spawning of broodstock with lower operational costs (Figure 2). At the MCLC@PSU, 117 L circular tanks (55 cm diameter; 63 cm height) are used in a water recirculating system (Hajisamae *et al*., 2022). Each tank is provided with a sand substrate and approximately 70 L of seawater with continuous aeration. A single broodstock is stocked in each tank. The crabs in the spawning tanks are provided with an optimum light intensity of approximately 0.2–5.0 lux during daytime and darkness at night. Disturbance is minimized during the operation.

Incubation tank

The incubation tank is another critical facility that supports successful broodstock hatching. Its primary role is to incubate fertilized eggs attached to the broodstock's

FIGURE 1
Broodstock housing system at the Mud Crab Learning Centre, Prince of Songkla University

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FIGURE 2
Mud crab broodstock spawning tanks

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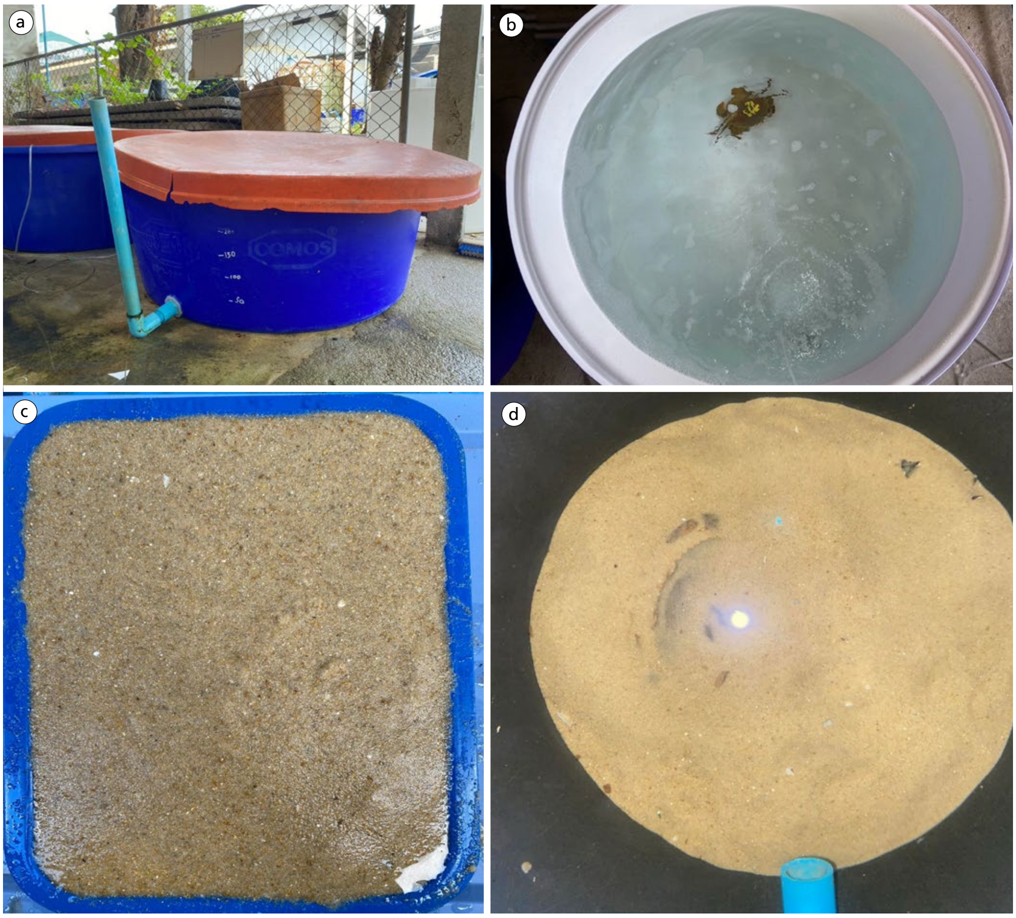
FIGURE 3
Broodstock facilities at the Mud Crab Learning Centre, Prince of Songkla University
A 280 L mud crab broodstock circular holding tank (a); a mature female visible in the tank (b); clean and filtered sand is placed in a tray for disinfection (c); and a mature broodstock buried in the sand substrate placed in the incubation tank



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pleopods, ensuring proper conditions for embryonic development. At the MCLC@ PSU, a 280 L circular tank (Figure 3a and Figure 3b) is employed and placed outside the spawning house. The tank is filled with 200–250 L of treated seawater, continuously aerated for 24 hours, and kept free of any substrate. The optimum light intensity for this incubation tank is approximately 100 lux during daylight hours, and darkness at night. This preparation is done a few days before the expected date of broodstock spawning in the tank. Once the broodstock spawn, they are immediately transferred to this incubation tank for the incubation of fertilized eggs and hatching of zoea (Hajisamae *et al*., 2022).

Substrate

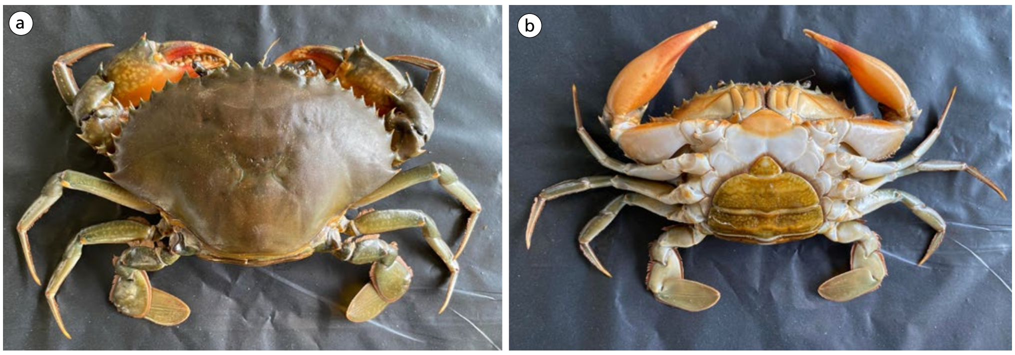
For most commercially valuable brachyuran crabs, sand substrate is commonly provided in broodstock tanks. This substrate offers refuge, facilitates egg extrusion and clutch development, and helps minimize egg loss throughout the incubation period (Ravi and Manisseri, 2013; Fazhan *et al.*, 2022). Female mud crab broodstock require a sandy bottom to spawn their eggs. Crabs excavate a shallow depression in the sediment and by extending their abdomen over it, create a chamber that allows the extruded eggs to attach successfully to the setae of their pleopods. Failure to provide sand in broodstock tanks will result in poor spawning that is often aborted as well as low hatching rates (Shelley and Lovatelli, 2011). Captive-propagated *Scylla serrata* broodstock were provided with gravel (Alava *et al*., 2007) or pebble substrate and topped with around 12–15 cm of sand (Millamena and Quinitio, 2000; Hamasaki, 2003) to facilitate the egg extrusion process (Azra and Ikhwanuddin, 2016). Recently, Fazhan *et al*. (2022) reported that fine sand (< 70 µm) substrate rather than coarse sand should be utilized in *Scylla* broodstock rearing, especially with *Scylla olivacea*, to maximize reproductive output. When using fine sand, the eggs that fall during the extrusion process remain in proximity to the female and aggregate on the surface of the sand substrate, thereby enabling easy recollection onto the pleopods by the female broodstock.

After experimental tests at the MCLC@PSU, it was found that using fine or medium sand (277.8 ± 43.1 µm) at a thickness of 5 cm, placed at the bottom of the tank, provided maximum egg extrusion and the most comfortable handling method for *S. paramamosain* broodstock of 200–400 g (Figure 3c and Figure 3d) (Hajisamae *et al*., 2022). Removal of large particles as well as washing and disinfecting the sand prior to use are essential as part of biosecurity measures.

BROODSTOCK SOURCE AND SELECTION

Most of the broodstock used are either from wild catches or ponds (Quinitio and Parado-Estepa, 2008; Tran, 2017). Currently, wild-sourced gravid female crabs are preferred as broodstock. To obtain wild-sourced crabs, close communication with local collectors is essential to ensure good quality crabs. Healthy adult female crabs (active with complete limbs, absence of external parasites and no obvious abnormalities) of 200–400 g with mature ovaries, preferably stage 4, are carefully selected (Figure 4). Females with their claws untied are preferred. Maturity of the female crab is evaluated based on the abdominal shape and colour. Ovarian maturation stage is assessed by using a torch light technique to detect ovarian shadow. The crabs are carefully transported to the broodstock facility as soon as possible after collection (Hajisamae *et al*., 2022).

FIGURE 4
Ideal external features of a mature and healthy mud crab broodstock
Dorsal view (a); and abdominal view (b) of an adult mud crab



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PREPARATION OF BROODSTOCK AND STOCKING IN TANK

Upon arrival, the crabs are cleaned and disinfected in 150 ppm formaldehyde for 30 minutes and subsequently subjected to a 3-day acclimatization period (Waiho *et al*., 2015). Information such as crab carapace width, carapace length, body weight and date of stocking are recorded. An identification number is marked on the carapace of each individual using a specific marker. Acclimatized females can be held in various types of tanks or buckets in different environmental conditions based on the technique familiar to, or developed by, the hatchery technicians.

Upon arrival, the crabs are inspected, cleaned and stocked immediately in tanks with a water recirculating system (Hajisamae *et al*., 2022). Crabs and the culture system are monitored daily, coinciding with feeding to minimize unnecessary disturbances.

Normally, the broodstock are held in a spawning tank for 20–40 days. Crabs held for more than 40 days without any sign of spawning are discarded and replaced by other female crabs with mature ovaries. The overall broodstock preparation process is visually summarized in Figure 5.

FIGURE 5
Mud crab broodstock preparation for stocking
Weighing of broodstock (a); measuring the carapace width (b); and determining the ovarian maturation stage using a flashlight (c)

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FEEDING AND WATER MANAGEMENT

The broodstock are normally fed either a natural, artificial or mixed diet (Azra and Ikhwanuddin, 2016). The natural diet includes fish, mussel meat, squid, bivalves and shrimps that are high in protein, essential fatty acids and other nutrients. These nutrients play a crucial role in the growth and maturation of mud crabs (Aaqillah-Amr *et al*., 2022). However, frozen and shucked blood cockles are preferred for feeding broodstock due to their high nutrient contents, ease of handling, and effectiveness in supporting successful production (Figure 6a) (Hajisamae *et al*., 2022). Feeding on a daily basis commences from the second day of stocking at 3–5 percent of body weight, in the evening, until crabs begin to bury themselves in the sand. Once the crabs start to bury themselves, the feed is reduced to approximately 1–2 percent of body weight as the crabs require less food. Uneaten food can adversely affect water quality. A few days before spawning, the crabs stop feeding as they prepare for spawning. After spawning, the crabs are transferred to the incubation or hatching tanks and fed with blood cockles at 1–2 percent of body weight.

At MCLC@PSU, the sea water is chlorinated (30 ppm) for 7 days, followed by the addition of sodium bicarbonate (200 g/m^3) before it is used in the broodstock tanks. Water salinity of 32–35 psu, pH of 7.5–8.5, alkalinity of 120–180 mg/L, dissolved oxygen of 4.7–5.6 mg/L, ammonia of < 0.25 mg/L, and a temperature of 27–29 °C are maintained. Continuous water circulation and aeration is provided in the tank system. Once the mud crab spawns, typically at night, it is transferred to an incubation tank the following morning. The sand substrate is removed from the spawning tank, cleaned with freshwater, then chlorinated and aerated for 7 days before it can be reused. The tank is cleaned with diluted detergent and freshwater before returning the cleaned sand substrate for the new batch of broodstock (Figure 6b and Figure 6c). Table 1 shows a general comparison between the broodstock management strategy applied in Viet Nam and the modifications applied in Thailand.

FIGURE 6
Mud crab broodstock feeding and water management
Blood cockles for broodstock feeding (a); water filters (b); and water filtration system (c)

TABLE 1
Broodstock management in Viet Nam and in Thailand

Characteristics	**Management**	
	Viet Nam	**Thailand**
Tank	100 L, composite or cement; recirculating or open	Housing or spawning tank: 117 L circular plastic tank; Incubating tank: 280 L circular plastic tank.
Substrate	Sand bottom	Sand bottom (diameter of sand particles 277.8 ± 35.7 μm).
Density	1 ind./tank of 100 L	1 ind./tank of 70 L.
Eyestalk ablation	Cutting or tying one eye stalk	Not performed.
Light	Darkness	0.2–5.0 lux for spawning tank and 100 lux in incubation tank during daytime, darkness at night.

TABLE 1 (CONTINUED)

Characteristics	Management	
	Viet Nam	Thailand
Water quality	Salinity 28–33 psu temperature 25–30 °C	Salinity 32–35 psu, pH 7.5–8.5, alkalinity 120–180 mg/L, dissolved oxygen 4.7–5.6 mg/L, ammonia < 0.25 mg/L, temperature 27–29 °C.
Water exchange	Recirculating or open system (100% daily)	Housing tank: recirculating system. Incubating tank: 50–70% daily.
Feeding	Fresh feed (mollusc, polycheate, marine fish, shrimp, at 5–10% body weight)	Housing tank: frozen-shucked blood cockle at 3–5% body weight; Incubating tank: frozen-shucked blood cockle at 1% body weight.
Culture duration	5–30 days after eyestalk ablation	5–40 days
Maximum duration of crab being housed	–	40 days
Incubation of berried crab	Individual culture, bottom without sand	Individual culture, bottom without sand.
Incubation period	9–12 days	9–12 days
Hatching rate	62.8–96.8%	80%
Fertilization rate	–	95%
Spawning rate	–	70%

Sources: Tran, N.H. 2017. Principles and techniques of mud crab farming. Ho Chi Minh City, Viet Nam, Nha Xuat Ban Nong Nghiep.

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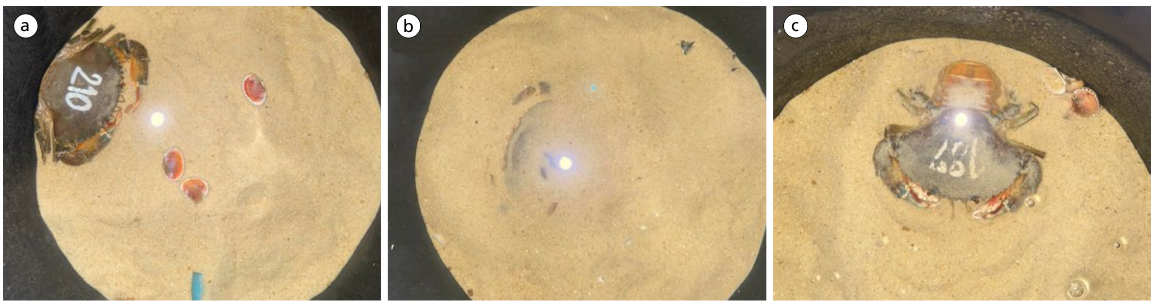
INCUBATION MANAGEMENT

When spawning is imminent, frequently indicated when a crab buries itself in the sand and does not eat for a few days, the incubation tanks need to be adequately prepared (Figure 7). Once a crab has spawned (eggs attached to the abdominal flap; a female is now referred as "berried"), it is then moved to the incubation tank until hatching, which occurs usually in 9–12 days. The duration of incubation period depends on water temperature, salinity and food availability. It has been observed that the incubation period is shorter when the water temperature is higher (Hajisamae *et al*., 2022).

Water is exchanged at a rate of 50–70 percent daily. Feeding with blood cockle is done daily at 1–2 percent of body weight. The egg mass is inspected regularly to determine egg development and to check for the presence of infections and parasitic infestations. Normally, development of fertilized eggs is clearly observed on day 5 of incubation. Formaldehyde (150 ppm) is used to soak the crab for 30 minutes on

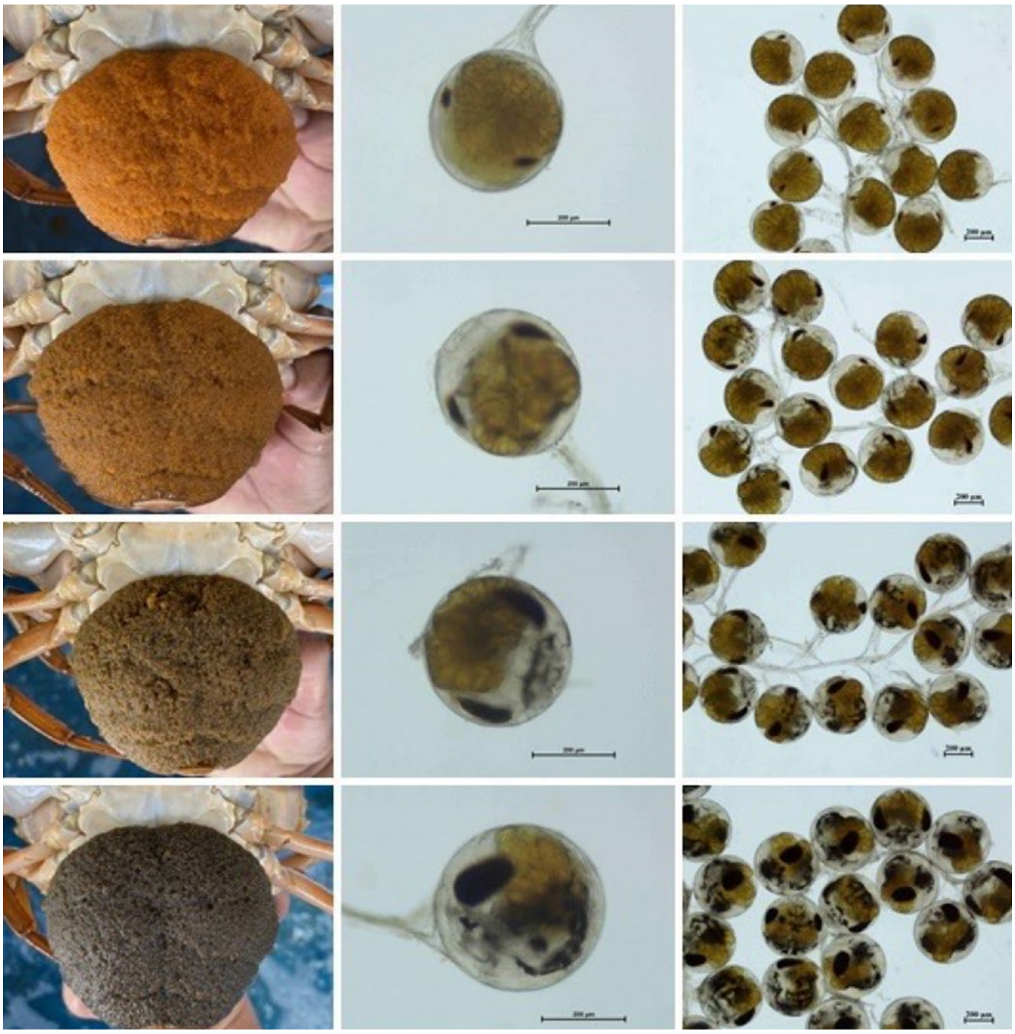
FIGURE 7
Broodstock behaviour during housing in the system
General behaviour of broodstock prior spawning (a); burrowing behaviour prior to spawning (b); and spawning (c)



days 3–5 of incubation after observing the development of eggs. Feeding is stopped on day 8–9 of the incubation period, when the egg mass has turned dark brown or grey and is ready to hatch. Regular food provision during the incubation period at MCLC@PSU is similar to the practice reported by Quinitio and Parado-Estepa (2008) but differs from those reported by Shelley and Lovatelli (2011) and Azra and Ikhwanuddin (2016) – who indicate that crabs do not require feeding during the incubation period.

After egg hatching, the zoeae are fed either umbrella stage *Artemia* or rotifers, and this live feed must be prepared based on the estimated date of hatching. Pre-hatching normally occurs at 20:00–21:00 and complete hatching happens in the early morning, usually between 04:00–06:00. Collection of zoeae is done after the eggs have fully hatched in the morning. The berried crab and its corresponding embryonic development stage are shown in Figure 8.

FIGURE 8
Spawned eggs of *S. paramamosain* and the corresponding embryonic development



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COST OF BROODSTOCK PRODUCTION

Chema *et al.* (2023) report an average production cost of USD 46/ind. for berried female of *S. paramamosain* at the Marine Crab Learning Centre, Prince of Songkla University, Thailand (Table 2). This total cost includes USD 29 allocated to fixed costs, such as infrastructure and equipment, and USD 17 to variable costs, which cover expenses like feed and maintenance (Chema *et al.*, 2023).

TABLE 2
Production cost for a single mud crab broodstock at the Mud Crab Learning Centre, Prince of Songkla University

Items	Cost/ind. (THB)	Cost/ind. (USD)
Fixed cost	1 028	29
Variable cost	598	17
Total cost	**1 626**	**46**

Source: Chema, N., Khongpuang, S. & Hajisamae, S. 2023. Cost-return analysis of a small-scale berried female mud crab (*Scylla paramamosain*) production using a water recirculation system. Technical Report. Pattani, Thailand, Prince of Songkla University.

PROBLEMS AND CHALLENGES

In the field of crustacean aquaculture, maintaining a high-quality broodstock supply is critical for reliable hatchery operations. However, the challenges associated with sourcing, managing, and optimizing broodstock quality pose significant obstacles. High-quality broodstock is essential to support the production of robust larvae, but issues such as limited supply, disease management, and optimizing nutrition and environmental conditions remain. To address these concerns, a combination of improved sourcing practices, biosecurity measures, nutritional advancements, and environmental controls is essential for advancing broodstock management and enhancing overall hatchery success.

- *Broodstock sourcing*: Currently, the primary source of high-quality broodstock remains limited to wild populations. While captive-propagated broodstock are available, they often lack the quality seen in their wild-sourced counterparts. This quality gap is attributed to the absence of selective breeding practices in pond-reared crabs, which would allow for the enhancement of beneficial heritable traits. Therefore, domestication of broodstock is crucial to consistently produce quality larvae that support hatchery operations.
- *Disease management*: Mortality and health issues in broodstock, often due to shell diseases, bacterial infections, viral pathogens and parasites, represent key challenges in broodstock management. To mitigate these issues, strict biosecurity protocols in broodstock facilities are essential to prevent disease outbreaks and ensure the overall health of the stock.
- *Nutritional requirements*: Broodstock production relies heavily on natural food sources that provide the necessary nutrients for embryonic and larval development. Feeding broodstock with highly nutritious, palatable, and easily handled foods that minimize water contamination can enhance broodstock performance. Such nutritional improvements can help reduce egg incubation time and increase both the quality and quantity of larvae produced.
- *Environmental management*: Maintaining optimal environmental conditions, particularly for spawning and egg incubation, is crucial for producing high-quality broodstock. Attention to factors such as water quality, temperature, and aeration can significantly influence broodstock health and reproductive success.

CONCLUSION

The current limited production of berried females in captivity reflects the inconsistent and insufficient production of mud crab seed, thereby impacting the development of the mud crab aquaculture industry worldwide. Several efforts in different countries have been conducted to achieve regular production of broodstock for all four mud crab species. Scientific and technological knowledge related to broodstock production is well-established, covering areas such as the design and management of broodstock housing systems, spawning and incubation tanks, and the use of sand substrates and specialized facilities. Moreover, careful consideration is required for water and food management, as well as light and temperature control. The selection of quality broodstock from different sources is crucial for the success of spawning, hatching, and providing quality seed. The successful development of broodstock production technology in Thailand could support the growth of mud crab supply chain aquaculture in many countries.

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Mud crab hatchery and nursery systems in Viet Nam

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ABSTRACT
The common mud crab species in Viet Nam are *Scylla paramamosain* and *Scylla olivacea*, found particularly in the Mekong Delta region. Mud crab production plays a significant role in the economy of the aquaculture industry in Viet Nam. Due to the lack of wild seedstock, several hatcheries were established in the country. The full cycle of hatchery operation includes broodstock management, spawning and hatching, larval rearing and nursery rearing. For larval rearing, tanks with a darker background with sufficient light source are utilized. Rotifers and *Artemia* are used as feeds for the zoeal stages. The duration of culture from zoea 1 to crab instar ranges from 23 to 30 days. Thereafter, the crab instars (crablets) are further reared in nursery tanks or shallow ponds until the size is desirable for transfer in grow-out ponds, where they are grown to adult size. A survival rate of 5–11 percent from zoea 1 to crab instar can be obtained. The major constraints in the hatchery operation of mud crab are the following: inconsistent broodstock quality, cannibalism, diseases, and lack of artificial feeds specifically formulated for mud crab. Although cannibalism can be somewhat managed by providing shelters and size grading of crabs, better strategies are needed. Research priorities need to focus on disease management that involves the prevention and control of the pathogens and alternatives to antibiotics. Likewise, the development of commercial diets for both broodstock and larvae as substitute to live feeds should be addressed.

INTRODUCTION
The common mud crab species in Viet Nam are *S. paramamosain* and *S. olivacea*. Mud crab breeding and culture in the country were initiated in the late 1990s. Crabs of various sizes, large enough to be sold, have been excessively harvested in all the fishing communities along the coast where the crabs are found. Due to the lack of wild seedstocks, hatcheries have been established particularly in the Mekong Delta region, mainly focusing on *S. paramamosain*. Shrimp hatcheries were converted to produce mud crab seeds as a full cycle operation or to alternately produce crab and shrimp based on demand. As of now, there are approximately 523 mud crab hatcheries in the Mekong Delta, some of which only operate seasonally. A single hatchery on average can produce annually between 700 000–10 000 000 crablets with a survival rate of 5–11 percent. Nurseries are operated to culture megalopae and crab instars to the juvenile stage in shallow and lined ponds or net cages within 2–3 weeks before stocking in grow-out ponds.

HATCHERY OPERATION
The size of the mud crab hatchery depends on the desired production and the financial capability of the investor (The Mangrove Crab Technical Committee 2018, 2021) (Figure 1). Areas for broodstock, hatching, larval rearing and live food culture need to be treated as separate units to minimize the risk of spreading potential pathogens as a biosecurity measure (Figure 2). Mud crab hatchery operation requires a relatively

high level of biosecurity to obtain consistently high larval survival and production of crablets for the nursery phase.

FIGURE 1
Mud crab hatchery rearing tanks (a) and circular hatchery tanks illuminated with LED light (b) in the Mekong Delta

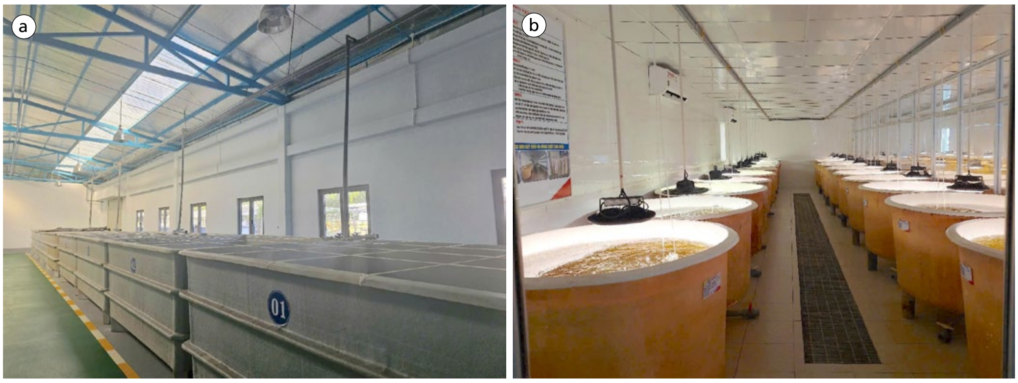

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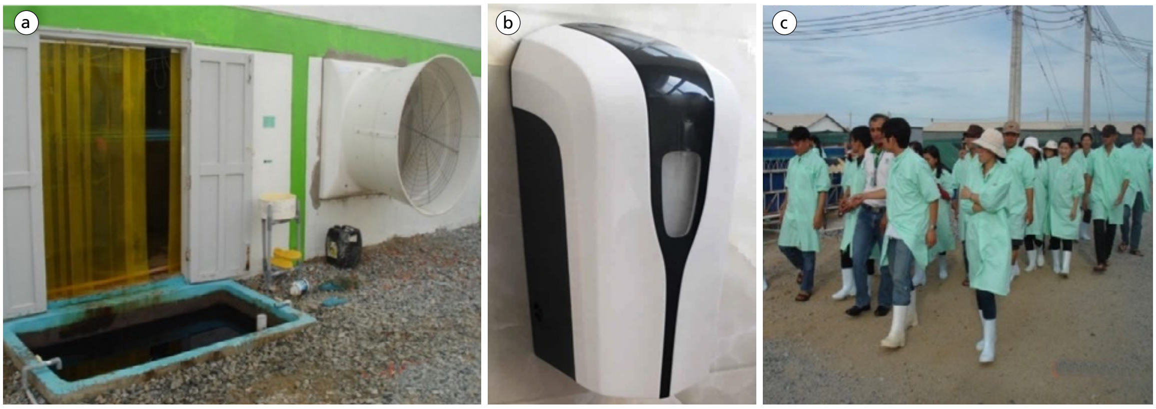
FIGURE 2
Biosecurity measures in the hatchery include foot baths (a), hand disinfection with alcohol (b), and technicians wearing proper attire (c)



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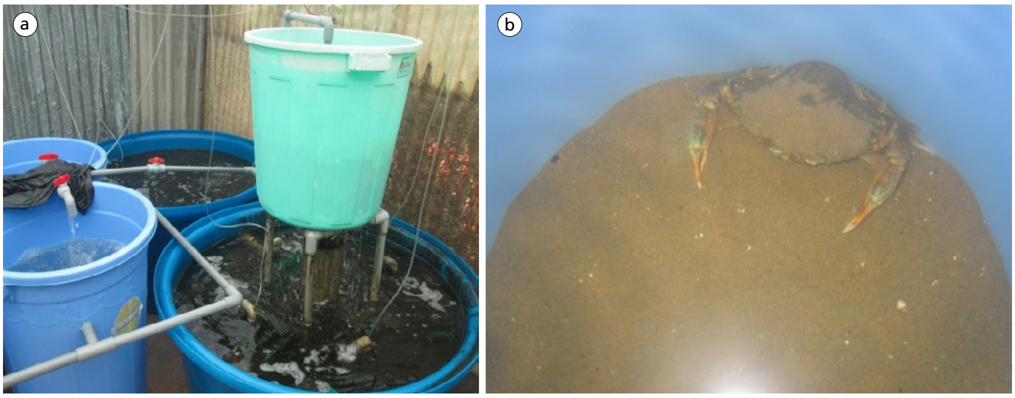
Broodstock culture

Mature female crabs with dark orange ovaries obtained from either brackish water ponds or mangrove forests are held in tanks until the eggs are spawned. Unilateral eyestalk ablation of immature females is sometimes performed to induce maturation. Ablation is carried out after the crabs have recovered from handling and transportation stress (usually 2–3 days).

Keeping crabs healthy in captivity is essential for successful larval production. Crab broodstock can be held together in large tanks (≥ 10 m^3 capacity; 80–100 cm height) at 1.5 ind./m^2, or individually in smaller containers for several weeks (Figure 3). It has been found that keeping crab broodstock in low light conditions appears to minimize stress levels, resulting in better reproductive performance (Shelley and Lovatelli, 2011). Therefore, crab broodstock are housed in facilities where light level is low, or the existing facilities use shading material to maintain a low light intensity. Water quality parameters are maintained within acceptable levels (temperature 25–30 °C, salinity 30 ppt, dissolved oxygen > 5 mg/L, alkalinity 80–120 mg $CaCO_3$/L. The inclusion of shelters in the tank provides refuge for the crabs and may minimize fighting among them. Female crabs require access to a sandy bottom in the tank to spawn their eggs

FIGURE 3

Recirculating unit of the rearing system (a) and broodstock tank filled with sand (b)



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successfully. Failure to provide sand will result in poor (often aborted) spawning, or low hatching rates.

Broodstock specimens are fed natural food such as bivalves (clam, blood cockle, etc.), fish, squid or marine worms, and are fed twice a day (usually at 07:00 and 17:00). The diet may be supplemented with artificial feed. Crabs are fed 2–8 percent of their body weight or until satiation. Uneaten feed and waste materials are regularly removed. Large volumes of water need to be exchanged regularly in order to maintain good water quality conditions in the tank.

Once spawning occurs (with the egg mass appearing under the abdominal flap, "berried"), the female crab is transferred to an incubation tank where the water quality and other environmental parameters are monitored and controlled. A single crab is placed in each hatching tank to allow for individual monitoring of larvae from each female (Figure 4). During the egg incubation period, the berried crabs are not fed to reduce waste and minimize water deterioration.

Some hatchery operators purchase berried crabs from nearby broodstock facilities instead of maintaining broodstock in their hatchery (Figure 5). These are stocked individually in buckets or small tanks with clean seawater and aeration until their eggs hatch.

Larval rearing

Hatchery tanks made of concrete, fiberglass, or marine plywood lined with high density plastic or canvas material are used (Figure 6). Rearing tanks can vary in design, including circular tanks with conical bases, hemispherical and/or rectangular. The internal

FIGURE 4

Berried female (b) stocked individually in a container with clean seawater and aeration (b)

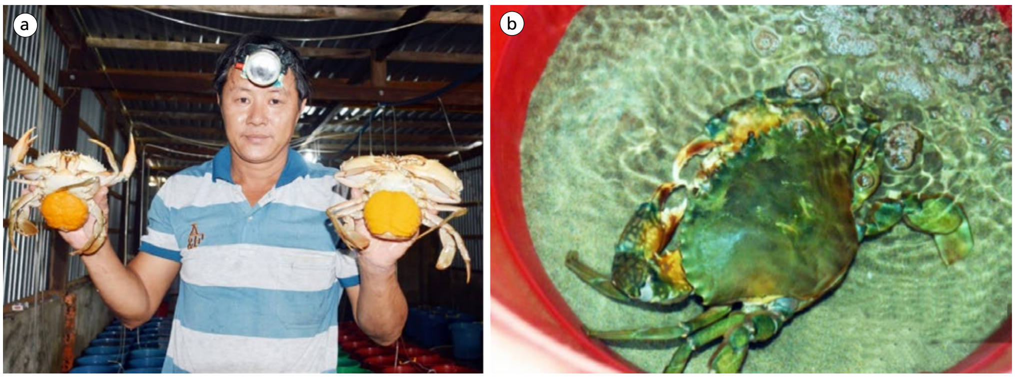

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FIGURE 5

A berried crab from a broodstock rearing facility sold to hatchery operators

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colour of rearing tanks is a key factor influencing larval performance and has been shown to significantly impact survival rates. Larvae grown in black tanks or with a darker background have higher survival rates than other colours (blue, red and orange) (Alimuddin *et al.*, 2019).

The rearing of crab larvae requires sufficient light, but direct strong sunlight should be avoided. Improved survival is generally achieved with a 12–hour light/dark cycle; natural light is the primary light source for the larval rearing area. Recently, the application of LED bulbs has been observed to increase larval activity (such as moulting rate and food intake) (Figure 7), with Khoa *et al.* (2023) reporting a 20–30 percent improvement in larval survival.

FIGURE 6

Hatchery tanks made of concrete (a), fiberglass (b), marine plywood lined with high density plastic (c) and canvas material (d)

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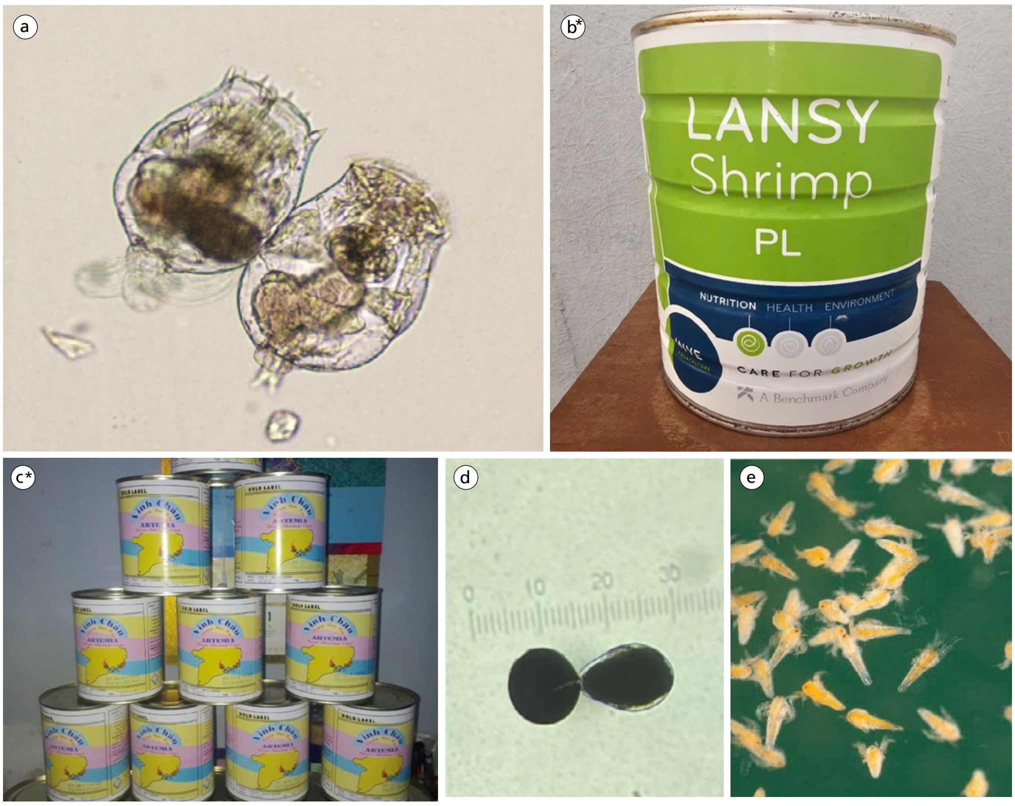
Rotifers and *Artemia* are both fed to the crab larvae at different densities (Figure 8). The rotifer density in the rearing tanks is maintained at approximately 20 ind./ml (Table 1). Umbrella stage *Artemia* are given from zoea 1 to 2 alone or in addition to rotifers. Newly hatched *Artemia* are fed to zoea 3–4 at 1–2 ind./ml, while *Artemia* biomass is fed to zoea 5 and megalopa. When available, minced *Acetes* are given to later-stage megalopae. Formulated feed developed for shrimp larvae is also fed to

FIGURE 7
Experimental setup using LED bulbs in crab larval rearing

FIGURE 8
Rotifers (a), shrimp formulated diet* (b), and *Artemia (cysts in can [c]; umbrella stage [d]; newly hatched [e]), serve as feed for mud crab larvae**



* The products shown are not preferred or endorsed over other similar products available on the market.

crab larvae. Prebiotics and probiotics are sometimes utilized to enhance the health conditions of the larvae. Recent studies have shown that probiotics can also improve growth and digestion, enhance immune responses and help control diseases in mud crab larvae (Khoa, 2018).

Microalgae are added to larval rearing tanks at 0.5–5.0 × 10^4 cells/ml as feed for the rotifers. Microalgae are also considered as a water conditioner. The microalgae used in crab larval rearing include *Tetraselmis* spp. and *Nannochloropsis* spp.

TABLE 1
Summary of mud crab larval rearing protocol

Larval density	Protocol 1: 100–150 zoea 1/L Protocol 2: 200–300 zoea 1/L; 25–50 zoea 5/L Protocol 3: 200–300 zoea 1/L; 100–150 zoea 4/L; 25–50 megalopa/L
Larval stage	Feeds and feeding:
Zoea 1–2	Rotifers: 20 ind./ml + algae 0.5–5.0 × 10^4 cells/ml Umbrella stage *Artemia* 1–2 ind./ml (every 3 hours) alone or with rotifers
Zoea 3–4	Newly hatched *Artemia* 1–2 ind./ml (every 6 hours) Artificial feed 1–2 g/m^3 (every 6 hours) with or without algae
Zoea 5–megalopa	Enriched *Artemia* 1–3 ind./ml (every 6 hours) Artificial feed 2–3 g/m^3 (every 6 hours)
Megalopa to crablet instar	*Artemia* biomass, *Acetes* or trash fish (until satiation, 06:00 and 16:00) Artificial feed 2–5 g/m^3 (every 6 hours)
Water quality	25–30 °C; 25–33 ppt; 7.5–8.5 pH; < 1 ppm NH_4; < 0.1 ppm NO_2; > 100 ppm alkalinity
Light	5 000–8 000 lux, 12-hour light/dark cycle
Substrate	Nylon nets (mesh size ~1 cm) or netting bundles placed in the tank starting from late megalopa stage (benthic stage)
Water exchange	Rearing water replaced at 30% daily from day-3, up to 80% as larvae mature
Culture duration	23–30 days
Survival rate	5–11% from zoea 1 to crab instar 1 (at zoea 1 stocking density of 300 ind./L)

The quality of *Artemia* has been found to affect larval survival. Hence, *Artemia* enrichment products are used to maximize their nutritional value. *Artemia* enriched with high doses of vitamin C, docosahexaenoic acid and taurine have been reported to improve metamorphosis from zoea 5 to megalopa and from megalopa to crab instar. Residual rotifers and *Artemia* usually become nutritionally deficient after 24 hours and may start to die. If the density of residual live feeds increases, it is necessary to remove a substantial proportion of these before adding subsequent feeds.

The rearing water is replaced at 30 percent daily from day-3 and up to 80 percent as larvae mature and when levels of luminescent bacteria are high. Aeration is provided throughout the rearing period. Shelters such as nylon nets or netting bundles are placed in the tanks starting from the late megalopa stage. Since megalopae are cannibalistic, these must be eventually transferred to large tanks or ponds provided with suitable shelters.

NURSERY OPERATION

The surface area of the rearing tank is important once the megalopae have settled and metamorphosed into crab instar (crablet) stage. Common tank designs for culturing crablets include rectangular concrete tanks with flat bottoms that slope towards a sump pit for water drainage, shallow ponds lined with plastic material and equipped with drain pipes, and net cages placed in ponds (Figure 9). These are provided with freshwater and seawater supply pipes as well as aeration lines.

Nursery tanks or ponds are often exposed to the elements, which can cause the temperature of the rearing water to rise, particularly during the summer months. This increase in temperature can lead to high crablet mortality. To mitigate this, nursery systems are typically covered with an overhead awning or roof to shield the rearing facilities from direct sunlight and rain. Additionally, abrupt changes in salinity due to heavy rainfall can stress the crablets, potentially resulting in mortality.

Various materials can be placed or suspended in nursery tanks to provide three-dimensional shelters, increasing the surface area available for benthic crablets. Suitable materials include netting bundles, leaf fronds or straw, and cut PVC pipes (Figure 10).

FIGURE 9
Concrete tanks (a), shallow lined ponds (b), net cages (c), and composite tanks used for rearing crablets during the nursery phase (d)

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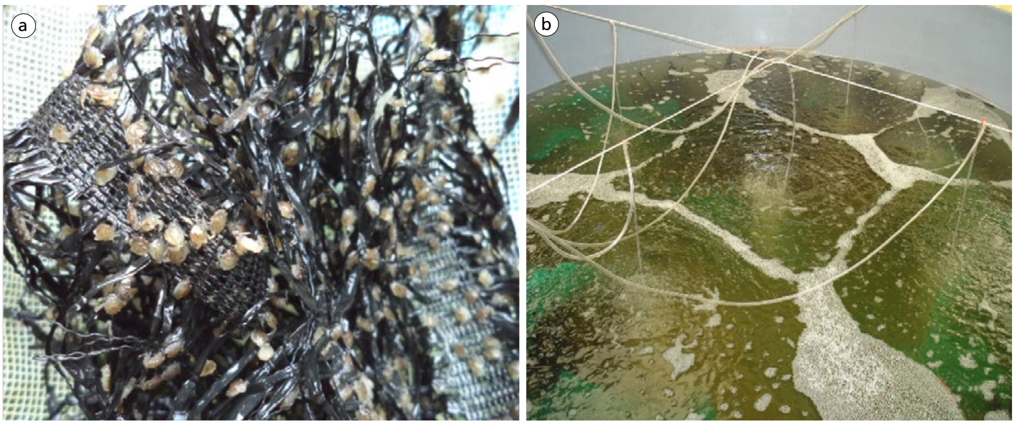
FIGURE 10
Netting material used as shelter for crablets (a) visible at the bottom of the nursery tank (b)



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These materials create additional surfaces for crablets to inhabit, promoting their growth and survival.

Megalopae and crablets are commonly fed with trash fish, *Acetes* and shrimp pellet until satiation.

DISEASE MANAGEMENT

Mass mortality in crab larvae is primarily attributed to bacterial infections, which has led to an over reliance on antibiotics such as oxytetracycline (OTC) to mitigate the risks of batch rearing failure. However, the widespread use of antibiotics is discouraged and often prohibited in many countries due to concerns about its broader impacts. Fungal infections, caused by species such as *Lagenidium*, *Sirolpidium*, *Haliphthoros*, and *Atkinsiella*, can also contribute to mortality during larval rearing, requiring distinct treatment strategies. The greatest concern with the unregulated use of veterinary drugs is the development of antibiotic-resistant bacteria in the hatchery, which can also pose a risk of resistance spreading to other animals and even humans.

Bacteria

Pathogenic *Vibrio* spp. are major contributors to diseases in farmed aquatic organisms. The zoea stage is particularly susceptible to luminous bacteria, with several species playing a significant role in disease outbreaks. *V. harveyi*, along with *V. alginolyticus* and *V. parahaemolyticus*, have been isolated and tested for their pathogenicity to zoea. Additionally, *Vibrio* spp. have been implicated in shell disease in captive crab broodstock. This condition arises from a combination of chitinoclastic bacteria and fouling organisms, which together exacerbate the disease (Figure 11) (Tendencia *et al*., 2017; Jithendran *et al*., 2010; Faizah *et al*., 2016).

FIGURE 11
Crab broodstock with shell disease

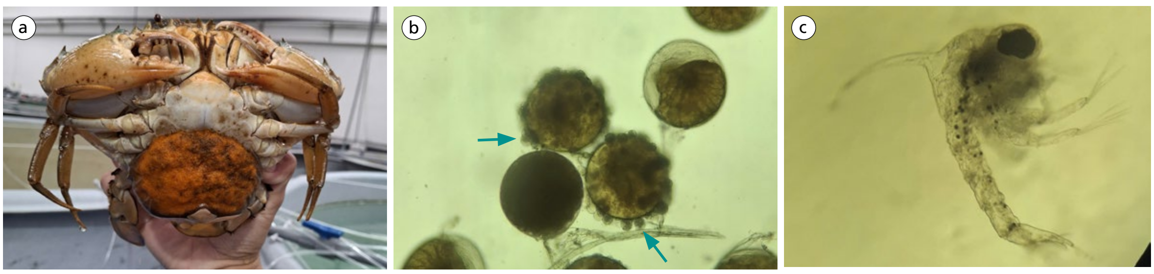
Viruses

White Spot Syndrome Virus (WSSV) infection is characterized by rapid onset of disease, with up to 90 percent of the stock becoming infected within 2 to 7 days. WSSV can be transmitted to crabs through vertical transmission from wild broodstock or horizontal transmission in monoculture systems. Additionally, crabs can become infected through feeding on or when reared with WSSV-infected shrimp (Jithendran *et al*., 2010; Faizah *et al*., 2016).

Fungi

A number of fungi species including *Lagenidium scylla*, *Haliphthoros philippinicus* and *Atkinsiella fluminensis,* have been frequently observed to infect the eggs, larvae and ovaries of mud crab (Figure 12) (Jithendran *et al*., 2010; Faizah *et al*., 2016). Eggs may detach from berried females during the incubation period, leading to partial hatching or complete loss of the egg mass. *Haliphthoros* spp. cause abortion and resorption of eggs,

FIGURE 12
Mud crab egg mass (a), eggs (b) and zoea (c) infected with the fungus *Lagenidium*. Developing zoospores are visible in figure (b) (arrows)

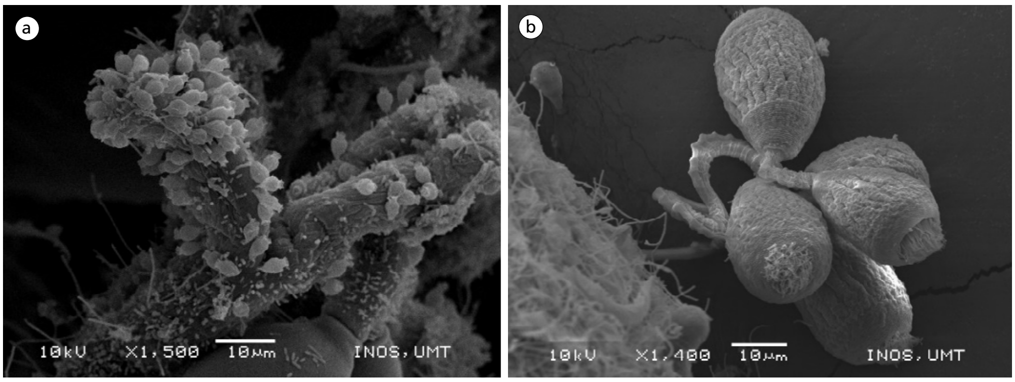


while larvae are highly susceptible to infections from the non-host-specific pathogen *Lagenidium* spp., leading to significant mortality. To minimize the risk of infection, bath treatments with formalin and fungicides are commonly administered.

Parasites

Protozoa such as the stalked peritrich ciliates, *Epistylis* sp., *Zoothamnium* sp., and suctorian ciliates, *Acineta* sp. and *Lagenophry* sp., have been observed to attach to the shell and gills of the crabs (Figure 13) (Faizah *et al.*, 2016). *Zoothamnium* infestations on the eggs of berried females, particularly those collected from brackish water areas, are typically linked to water rich in organic matter and other nutrients (Figure 13). These infestations can have negative effects, as *Zoothamnium* can impair egg development, reduce hatching success, and increase the risk of disease transmission. Additionally, the presence of *Zoothamnium* may indicate poor water quality, further exacerbating stress on the broodstock and potentially leading to higher mortality rates in the larvae.

FIGURE 13
Electron microscopy of *Zoothamnium* sp. colonizing the mud crab larvae (a) and a close-up view (b)



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Abnormalities and deformities

In hatchery settings, delays or failure to moult from zoea 5 to megalopa can result in several negative consequences, including abnormal swimming behaviour and the inability to consume food, which significantly impairs the larvae's survival and development (Faizah *et al.*, 2016). Such delays or failures in moulting are often attributed to unsuitable environmental conditions, such as suboptimal water temperature, salinity, or oxygen levels, as well as nutrient deficiencies. Inadequate levels of essential nutrients, particularly in the larval diet, can hinder physiological processes necessary for moulting, leading to developmental abnormalities and increased vulnerability to stress and disease. Ensuring optimal environmental conditions and a balanced, nutrient-rich diet are crucial to support proper larval development and successful metamorphosis.

CONSTRAINTS

The major challenges in the hatchery operation of mud crabs include inconsistent broodstock quality, cannibalism, diseases, and the lack of commercially available formulated feeds specifically designed for mud crabs. While cannibalism can be managed through the provision of shelters and size grading, more effective strategies are needed. Research efforts should prioritize disease management, focusing on the prevention and control of pathogens as well as the development of alternatives to antibiotics. Additionally, the development of commercial diets for both broodstock and larvae, as a viable substitute for live feeds, is a critical area for improvement.

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Hatchery and nursery systems: Philippines, India and Bangladesh

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ABSTRACT

In the Philippines, India and Bangladesh, the basic techniques used in the hatchery and nursery of mud or mangrove crabs are almost similar and vary in some degree. The techniques are not absolute and depend on the conditions in each country. Philippines and India use ovigerous *Scylla serrata* sourced directly from the ponds, trading centres and sometimes from the wild, while Bangladesh obtains berried crabs only from the wild. Upon arrival in the hatchery, crabs are subjected to conditioning, formalin bath and screening for viruses and other pathogens. They are held in quarantine and later stocked in broodstock tanks when negative for viruses and other pathogens. In Bangladesh, the berried crabs are subjected to formalin bath and held in aerated buckets until their eggs hatch.

Newly hatched zoeae are collected immediately and rinsed with low dose formalin or just with disinfected flowing seawater. Zoeae are stocked at a density of 80–100 ind./L in the Philippines and Bangladesh, and 70–80 ind./L in India. Rotifers and *Artemia* are commonly utilized live food for crab larvae. However, newly hatched zoeae are fed umbrella stage *Artemia* or newly hatched small-sized strain *Artemia* if rotifers are insufficient. Commercially available shrimp formulated diets are also fed to zoeae. Application of prophylaxis is done to prevent bacterial and fungal infections and protozoan infestation in larvae. The frequency and volume of water to be changed depends on the water condition in the tank.

The nursery phase has been established in the Philippines using net cages installed in brackish water ponds to grow the megalopae or crab instars or utilizing small ponds where crab instars are directly stocked. In India, the nursery phase is done in brackish water ponds or creeks, and net cages in ponds. Megalopae or crab instars are fed either *Artemia* biomass or finely chopped trash fish and molluscs. At present, there is no nursery system established in Bangladesh since commercial production of crab instars has not been achieved.

INTRODUCTION

Hatchery is the first phase in the culture of crab and has an important part in meeting the increasing seedstock requirements for farming. Nursery is the transitional phase which links the hatchery to pond grow-out culture. In the Philippines, both the hatchery and nursery technologies developed were based on the research and development conducted starting in the mid-1990s and continuously refined to become more economically viable. There are many techniques applied in both hatchery and nursery systems. Philippines, India and Bangladesh have some similar basic techniques but vary in some degree. These techniques are not absolute and depend on the conditions (availability and types of materials, technical capability of staff, design or layout of existing hatchery, etc.) in each country.

PHILIPPINES

Seawater source

Prefiltered or raw seawater from the nearby sea is pumped and passed through settling tank or directly to a rapid mechanical sand filter or sand filter tank and stored in the reservoir. Seawater is treated with chlorine and neutralized either with sodium thiosulfate or strong aeration for several hours. Some hatchery owners use filtered seawater that is treated with ultraviolet light or ozone prior to use in the hatchery.

FIGURE 1
Determination of ovarian maturity by pressing the first abdominal segment underneath the carapace

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Broodstock management

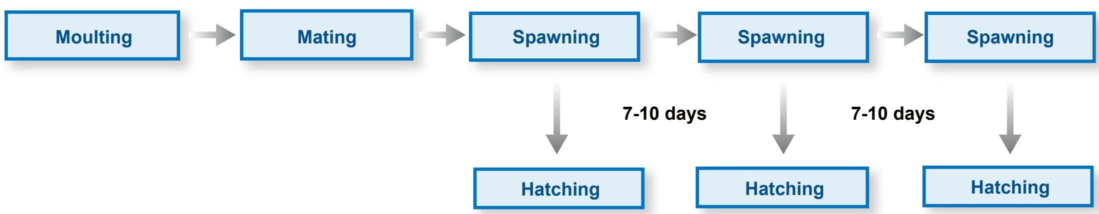
Although three species of mud crab have been cultured in captivity, *S. serrata* is the species preferred by crab growers. *S. serrata* broodstock is commonly sourced from the wild, trading centres or directly from commercial ponds. Healthy adult crabs at an advanced stage of ovarian maturity (orange to dark orange ovaries) and with no missing limbs are selected. The condition of the ovary is assessed by depressing the first abdominal segment underneath the carapace (Figure 1) or by using a strong light focused on the ventral side of the carapace. The ovary is full when the light does not penetrate through the anterior part of the carapace. Adult crabs from brackish water ponds contain higher lipids than those sourced from the wild perhaps since food is always available during culture while wild crabs constantly search for food (Alava *et al*., 2007). Lipids play important roles in the biochemistry, metabolism and reproduction of decapod crustaceans. Furthermore, the newly spawned eggs of pond-reared crabs contain n-3 highly unsaturated fatty acids as well as n-3 and n-6 fatty acids that were found to be significantly higher than those of wild-sourced crabs. Hence, the hatchery operators often utilise pond-reared crabs for hatchery use.

Female crabs with maturing or fully mature ovaries are usually obtained to reduce the latency period from maturation to spawning (Quinitio, De Pedro & Estepa, 2007). It is difficult to determine whether a particular female has been mated through external examination. Hence, several females per batch are obtained to have a higher possibility that mated females will give viable eggs. Pond-reared crabs have also been observed to have more mated females than those sourced from the wild.

Screening for viruses (white spot syndrome virus or WSSV, acute hepatopancreatic necrosis disease, etc.) and other pathogens is done by taking samples of leg muscle tissues after acclimation in the hatchery. Crabs are then disinfected through a 30-minute formalin bath. Crabs are maintained in separate quarantine tanks. If crabs test negative in the screening, they are transferred to maturation tanks that range from 5–10 tonnes in size and provided with sand substrate, aeration and shelters. They are stocked at 1–2 ind./m^2. Disinfected seawater of 30–34 ppt is used for maturation and spawning of *S. serrata*. Crabs are fed at 3–5 percent of their body weight per day or on an *ad libitum* basis. Fish, molluscs (mussel, oyster, snail or clam), squid, and marine or brackish water polychaetes are fed to crabs alternately. Food items are washed well with freshwater prior to feeding. Live marine or brackish water worms are depurated and disinfected prior to feeding as these can be a vector for WSSV (Vijayan *et al*., 2005). Formulated pelleted feeds, whenever available, are sometimes provided in combination with the natural food. About 50 percent of the seawater is changed 3–4 times per week in a static system. In a water recirculating system, more than 100 percent of the seawater is recirculated daily.

Although crabs are not difficult to breed, an eyestalk is sometimes ablated in a crab with immature and maturing ovary to induce maturation and spawning. Crabs can spawn up to three times from a single mating. Re-maturation takes place about one month after spawning. In *S. serrata*, second spawning occurs typically 41–46 days after the first spawning while the third spawning occurs 34 days after the second spawning (Quinitio *et al*., 2011). However, there is usually a decrease in the number of zoeae in repeat spawning. The interval from spawning to hatching ranges from 7–10 days (Figure 2).

FIGURE 2
Interval from one spawning to subsequent spawnings in *Scylla serrata*



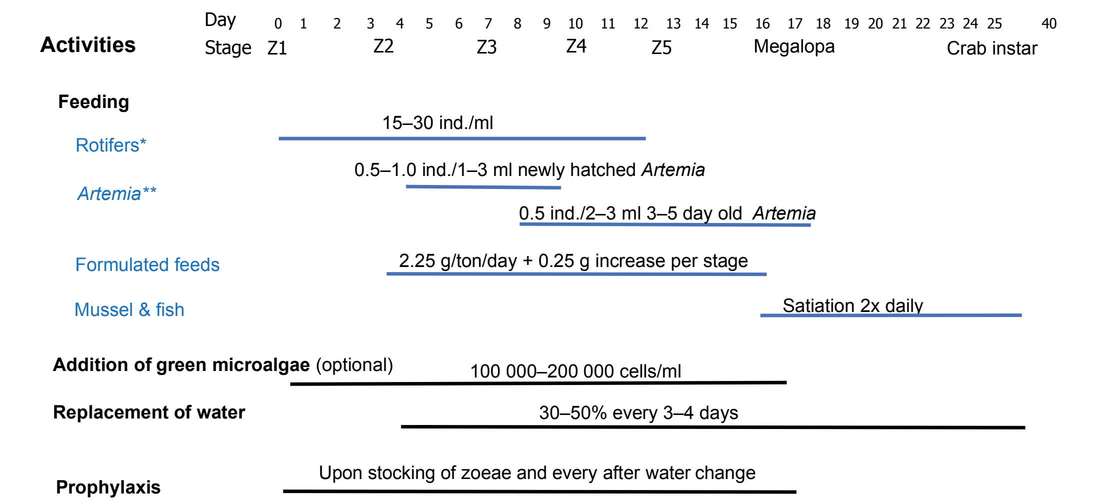
Ovigerous crabs (females carrying eggs attached to the abdominal flap) are retrieved from the tank and disinfected with 150 ppm formalin prior to stocking individually in 500 L incubation or spawning tanks with aerated seawater. Detached eggs, faeces, and excess feeds are siphoned out daily prior to water change of 50–80 percent. Feeding is discontinued when the egg mass starts to turn brown or light grey. After hatching, the quality of the zoeae may be determined by exposing them to 40 ppm formalin (37 percent formaldehyde was considered as 100 percent in the computation) for 3 hours. If mortality of a certain batch of mud crab zoea 1 is only within 0–18 percent in 3 hours, then it is worth rearing the larvae as it is a good quality batch. If the mortality is > 38 percent, then it is of poor quality and may be terminated as early as zoea 1 (Quinitio, dela Cruz & Parado-Estepa, 2018).

An ongoing study is being done to enhance broodstock performance by providing them with suitable diet (polychaetes and molluscs) and optimum water temperature in recirculating aquaculture system with polychaete-assisted sand biofilters.

Larval rearing

The newly hatched zoeae are collected immediately, rinsed with low dose formalin and stocked at 80–100 ind./L in tanks. Rotifers and *Artemia* are commonly utilized natural food for crab larvae. Figure 3 shows the feeding and water management of mangrove crab in the hatchery. Rotifers are fed immediately to newly-hatched zoeae. Rotifers are used as these are small and easy to propagate. Survival is more consistent than feeding them with *Artemia* alone at the beginning of zoea 1 as observed in *S. serrata*. The density of rotifers maintained in the larval tanks is 15–30 ind./L. However, if rotifers are insufficient, larvae are fed umbrella stage *Artemia* or newly hatched small-sized strain *Artemia*. It is laborious to maintain both the green microalgae and rotifer culture

FIGURE 3
Feeding and water management of mangrove crab in a mud crab hatchery



* If not available, rotifers can be substituted with umbrella stage or small-strain *Artemia* nauplii.
** *Artemia* can be enriched with highly unsaturated fatty acid emulsion.

but when algal concentrate or paste is available for feeding the rotifers, the culture of green microalgae in the hatchery is reduced. There are now two companies producing the algal concentrates in the Philippines (Figure 4). There are several commercially available formulated shrimp diets with various levels of highly unsaturated fatty acids and other essential nutrients that are also used to feed crab zoeae. *Artemia* that are 3–4 days old (enriched with algae) are fed to later stage of zoea 4 until early megalopa stage. Older megalopae and crab instars are fed minced fish and mussel. Green microalgae are sometimes added in the larval rearing tank to improve the water quality and serve as shading. Moderate aeration is provided.

Treated seawater (chlorinated then neutralized and ultraviolet or ozone-treated seawater) is used in the entire larval rearing. Application of prophylaxis is practised to prevent the occurrence of bacterial and fungal infections, as well as protozoan infestation in larvae. The frequency and volume of water to be changed depends on the water condition in the tank. Suitable ranges of water parameters are shown in Table 1. Late zoea 4 or early zoea 5 are transferred to other tanks with new seawater and maintained until early crab instar stage. Survival rate ranges from 3–12 percent.

FIGURE 4
Green microalgae, *Nannochlorum*, algal concentrate for feeding rotifers. The rotifers are fed to early zoea stage

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Nursery

The nursery phase of mangrove crab has been developed as a link to the hatchery and the grow-out phase. Megalopa or crab instar (or crablet) stage, both products of the hatchery, are further grown to juvenile stage which are less vulnerable to fluctuating conditions of the pond during grow-out. Further rearing is done in net cages that are placed inside the brackish water earth ponds. In some areas in the country, the megalopae are sometimes collected from the wild and stocked in the pond for several weeks until the size is suitable for pond stocking and grow-out. Crablets (< 1.5 cm carapace width [CW]) are also collected and sold to nursery operators.

TABLE 1
Suitable ranges of water parameters for mangrove crab larviculture

Parameter	Range
Temperature	27–30 °C
Salinity	28–32 ppt
Dissolved oxygen	≥ 5 ppm
pH	7.5–8.5
Unionized ammonia	≤ 1 ppm
Nitrite	≤ 0.1 ppm

Source: The Mangrove Crab Technical Committee 2018, 2021. *The Philippines recommends for mangrove crab*. Los Banos, Philippines, DOST-PCAARRD.

Before transferring megalopae or crab instars into the ponds, unwanted species that may compete with or harm the crabs are eliminated by drying and treating the pond water with organic (tobacco waste, derris roots, or teaseed cake) or inorganic (ammonium sulphate with lime or other combinations) pesticides. Fertilization of the pond water is done to grow the natural food. Net fences are placed on the dykes or at the base of the dykes to prevent the entry of other crab species (The Mangrove Crab Technical Committee 2018, 2021). This is part of pond preparation which also includes steps to ensure good water and soil conditions to enhance survival and growth.

Poles with net shades as roofing are placed in the ponds so that cages can be tied to them (Figure 5). The net shade lessens the intensity of the heat especially during extremely hot days. Net cages with about 1 mm mesh are installed inside the pond. There must be at least 1 m of space between cages to allow good water circulation. Cages range from 12–20 m^2 in size. Stocking density is about 200 megalopae/m^2 or up to 50 crab instars/m^2 of cage area (Parado-Estepa *et al*., 2015). Megalopae or crab

FIGURE 5
Net cages installed in brackish water earth pond for growing megalopae and/or crab instars

instars are reared for 2–4 weeks but sorting according to size is done either on the second or third week if crabs are not disposed immediately (The Mangrove Crab Technical Committee 2018, 2021).

Crabs, like all crustaceans, need to moult before they can develop further and grow. The newly moulted crab is very soft and unable to eat thus, is weak and easily becomes prey to hard-shelled crabs. Shelters are provided as refuge or hiding area. Several types of shelters have been tried, but nets consistently appear to be effective. Nets have increased surface area which makes them convenient for the crabs to seek shelter. Crabs are fed with either low-value fish, mussel or other mollusc meat, formulated diet (pellets), or a combination of these. Fish and mollusc meat are chopped then washed with clean water before given to the crabs. Feeding is done 2–3 times daily, during the early morning and night or with another feeding in between. When crabs are less than 2 cm CW, they are fed at 100 percent of the total weight of the stock inside a particular net cage and at 80 percent when they are bigger (Parado-Estepa *et al.*, 2015; Alava, Sumily and Parado-Estepa, 2017). A feeding tray is placed in each cage to monitor the feeding consumption.

Megalopae and crab instars are harvested after 2–3 weeks. Crabs that attain 2.0–2.5 cm CW are sold to farmers. However, farmers may opt for bigger sized crabs (3–4 cm CW). Thus, those produced after 2–3 weeks are harvested and sorted according to size then stocked in the same net cages at a lower density of 5–10 ind./m^2. After another 2 weeks the crabs attain the desired 3–4 cm size. Crabs are easily retrieved in net cages.

Problems encountered

The major problems encountered during the hatchery and nursery rearing include the following:

- Inconsistent quality of broodstock.
- Inadequate supply of good quality seedstock for farming in grow-out ponds and for soft-shell crab production.
- Bacterial (e.g. *Vibrio*, *Leucothrix*, *Pseudomonas*, *Aeromonas*) and fungal (e.g. *Lagenidium*, *Sirolpidium*, *Haliphthoros*) infections and ciliates (e.g. *Zoothamnium*, *Epistylis*, *Vorticella)* infestations are some of the common causes of mortality in eggs and larvae.
- High mortality at zoea 5 to megalopa and megalopa approaching the crab instar stage.
- Cannibalism especially during the nursery phase when crabs frequently moult.

INDIA

Most of the technology described here is based on the practices developed by the Rajiv Gandhi Centre for Aquaculture (RGCA), a research arm of the Marine Products Export Development Authority (MPEDA). Mangrove crab hatchery was established in 2004 after two RGCA technicians underwent training at the Aquaculture Department (AQD) of the Southeast Asian Fisheries Development Center (SEAFDEC). This was followed by an on-site training on the actual larval rearing conducted at RGCA hatchery which lasted one complete rearing cycle. Crablets were produced and the survival rate gradually increased over the succeeding cycles. Thereafter, nursery and grow-out phases were established. The technology was improved through the years adopting to the conditions in India. The first large-scale mangrove crab hatchery was established by RGCA in Thoduvai, Tamil Nadu in 2013 (Figure 6). RGCA was granted the patent in 2011 by the Controller General of Patent, Design and Trademarks, India (Figure 7). The patent, an impressive milestone in India's aquaculture sector, is valid until 2030.

FIGURE 6
Mangrove crab hatchery of Rajiv Gandhi Centre for Aquaculture in Thoduvai, Tamil Nadu, India

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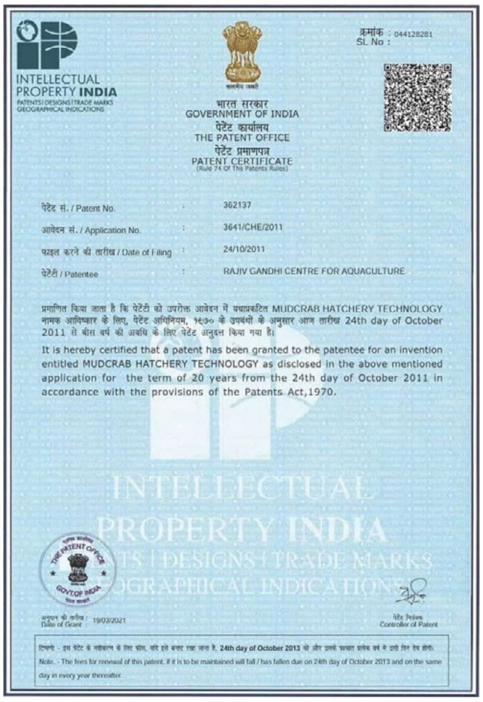
FIGURE 7
Patent certificate awarded to the Rajiv Gandhi Centre for Aquaculture for its mud crab hatchery technology



INTELLECTUAL PROPERTY **INDIA**
PATENTS | DESIGNS | TRADE MARKS
GEOGRAPHICAL INDICATIONS

क्रमांक : 044128281
SL No :

भारत सरकार
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THE PATENT OFFICE
पेटेंट प्रमाणपत्र
PATENT CERTIFICATE
(Rule 74 Of The Patents Rules)

पेटेंट सं. / Patent No.	:	362137
आवेदन सं. / Application No.	:	3641/CHE/2011
फाइल करने की तारीख / Date of Filing	:	24/10/2011
पेटेंटी / Patentee	:	RAJIV GANDHI CENTRE FOR AQUACULTURE

प्रमाणित किया जाता है कि पेटेंटी को उपरोक्त आवेदन में यथाप्रकटित MUDCRAB HATCHERY TECHNOLOGY नामक आविष्कार के लिए, पेटेंट अधिनियम, १९७० के उपबंधों के अनुसार आज तारीख 24th day of October 2011 से बीस वर्ष की अवधि के लिए पेटेंट अनुदत्त किया गया है।

It is hereby certified that a patent has been granted to the patentee for an invention entitled MUDCRAB HATCHERY TECHNOLOGY as disclosed in the above mentioned application for the term of 20 years from the 24th day of October 2011 in accordance with the provisions of the Patents Act,1970.

THE PATENT OFFICE
GOVT.OF INDIA

Date of Grant : 19/03/2021

Controller of Patent

Note. - The fees for renewal of this patent, if it is to be maintained will fall / has fallen due on 24th day of October 2013 and on the same day in every year thereafter.

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Seawater source

The seawater for the hatchery pumped from the sea is passed through the rapid sand filter after which the water is treated with ozone. The seawater is stored in an overhead tank and is further disinfected using ultraviolet light prior to use.

Broodstock management

Active hard-shelled and mature female crabs (500–800 g; 13–14 cm CW) are sourced from Tuticorin, Kodiyakarai (Vedaranyam), Palayar, Killai (Pitchavaram) and Pamban, Tamil Nadu. The mature crabs are normally transported in woven gunny bags, bamboo baskets, cardboard or thermocol boxes with holes to allow sufficient ventilation. During transport, the crabs are covered with mangrove leaves or cloth moistened with seawater.

Upon arrival in the hatchery, the crabs are subjected to conditioning, a formalin bath and screening prior to stocking in the broodstock holding facility. The crabs are transferred into 20 L basins and fresh seawater is added every 5 minutes for about 30 minutes. Crabs are then treated with 150 ppm formalin for 30 minutes. Crabs are untied and kept in quarantine tanks until these are screened for the presence of mud crab reovirus (MCRV) and white spot syndrome virus (WSSV). Specimens that test negative for MCRV and WSSV are transferred to the broodstock tanks for maturation and spawning.

Broodstock are housed in 10-tonne holding tanks provided with a layer of washed medium coarse sand (5–10 cm thickness) at a stocking density of 1 ind./m^2. The tank

TABLE 2
Ranges of water parameters maintained for crab broodstock

Parameter	Range
Temperature	30 ± 2 °C
Salinity	31 ± 4 ppt
Dissolved oxygen	> 4 ppm
pH	8.0 ± 0.5
Unionized ammonia	Nil

is filled with filtered seawater with a depth of 80–100 cm and provided with constant aeration. PVC pipes of 6-inch diameter are provided as hideouts. The sand bottom is cleaned every fortnight to remove accumulated organic wastes. The crabs are fed with squid, trash fish, mussel and polychaetes at 5–10 percent body weight. Water exchange is done at the rate of 40–50 percent every other day. The water quality parameters maintained are shown in Table 2.

Larval rearing

Crabs that spawn are transferred to separate tanks. Upon hatching, aeration is turned off to allow dead zoeae, unhatched eggs and faeces to settle at the bottom. The newly hatched zoeae are collected as early as possible to prevent possible microbial infection in larvae. The spent crab is removed from the tank. Newly hatched zoeae are stocked at 70–80 ind./L. Table 3 shows the feeding scheme used in the hatchery. Major food items for the zoeae are rotifers and *Artemia*.

TABLE 3
Feeding of mangrove crab during larval rearing

Stage	Food items	Density (ind./ml) / Amount of food
Zoea, Z1–Z2	Rotifers enriched with algae	10–20
Z3	Rotifers enriched with algae	10–20
Z4	*Artemia* nauplii	0.5–1.0
Z5	*Artemia* nauplii enriched with algae	0.5–1.0
Megalopae	Enriched *Artemia* biomass (live) Squid and live or frozen *Artemia* biomass (for benthic megalopae)	1.0 Based on consumption
Crab instars	Squid and frozen *Artemia* biomass	Based on consumption

Water (30–50 percent of total volume) is changed every three days based on the water quality. The water parameters are maintained as follows: salinity at 31 ± 3 ppt, temperature at 29 ± 1 °C, pH at 8.0 ± 0.5, and dissolved oxygen at > 4 mg/L.

When the larvae moult to zoea 5, some are transferred to tanks containing ozone-treated seawater to thin out the population. The remaining larvae are reared in the same tank until crab instar. The survival rate from zoea 1 to C1–C2 is generally around 7–10 percent. It takes 25–30 days for the newly hatched zoea to reach crab instar. The success of larval rearing primarily depends on the production and timely provision of sufficient live food. The microalgae, *Nannochloropsis salina*, *Nannochloropsis oculata*, and *Chlorella marina*, including other species. (Figure 8) are mass-cultured as feed for the rotifer, *Brachionus plicatilis*. The green microalgae are added to the rearing water when rotifers are fed to the early zoea stages.

Nursery

The growing of megalopae or crab instars to juvenile stage is done in brackish water ponds or creeks with salinity ranging from 15 to 35 ppt. PVC pipes, nets and seaweeds (*Gracilaria* sp.) are used as refuge to minimize cannibalism. Crab instars are grown in 5 × 4 × 1 m net cages at 30 ind./m^2. Megalopae or crab instars are fed either *Artemia* biomass or finely chopped trash fish. The culture period is 30–40 days or when crablets reach 1.5–4.5 cm CW for farming in grow-out ponds (Figure 9). The crablets are supplied to farmers in Andhra Pradesh, Tamil Nadu, Maharasthra, state fisheries departments, universities and colleges for research purposes, and RGCA-MPEDA demonstration projects.

FIGURE 8

Natural food cultures maintained in the algal laboratory (a) are gradually scaled up to bigger tanks (b) for feeding the rotifers at the Rajiv Gandhi Centre for Aquaculture

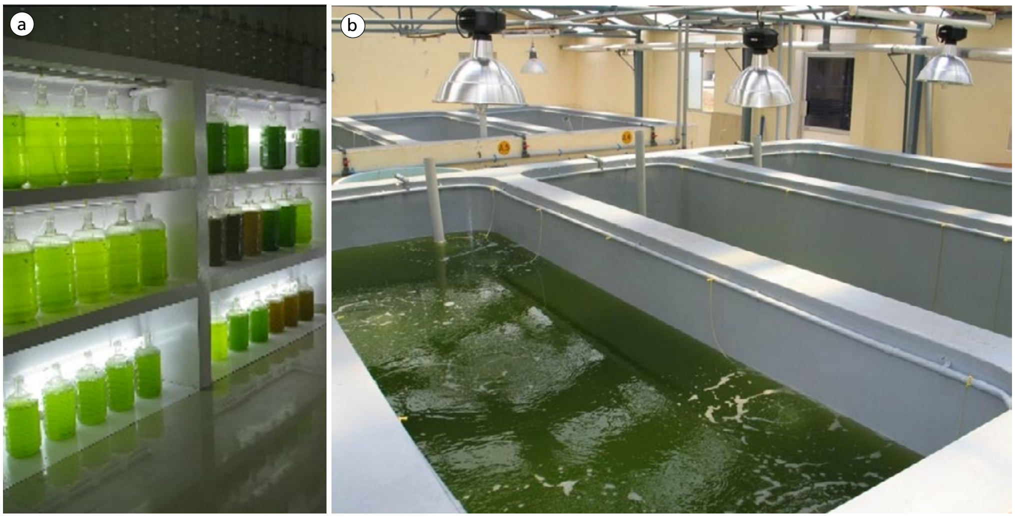

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FIGURE 9

Mud crablets ready for pond stocking

©RGCA

Problems encountered

The problems encountered are as follows:

- Vibriosis and occurrence of round pink coloration at the tank bottom.
- Protozoan infestation usually obtained from live food culture.
- Large variation in larval sizes.
- Megalopae mortality due to incomplete moulting.
- Abnormalities due to bacterial infection.
- Cannibalism.

BANGLADESH

Scylla olivacea is the predominant mangrove crab species in Bangladesh. Crab seed stocks for soft-shell crab production, grow-out farming, and fattening are primarily sourced from the wild. This practice has led to a significant decline in the crab population in recent years, with collectors increasingly encroaching into the inner mangrove forests. Recognizing the urgency of this issue, the government prioritized the establishment of hatcheries to sustain the mangrove crab industry.

In 2014, the Southeast Asian Fisheries Development Center/Aquaculture Department (SEAFDEC/AQD) was engaged to provide training on mangrove crab culture at the Bangladesh Fisheries Research Institute (BFRI) in Paikgacha, Khulna Division. This training was part of the project titled "*Management of the Sundarbans Mangrove Forest Diversity Conservation and Increased Adaptation to Climate Change*" initiated by the Ministry of Environment and Forests and the Bangladesh Forest Department, with support from Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (German Agency for International Cooperation). However, the existing aquaculture facilities at BFRI were inadequate for crab hatchery operations, only a limited number of crablets were produced. Furthermore, the availability of seawater for hatchery use was a significant challenge in Khulna Division.

FIGURE 10

Crab hatchery established by the Department of Fisheries in Cox's Bazar, Bangladesh

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In 2016, a crab hatchery was established by the Nowabenki Gonomukhi Foundation (NGF) in Mushiganj, Shyamnagar, Khulna Division, where crab hatchery technology from Viet Nam was introduced. Subsequently, in 2018–2019, the Department of Fisheries (DoF) constructed a crab hatchery in Cox's Bazar under the project "*Culture of Cuchia (Mud Eel) and Crab in Selected Areas of Bangladesh and Research Project Component-A (DoF)*" (Figure 10). Unlike Khulna Division, the salinity levels in Cox's Bazar are more favorable for larval rearing of mangrove crabs, making it an ideal location. This region also hosts several established shrimp hatcheries, further supporting aquaculture activities. Another hatchery in Cox's Bazar has also experimented with mangrove crab larval rearing.

More recently, a hatchery was established in Kalbari, Datinakhali, Shyamnagar, Khulna Division. The hatcheries currently in operation utilize a combination of locally introduced technologies and practices adapted from international training received by technicians and staff, with site-specific modifications to optimize outcomes.

Seawater source

In the Khulna Division where salinity can be very low, especially during the rainy season, brine is hauled into the hatchery, causing an additional expense. In Cox's Bazar DoF crab hatchery, seawater from the sea is pumped into the settling tank, passed through a sand filter then disinfected with chlorine, neutralized, and transferred to the overhead reservoir. Sometimes, further disinfection is done using an ultraviolet light sterilizer or ozoniser after the seawater is passed through a series of cartridge filters prior distribution to the rearing tanks.

Broodstock management

In Cox's Bazar, berried crabs are usually sourced from Sonadia and Naziratek while those in Khulna Division are mostly from Sundarban. Berried crabs brought to the hatchery are disinfected with formalin and stocked in big buckets or small tanks until the eggs hatched (Figure 11). Moderate aeration is provided continuously. Feeding is stopped when the egg mass of female turns brown or grey. Water is changed daily after the removal of uneaten feeds and faeces.

Larval rearing

Newly hatched larvae are subjected to formalin bath briefly prior to counting and stocking in tanks at 80–100 ind./L. Rotifers or umbrella stage or newly hatched *Artemia* (small strain) nauplii are fed to newly hatched zoeae. Artificial diet formulated for shrimp is fed to zoea 2 onwards. Prophylaxis is applied at the start of the culture period and after every water change. No water replacement is done on the first few days, but addition of fresh seawater is done daily until the tank is almost full, or water is drained and replenished every 3–4 days. Thereafter, water is changed depending on the quality. Siphoning of sediments is done whenever necessary. Probiotics are sometimes applied. Zoea 4 or 5 are transferred to new tanks and held there until crab instar stage. Late megalopae are fed minced fish, molluscs and frozen (thawed) biomass *Artemia*. A survival rate of 3 percent from zoea 1 to crab instar has been achieved at DoF in 2022. Crab instars produced were further grown in nursery tanks (Figure 12) and then in ponds. These were distributed to some farmers in Cox's Bazar.

FIGURE 11
Ovigerous females held in 100-L buckets provided with disinfected seawater and aeration

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Nursery phase

A nursery system has not yet been established due to the lack of commercial scale crablet production. However, the limited quantities of crablets that are produced are sold to farmers.

FIGURE 12
Crab instars produced at the Department of Fisheries hatchery in Cox's Bazar, Bagladesh

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Problems encountered

The problems encountered in the hatchery and nursery phases in Bangladesh include the following:

- Low and inconsistent survival rate from zoea to crab instar.
- High operational cost (feeds, chemicals and other inputs).
- Inconsistent supply of feeds (e.g. low value fish, molluscs).
- Lack of biosecurity measures.
- Frequent power outage.
- Lack of established nursery system.
- Acceptability of farmers to use hatchery-reared crablets (< 2 cm CW).
- Lack of R&D on commercial-scale production of crablets to support the industry.

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Review of mud crab seed production

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ABSTRACT

Mud crab larval rearing is a major process that directly determines the success or failure of the mud crab aquaculture industry, since this is the phase from which the seedstock requirement of the industry is sourced. The global mud crab aquaculture sector has advanced significantly in recent years, making small- and medium-scale hatchery operations increasingly feasible and sustainable. However, additional research is required to address both persistent and emerging issues. The culture parameters used during larval rearing should closely replicate the larvae's natural environmental conditions to optimize growth and survival. Likewise, a deep understanding of the complex mud crab life cycle, particularly the critical transition from open ocean to intertidal zones, is essential for designing practical and effective hatchery conditions. This review summarizes the recent knowledge on the various culture parameters for the mud crab larvae and crablet stages and highlights some future directions that warrant urgent attention to propel seed production of mud crabs forward.

INTRODUCTION

Considerable attention has been given to fully incorporate the mud crab genus *Scylla* into the aquaculture sector at the global scale. However, the main obstacle that continues to impede its full integration is the low and unpredictable survival of early life stages, especially during the zoeal stages. Farmers and aquaculturists rely heavily on wild-caught broodstock and seed stock to be used in their aquaculture facilities to keep up with the increasing demand for mud crabs in both local and international markets. Nonetheless, successes on the mass production of mud crab juvenile seeds have been reported in Viet Nam, Japan and the Philippines. Other countries like Thailand, Indonesia and China are also gaining momentum on seed production.

MUD CRAB LIFE CYCLE

Understanding the life cycle of the mud crab genus *Scylla* is instrumental for the development and optimization of culture conditions and parameters for its different life stages (Figure 1).

After progressing through ten embryonic stages, *Scylla* spp. hatch as zoea 1 in the open waters of coastal zones (Ates *et al*., 2012; Li *et al*., 2022). They go through five (zoea 1–5) early life stages as pelagic larvae, typically lasting approximately 20–30 days, thereby enabling them to achieve significant dispersal (Table 1). The subsequent megalopa phase is followed by a critical ontogenetic shift – from pelagic to benthic phase – and they also experience huge morphological changes such as the development of chelipeds, widening of the carapace, and reduction in dorsal spine length. However, it is reported in that some morphologically advanced larvae of *Scylla serrata* exhibited megalopal characteristics, such as long endopods of the second antennae, the presence of chelipeds, and pleopods with plumose setae as early as zoea 5.

FIGURE 1
General life cycle of the mud crab

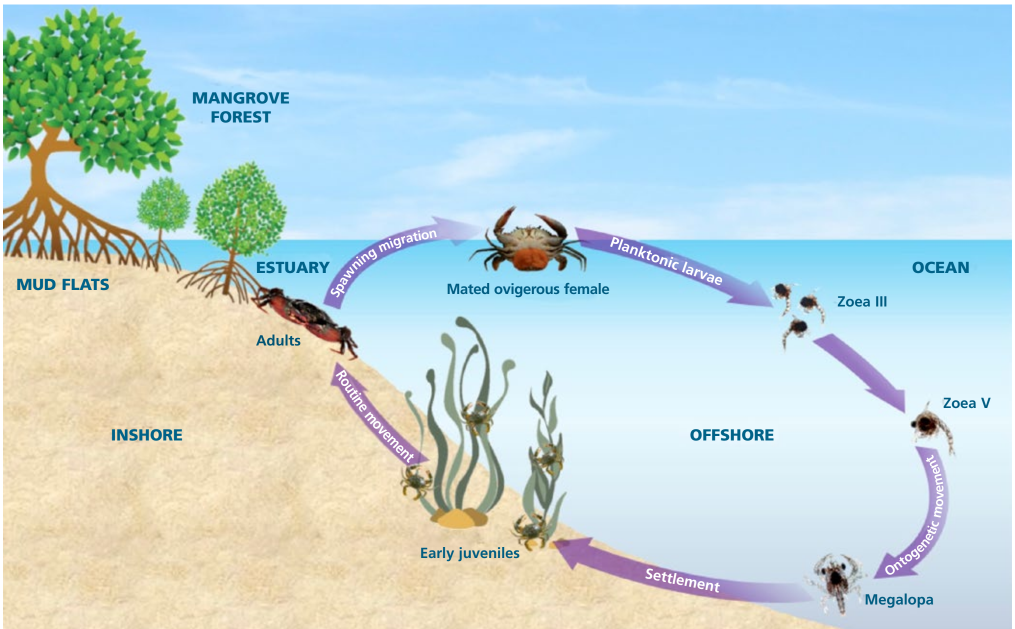

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TABLE 1
The development duration of *Scylla* during early larval stages (in days)

Species	Days							Source
	Z1	Z2	Z3	Z4	Z5	M	Total	
S. paramamosain	3	3	3	3	4–5	5–6	22–24	Li *et al.*, 2022
S. serrata	2	2	3	3	3	7	20	Yi, Lee & Lee, 2009
S. olivacea	18–19					–	18–19 (to reach Z5)	Jantrarotai *et al.*, 2006
S. tranquebarica	4	3	3	3	3	6	22	Thirunavukkarasu *et al.*, 2014
S. serrata	4–5	3–4	3	3	4–6	8–10	25–31	Motoh, de la Peña & Tampos, 1977
S. serrata	3–5	3–4	3–4	3–4	3–5	–	18–20 (to reach megalopa)	Heasman & Fielder, 1983
S. serrata	3	4	4	3	–*	3	18*	Paran *et al.*, 2022

Note: Z1: zoea stage 1; Z2: zoea stage 2; Z3: zoea stage 3; Z4: zoea stage 4; Z5: zoea stage 5; M: megalopa; C: crab instar. *Zoea stage 5 is not mentioned in Paran *et al.*, 2022.

During megalopa and crablet 1 phases, *Scylla* spp. transition back to the estuarine and brackish water intertidal zones as they develop towards their final mature crab form. In these habitats, they often seek shelter in seagrass beds or among mangrove pneumatophore networks as they develop into juveniles and finally mature and reach adult crab size (Webley *et al.*, 2009). Copulation generally occurs in the intertidal zones. Once their ovaries mature, females migrate offshore to spawn. Females spawn up to 5 million eggs per batch and can spawn up to three times consecutively, although the final spawn is generally of lower quality (higher aborted eggs, lower fertilization rates and fecundity, and reduced larval quality).

Although all *Scylla* species normally go through five zoeal stages before metamorphosing into megalopae, the occurrence of the additional zoea 6 stage, with additional setae numbers at the maxillule, maxilla, and maxilliped I and II has been reported in *Scylla paramamosain*. The presence of the zoea 6 stage is postulated to be linked with unfavourable dietary conditions (Zeng, Li and Zeng, 2004).

ZOEA COLLECTION AND QUALITY ASSESSMENT

Newly spawned larvae are phototactic, and thus can be easily collected at the water surface with the aid of a light source. Larvae should be collected as soon as they are spawned from the spawning tank to prevent and minimize bacterial infection. The quality of these larvae can be inspected via a formalin stress test, involving exposure to 40 mg/L of formalin for 3 hours. Larvae are considered of good quality if their mortality rate is low (0–18 percent) and are suitable to be incorporated into subsequent larval rearing systems.

LARVAL CULTURE PARAMETERS

Temperature and salinity

The growth and survival of mud crab larvae are highly dependent on these two critical environmental factors. Although they exhibit tolerance to the fluctuations in temperature and salinity, larviculture beyond the optimum range of 25–30 °C and 20–35 ppt would impede their growth and development. The tolerance of larvae is dependent on the species and growth stage. For example, the larvae of *S. serrata* and *Scylla olivacea* demonstrate higher tolerance to salinity compared to that of *Scylla tranquebarica*, and megalopae and crablets are more tolerant to salinity and temperature changes compared to larval stages, due to the development of functional gills and thickening of integument.

Stocking density

The recommended stocking density for mud crab zoeae is at 100–150 Z1/L for *S. paramamosain*, 75–100 Z1/L for *S. tranquebarica*, and 50 Z1/L for *S. serrata* (Table 2). When set too low, stocking density leads to excess food accumulation and subsequent deterioration of water quality; when set too high, it increases food competition, introduces stress and hinders proper development. The lower stocking density in *S. serrata* compared to other *Scylla* species might be attributed to the larger body size of its zoea (total body length of Z1: *S. serrata* = 1.33 mm, *S. paramamosain* = 1.26 mm, *S. olivacea* = 1.20 mm).

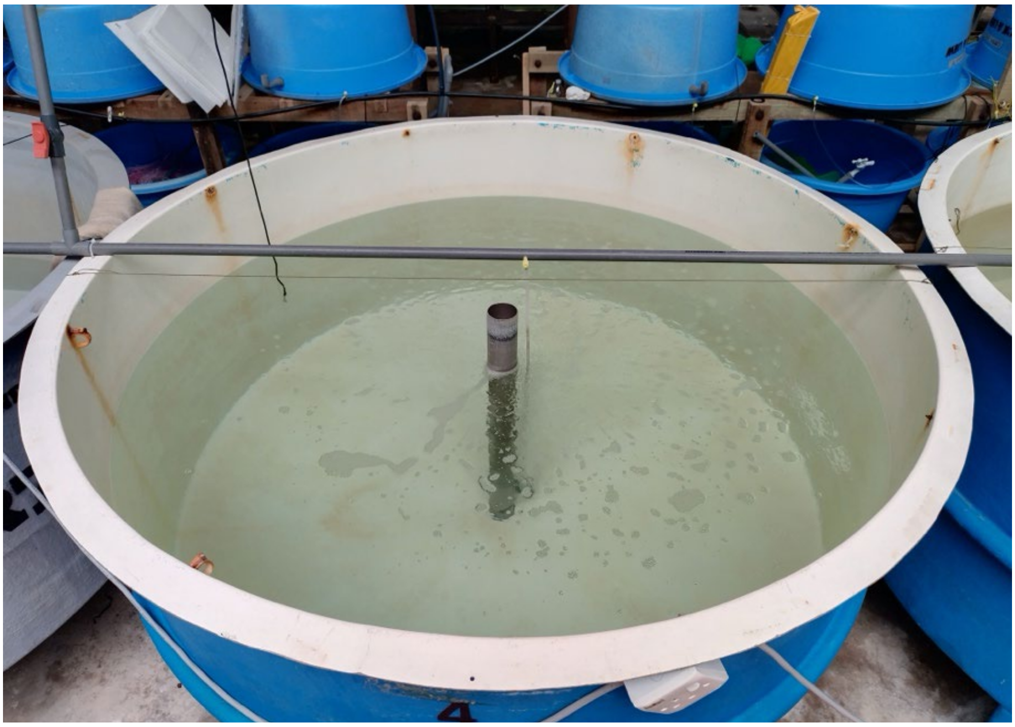
TABLE 2
The stocking density at zoea 1 (Z1) and the resulting survival rates of *Scylla* species

Species	Stocking density (Z1/l)	Survival rate (%)	Source
S. paramamosain	50 75 100	27 (up to Z5) 39 (up to Z5) 63 (up to Z5)	Djunaidah *et al.*, 2001
S. paramamosain	50 100, 150, 200	4 (up to day 22) 5 (up to day 22)	Nghia *et al.*, 2007
S. tranquebarica	75 100	52–55 (up to Z2) 50–54 (up to Z2)	Maheswarudu *et al.*, 2007
S. tranquebarica	30 45 60 75	(up to crablet) 1.86 (up to crablet) 1.82 (up to crablet) 3.30 (up to crablet)	Gunarto & Sulaeman, 2017
S. tranquebarica	50	2.88–3.88 (up to megalopa) 0.28–0.52 (up to crablet)	Syafaat *et al.*, 2019
S. serrata	30–50	2.7 (up to megalopa)	Quinitio *et al.*, 2001
S. serrata	50 75 100 150	8 (up to megalopa) 2–3 (up to megalopa) < 0.5 (up to megalopa) < 0.5 (up to megalopa)	Paran *et al.*, 2022

Aeration and water exchange

As mud crab larvae are pelagic and exhibit slow movement, it is critical to use sufficient but gentle aeration devices that produce fine air bubbles in the larval culture tanks to ensure their uniformity throughout the water column (Figure 2). Water exchange is minimal, especially if microalgae is incorporated into the system. However, when necessary – or when a flow through system is used – mesh nets can be installed at the water outlet as well as ensuring that the water flow is at a rate that does not cause larvae to be clustered on the filtering mesh net.

FIGURE 2
Aeration fitted at the centre of 1 000 L circular tank for uniform air distribution



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Prophylaxis

The early life stages of mud crab, zoeal stages in particular, are extremely sensitive and prone to disease due to their undeveloped immune systems. Thus, many hatcheries still rely heavily on the use of antibiotics (such as oxytetracycline, penicillin G or polymyxin B) – many during stages zoea 1–3, and occasionally zoea 1–5 – to effectively reduce bacterial infections and improve larval survival. However, aside from the potential residual antibiotics that might be transmittable to consumers, the use of antibiotics, especially over a prolonged period, is also linked to higher occurrences of morphological deformities in larval and juvenile stages (Pates *et al.*, 2017).

In addition to antibiotics, formalin is another commonly used prophylaxis agent in mud crab larviculture. Formalin, at an exposure concentration of 5 µg/L or 10 µg/L and duration of up to 96 hours, can be used in all five larval stages (zoea 1–5) to enhance larval survival and increase the transition percentage to megalopae (Pedro, Quinitio and Parado-Estepa, 2007). However, like antibiotics, the use of formalin also causes deformities and thus should only be used when necessary (Quinitio, de la Cruz-Huervana and Parado-Estepa, 2018).

Other emerging prophylaxis agents that show promising results in *Scylla* spp. larviculture include probiotics and biofloc. Both common bacterial probionts (such as *Alteromonadaceae* spp. and *Bacillus* spp.) and commercial probiotics have been proven to confer positive effects on mud crab larvae such as enhancing survival, growth, and development, as well as minimizing the occurrence of *Vibrio* and other pathogenic bacteria (Tran and Li, 2022). Biofloc, on the other hand, contains microbial communities that are beneficial as a supplemental diet for the larvae while maintaining water quality parameters, including the removal of nitrogenous compounds. The use of biofloc in the water column throughout the larval stages of *S. paramamosain* has been shown to enhance growth, with larvae transitioning from zoea 1 to megalopae within 17 days (Kasan *et al*., 2021). Additionally, higher survival rates were observed when crablets were fed a mixture of commercial pellets and biofloc pellets (Kasan *et al*., 2022).

Tank colour

Crustacean larvae, including mud crab larvae, are non-obligate visual feeders – that is they feed through random encounters or rely on chemosensors to locate food. However, mud crab larvae benefit from visual cues for better prey visibility. Consequently, the use of dark-coloured tanks, especially black tanks, has been shown to result in lower cannibalism rates, higher survival rates, shorter developmental durations, and more synchronized moulting. In contrast to culturing in white tanks, where the phototactic larvae aggregate and remain at the bottom, larvae cultured in black tanks exhibit a more uniform distribution in the water column (Rabbani and Zeng, 2005).

ASSESSMENT OF ZOEA AND MEGALOPA

Larval Stage Index

In addition to calculating the survival and mortality rates, and the total body length of crab zoea daily, it is also vital to characterise the growth and development of the zoea by estimating their Larval Stage Index (LSI) (Nghia *et al*., 2007). LSI can be calculated using the following equation:

$$\frac{\text{LSI} = ((\text{A1} \times \text{A2}) + \ldots + (\text{B1} \times \text{B2}))/\text{C}}{C}$$

Where $A1$ is the number of larvae at the earliest stage, $A2$ is the corresponding zoea stage, $B1$ is the number of larvae at the highest stage, $B2$ is the corresponding zoea stage, and C is the total sample size of all stages. The corresponding zoea stages are commonly designated as follows: zoea 1 = 1, zoea 2 = 2, zoea 3 = 3, zoea 4 = 4, zoea 5 = 5, megalopa = 6.

To estimate the LSI in each treatment, subsamples (e.g. 10 or 20 ind./tank) are sampled. Larvae are then identified according to their corresponding zoeal stages. For example, within a sample of 20 larvae, three zoea 2, five zoea 3, six zoea 5, and six megalopa are found, then the LSI value would be calculated as 4.35 ([[3 × 2] + [5 × 3] + [6 × 5] + [6 × 6]]/20).

Percentage of Megalopa Occurrence Index

The transition from zoea 5 to megalopa is a critical stage that involves not only physical changes but also changes in lifestyle (from pelagic to benthic). Thus, researchers calculate the percentage of successful megalopa transition from zoea 5 via the Megalopa Occurrence Index (MOI) (Gunarto *et al*., 2018; Syafaat *et al*., 2019). The MOI is an estimate of the occurrence of megalopa in every 100 zoea 5 individuals. For example, if a sample of 100 individuals contains 90 zoea 5 and 10 megalopae, then the MOI is 0.10 or 10 percent.

LARVAL CULTURE SYSTEM

Larviculture of mud crabs, albeit with inconsistent success rate, is still widely carried out by mud crab hatcheries. Most mud crab hatcheries adopt either clear water or microalgae-enriched culture systems, with either manual water exchange or recirculating systems. In clear water systems, a recirculating water system with a 100 percent water exchange rate every 3–4 hours resulted in higher larval survival rates 2–3 weeks post-hatching and better water quality compared to manual water exchange at 30–50 percent daily. In addition, a recirculating system also demands less labour and the need of fresh seawater, thereby reducing production costs. However, the first two larval stages (zoea 1 and 2) are weaker and extremely sensitive to mechanical shock and stress compared to other stages. Thus, the first two zoeal stages should be cultured in clear water or a microalgae-enriched non-recirculating system.

Microalgae are commonly used in the culture of crustacean larvae, including that of mud crabs. Aside from serving as nutritious feed directly for early larval stages or indirectly for live feed such as rotifers and *Artemia* – and thereby ultimately enhancing the survival and growth of crab larvae – microalgae are also useful in maintaining water quality of the culture system (stabilizing pH; increasing dissolved oxygen levels; and decreasing nitrite, nitrate, orthophosphate and total ammonia nitrogen levels as well as suspended solids), and preventing the growth of pathogenic microbes such as *Vibrio* in the water and sediment. In general, *Chlorella* sp. can be incorporated during the zoea 1–3 stages, whereas *Chaetoceros* sp. can be used from the zoea 4 stage onwards.

LARVAL DIETS

Mud crab larvae are carnivorous in nature. The diet for early larval stages of mud crab relies mostly on the use of live feed, and the use of artificial feed is still at the experimental stage. Some of the constraints include the unique feeding behaviour of zoeal stages, the developing foregut across zoea 1–5 stages, and the varying width of mouth opening at different larval stages.

Mud crab larvae, especially zoea 1, feed by pushing water, along with any food particles or prey, towards their mouths with their telson. It was reported that food particles of approximately 50–55 µm in size need approximately 3 minutes to pass through the gut and be digested by the zoea 1 of *S. serrata* (Maheswarudu *et al.*, 2007). Such feeding behaviour implies that food particles, especially artificial feed, must spread across the water column for the larvae to encounter easily. In addition to their unique behaviour, the digestive system of early larval stages (zoea 1–3) is still underdeveloped, possessing only a simple and continuous foregut. Two distinct compartments of the foregut are visible only in the zoea 4 and 5 stages (Lumasag *et al.*, 2007). As such, the need for easier and faster nutrient-absorbing formulation should be considered when designing artificial diets for the early larval stages of mud crabs (Waiho *et al.*, 2018). As mud crab larvae progress through the five zoeal stages, their feeding organ and digestive system develop rapidly and as a result the gut evacuation time increases with progressive developmental stages as well – from approximately 80 minutes in zoeal stages to about 120–135 minutes in the megalopa and crab instar stages. Furthermore, live feed facilitates faster gut evacuation time compared to artificial feed (Serrano and Serrano, 2012).

In terms of dietary nutritional requirements, high-protein diets (e.g. 50 percent lipid-free casein [Sheen, 2000], 32–40 percent protein [Catacutan, 2002], or 45 percent crude protein [Unnikrishnan and Paulraj, 2010]) are found to enhance growth and improve survival, owing to the high protease activity exhibited by the carnivorous mud crab larvae. Live feed enrichment experiments further highlight the positive impact of various essential and non-essential amino acids (such as histidine, leucine, tryptophan, arginine and valine) to larvae growth and survival (Dhont *et al.*, 2013). Fatty acids, both essential and non-essential, also play roles in improving the survival and development of mud crab during their early life stages. Mud crab larvae were found to thrive when fed a dietary highly unsaturated fatty acids (HUFA) content of 30 percent and docosahexaenoic acid (DHA)/eicosapentaenoic acid (EPA) in a ratio of 4:1 (Nghia *et al*., 2007). Other nutritional elements such as cholesterol, phospholipids and carbohydrates are also often incorporated into the feed formulation for mud crab larvae, based on their common usage in the diets of other crustacean or aquatic species. However, a better understanding of the nutritional needs of mud crabs and subsequent optimization of specific nutritional elements are needed to advance their larviculture.

Live feed

Mud crab larviculture is dependent on the use of live feed as the diet source for the early life stages. Among the shared characteristics of different types of live feed are their small size, fast proliferation rate (hence are mass cultured easily), slow swimming behaviour, tolerance to a wide range of culture parameters and free dispersal in the water column.

Rotifers

Brachinus plicatilis has a size range of 45–200 µm and is the commonly used rotifer species as the first feed of mud crab zoea 1, although in general any species within the genus *Brachinus* are viable (Davis *et al*., 2005). Rotifers are especially useful as vessels for transferring nutrients to larvae, as they can be fed and enriched with various feed sources (e.g. microalgae, yeast or specific nutrient elements). The enrichment of rotifers is often necessary as their nutritional contents fluctuate greatly. Owing to their small size, rotifers have been proven suitable as first feed for mud crab larvae, at least up to the zoea 2 stage, before co-feeding with *Artemia* up to megalopa. A rotifer concentration of 30–45 ind./ml is suitable for zoea 1 of *S. olivacea* and *S. paramamosain*, while *S. serrata* and *S. tranquebarica* larvae grow best with rotifers at 10 ind./ml co-fed with newly hatched *Artemia* nauplii (0.5 ind./ml) or rotifers at 20 ind./ml co-fed with newly hatched *Artemia* nauplii (3 ind./ml). Alternatively, both *S. serrata* and *S. tranquebarica* larvae may be fed a diet solely of rotifers at 20–40 ind./ml. Generally, rotifers are enriched using artificial enrichment supplements or various strains of microalgae.

Despite their size, suitability and the ease of transference of specific nutritional requirement to larvae via enrichment, rotifer cultures are difficult, labour intensive, and prone to unpredictable crashes, especially due to virus or fungal infections. Thus, hatchery owners have to concurrently produce several batches of rotifers and keep as backups, in case one or more batches collapse unexpectedly.

Artemia

In the larviculture of species such as mud crabs that have yet to have specific artificial feed formulations for their early larval stages, brine shrimp *Artemia* is a common, convenient, technically easy and readily available live prey that plays a pivotal role. Paired with the use of rotifers, research has shown that *Artemia* is the most efficient when fed to mud crab larvae from zoea 3 onwards (Ruscoe, Williams and Shelley, 2004b). Similar to rotifers, *Artemia* is also often enriched with commercial supplements or commercially available *Artemia* enrichment emulsion oils with high DHA and EPA contents, before being fed to crab zoeae.

In general, newly hatched *Artemia* nauplii (at 0.5 ind./ml) are given at early zoeal stages (zoea stages 1–3), whereas 24-hour-enriched nauplii (at 1.5–2 ind./ml) can be used for subsequent stages (Shelley and Lovatelli, 2011). It is important to note that *Artemia* nauplii density should be moderate (≤ 5 ind./ml) to minimize food, dissolved oxygen and space competition with crab larvae, and to reduce the possibility of water fouling. Most commercial crab hatcheries have resorted to the exclusive use of *Artemia* nauplii over labour-intensive zooplankton (rotifers), especially from the zoea 3 stage onwards.

Copepods

Copepods are part of the natural larval diet of most aquatic species, and compared to rotifers and *Artemia*, copepods are of superior nutritional value and digestibility. In addition, the various life stages of copepods (nauplii, copepodites, adults) imply that they are available at any preferred size as live feed. The use of copepods, however, is still in the experimental phase as their availability is seasonal and very geographically restricted. Nonetheless, when combined with rotifers, the larvae of *S. olivacea* were observed to also consume frozen copepods, resulting in excellent survival and growth (Jantrarotai, Temphakdee and Pripanapong, 2004). Similar to *Artemia*, copepods can also be enriched using artificial feed or microalgae to improve their nutritional content before being fed to mud crab larvae. For example, an experimental trial of mud crab (*S. olivacea*) larviculture from the zoea 1 stage to megalopa, using the copepod *Oithona rigida* enriched with a mixture of rice bran and *Nannochloropsis oceanica,* resulted in a higher survival (20 percent) compared to treatment with *O. rigida* enriched with rice bran (14 percent), *O. rigida* enriched with *N. oceanica* (12 percent), or *Artemia* (3 percent) (Yuslan *et al*., 2022).

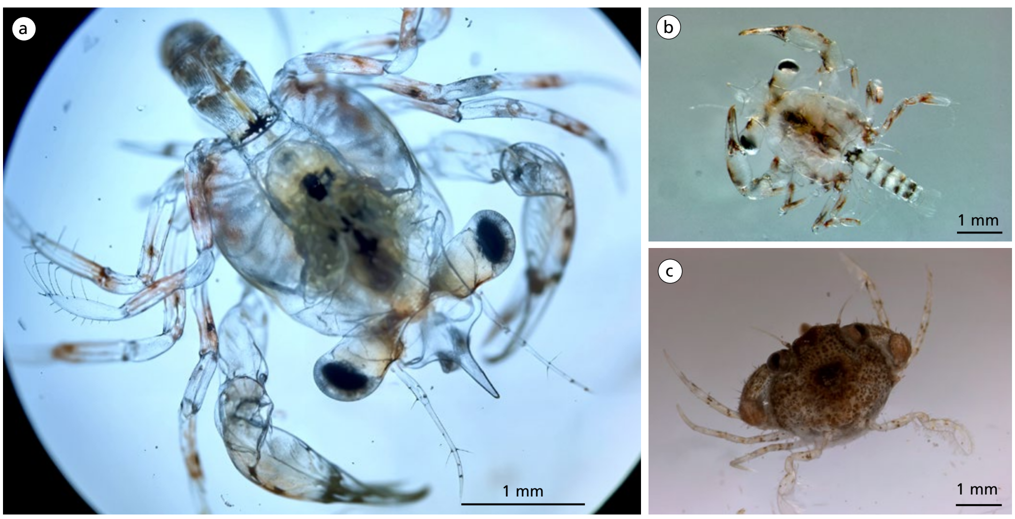
Artificial feed

The process of formulating an optimized diet for the early larval stages of mud crab is still in an early stage of development. Thus far, researchers have formulated microbound diets that showed promising results when used in addition to *Artemia* (1:1 ratio), resulting in enhanced survival and development from zoea stage 3 to 5. Microbound diets are beneficial as they offer advantages such as ease of storage, availability in any desired size, and cost-effective production. A significant increase in the ingestion rate of microbound diets was apparent after zoea stage 3, indicating that the more developed mud crab larvae after this stage (zoea 3) are capable and readily consume microbound diets, and the replacement of live feed with microbound diets is possible (Holme, Zeng and Southgate, 2006). In addition to microbound diets, researchers and farmers are also using commercial diet for shrimp larvae from zoea 3 onwards, although the outputs (e.g. survival, growth) are similar to using enriched *Artemia* nauplii alone. There are still a lot of uncertainties in the field of feed formulation for mud crab larvae.

MEGALOPA AND CRABLET CULTURE

After transitioning through five zoeal stages, mud crab larvae metamorphose into the megalopa stage that lasts for 7–10 days (Figure 3). In the wild, megalopae start to

FIGURE 3
The megalopae (a & b) and crablet stage 1 (c) of *Scylla paramamosain*



migrate back to the coastal zones and estuaries, and thus exhibit increased tolerance towards a larger range of salinity (15–45 ppt) and higher temperatures (20 °C) (Baylon, 2013). However, it is not until the first crab stage that they truly settle and adapt to the environmental parameters of intertidal zones. The moulting interval from the first crablet stage onwards increases gradually as they grow in size.

In general, mud crab nurseries encompass culturing megalopae to crablets stage 5 or 6 (C5 or C6), where their carapace width is around 10–12 mm, although some farms or facilities might proceed until the extended nursery stage to produce larger juvenile crabs. The transitions from zoea stage 5 to megalopa and the subsequent crablet stage is critical as they are prone to bacterial and fungal infections, and the occurrence of moult death syndrome is high (Hamasaki, Suprayudi and Takeuchi, 2002).

NURSERY CULTURE SYSTEM

While culturing megalopae and crablets individually in a laboratory setting can significantly improve their survival rate up to nearly 100 percent, this culture method is not feasible or practical for use in large farms and nurseries. The extensive labour and manpower needed for the whole operation, from manual feeding to monitoring and harvesting individual crabs, makes it operationally challenging and contributes to high capital and operating costs. Therefore, a communal rearing method is preferable for large-scale megalopa and crablet culture.

Cannibalism is, however, a major problem that can directly decrease the production of megalopae and crablets in communal rearing. This is largely due to the development of chelipeds or pincers at the megalopa stage. To mitigate the impact of cannibalism, shelters that mimic their natural environment (seagrass) such as black netting or seaweeds may be placed, either at the bottom or floated within the water column. When they reach the juvenile stage, substrates such as PVC pipes, bricks, or open sand substratum are suitable as shelters. The presence of shelter provides megalopae and crablets with a safe space to undergo the moulting process safely, without the risk of predation by other crabs. It is important to note that, in addition to shelter, the availability of sufficient food supply is another critical factor that contributes to cannibalism in crabs.

Specific research on the stocking density of megalopae is scarce. Hatchery-reared megalopae of *S. serrata* can be stocked at 10–30 ind./m^2 in net cages within brackish water nursery ponds, with reported high survival rates (48–53 percent) until the juvenile stage (Rodriguez *et al*., 2001). Increases in stocking density to 133 ind./m^2 in aquarium settings, however, resulted in lower survival rates (12–32 percent) with various diet treatments (Syafaat *et al*., 2016). With a stocking density of 70 ind./m^2 for 30 days from crablet stage 1 (*S. paramamosain*), individuals reached a final size of around 22–25 mm carapace width, while an extension of another 30 days of culture with a stocking density of 30 ind./m^2 yielded an encouraging survival of 64–67 percent, with individuals attaining a final carapace width range of 35–36 mm (Ut *et al*., 2007).

MEGALOPA TRANSPORTATION HANDLING

Mud crab larvae are still fragile during the megalopa stage and thus strong and continuous agitation should be minimized or avoided. Megalopae are normally packed in plastic bags for transportation. The stocking density during packing is often kept at a maximum of 200–300 ind./L to avoid them grasping each other, resulting in potential injury and consequent reduction of survival rate. If possible, lower stocking densities such as 50–150 ind./L greatly enhance the survival of megalopae. Research has shown that when stocked at 50 ind./L and subjected to 6 hours of simulated transport and shaking, megalopae can still achieve a survival rate of 99 percent. Additionally, transporting megalopae in lower temperatures (such as 24 °C) is more conducive, resulting in better survival rates compared to the more frequent temperature of 28 °C (Quinitio and Parado-Estepa, 2000).

NURSERY FEEDING

Once mud crab larvae reach the megalopa stage, they are able to feed on larger prey and food particles. *Artemia*, either live or frozen, can still be used as the main source of feed during the transitional megalopa to crablet stage, although other feed such as shrimp, fish, clams, mussels, polychaetes or artificial feed can be included, both in dried and wet form. Ut *et al*. (2007) showed that live *Artemia*, fresh chopped shrimp, or tilapia were equally superior as feed for juvenile crabs. In addition to *Artemia*, egg custard diet – which consists of a mixture of egg albumen, vitamin and mineral premix, milk powder, and cod liver or vegetable oil – is also being used as an alternative in mud crab nurseries. This choice is favoured for its production simplicity, cost-effectiveness, and readily available ingredients.

Microbound diets are artificial diets produced by combining all essential ingredients together using a binder, which is subsequently dried, crushed and sieved to the desired size (Genodepa, Southgate and Zeng, 2006). Microbound diets have been experimentally tested as feed for the megalopae of *S. serrata*, although the survival of megalopae was highest and the development time was shortest when fed with live *Artemia*. Subsequent optimization of microbound diets, especially on the dietary lecithin composition by Holme, Southgate and Zeng (2007), successfully resulted in a microbound diet that is equal or superior to live *Artemia* nauplii when fed to mud crab megalopae. However, microbound diets are comparatively higher in production cost due to the usage of squid meal that is not readily available in some countries.

Aside from trash fish, *Acetes* spp., a small planktonic shrimp genus, is abundant in most Indo-Pacific countries. When fed exclusively on live *Acetes* or in combination with commercial feed, megalopae of *S. paramamosain* moulted earlier into the crablet stage synchronously than with other treatments (minced shrimp meat, locally formulated feed, commercial feed, and live *Acetes* with minced shrimp meat or live *Acetes* with locally formulated feed). Additionally, megalopae fed with live *Acetes* had the highest survival in communal rearing (Ong, Fotedar and Ho, 2000). Thus, *Acetes* is a potential live feed source for megalopae culture that warrants future investigation.

With the lack of mud-crab-specific diets, most nurseries rely on the use of commercial shrimp (post-larvae) feed during megalopae culture, either alone or in combination with *Artemia*. Once they morph into the crablet stage, they are predominantly benthic in nature and their digestion system is fully developed. Thus, mud crab crablets can be fed with locally available fresh feed (such as minced trash fish, bivalves, shrimps), frozen adult *Artemia*, or artificial feed.

CRABLET CULTURE PARAMETERS

As mud crabs reach megalopae and subsequent crablet stage, they are more resilient to the changing water parameters. The optimal temperature remains similar to that of larvae (28–30 °C), whereas the optimal salinity of megalopae and crablets is lower (between 20–25 ppt) than the salinity used in larviculture since in nature they start to transition back to the intertidal zone during this life stage. To date, research on the optimization of culture parameters at the nursery stage is still limited. Table 3 summarises the feasible parameters used in various studies for nursery and grow-out culture.

Shelters and size-grading

As mud crabs develop into crablets and adopt a benthic lifestyle, they become territorial and are highly aggressive and cannibalistic. Seaweeds, sand substrates, shells, bricks and nylon netting are some of the commonly used shelter options during crablet stages, whereas PVC pipes of various sizes provide superior hiding options when crablets reach near-adult size. The shelter may be placed at the bottom layer or in the water column to provide sufficient surface area for the crablets. Utilizing bricks and clamshells as shelter resulted in higher survival rates among the crablets of *S. paramamosain* compared to

TABLE 3
Water quality parameters during nursery and grow-out culture of *Scylla* spp.

Parameters	Optimum range/value	Sampling frequency	Source
Dissolved oxygen (DO)	> 5 ppm	Twice a day	Shelley & Lovatelli, 2011
pH	7.5–8.5 (< 0.5 daily variation)	Twice a day	Ganesh *et al.,* 2015
Temperature	28–30 °C	Daily	Ruscoe, Shelly & Williams, 2004a; Gong *et al.,* 2015; Syafaat *et al.,* 2021
Salinity	20–25 ppt	Daily	Ruscoe, Shelley & Williams, 2004a; Nurdiani & Zeng, 2007; Baylon, 2010, 2011, 2013
Total ammonia nitrogen (TAN)	< 3 ppm	Weekly	Shelley & Lovatelli, 2011
Un-ionised ammonia (NH_3)	< 0.01 ppm	Weekly	Ganesh *et al.,* 2015
Nitrite (NO_2)	< 10 ppm at salinity > 15 ppt; < 5 ppm at salinity < 15 ppt	Weekly	Shelley & Lovatelli, 2011
Alkalinity	> 80 ppm (ideally 120 ppm)	Weekly	Shelley & Lovatelli, 2011
Hardness	> 2 000 ppm	Weekly	Shelley & Lovatelli, 2011
Hydrogen sulphide	< 0.1 ppm	Weekly	Shelley & Lovatelli, 2011
Turbidity	20–30 cm	Daily	Shelley & Lovatelli, 2011

Source: Adapted from Syafaat, M.N., Azra, M.N., Waiho, K., Fazhan, H., Abol-Munafi, A.B., Ishak, S.D., Syahnon, M., Ghazali, A., Ma, H. & Ikhwanuddin, M. 2021. A review of the nursery culture of mud crabs, genus *Scylla*: Current progress and future directions. *Animals*, 11: 2034.

using sand substrate (Ut *et al*., 2007). Although no colour preference research has been conducted on crablets, adult *S. tranquebarica* showed strong bias towards blue and white shelters compared to green, red and black PVC pipes as shelter (Kawamura *et al*., 2020). Additionally, Kawamura *et al*. (2020) observed that adult mud crabs were more tolerant to other conspecifics and up to four crabs could be found per shelter.

Seaweed is a common type of shelter utilized in mud crab nursery. Recent research showed that different species of seaweeds impact mud crab growth and survival differently. Green seaweed *Cladophora* sp., when used as shelter, promoted faster growth rate in juveniles of *S. paramamosain* compared to red seaweed *Gracilaria tenuistipitata* from week-2 onwards, and higher survival at week-3 (Toi *et al*., 2023). In a separate experiment, *G. tenuistipitata* was superior to green seaweed *Enteromorpha intestinalis* when used as shelter in the culture of juveniles *S. paramamosain*, with treatments incorporated with *G. tenuistipitata* had higher crab survival and better water quality (lower nitrogenous compounds) (Van *et al*., 2022). The benefit of using seaweed over other artificial shelter types is that in addition to providing refuge to crablets, seaweeds are also natural bioremediation agents to reduce nitrogen and phosphorus compounds.

In addition to the provision of shelter, periodic size-grading of crablets is important to minimize cannibalism and ensure higher production of mud crabs. This is because cannibalism occurrence increases significantly when there is a difference in body size within the cultured population, and the occurrence of cannibalistic behaviour increases with body size. For example, *S. serrata* of 51–70 mm internal carapace width (ICW) exhibited cannibalistic interactions ten times higher than the smaller (20–30 mm ICW) size class (Mirera and Moksnes, 2013).

Stocking density

Optimal stocking density in mud crab nursery culture is important. Too high stocking densities will result in cannibalism, insufficient food and suboptimal growth, while too low stocking densities may lead to reduced production. During instar or crablet stages, they can be stocked at higher densities but as the crablets increase in size the optimal stocking density is significantly reduced (Table 4).

TABLE 4
Stocking density trials in *Scylla* species

Species	Life stage (body size)	Stocking density (ind./m^2)	Survival rate/results	Source
S. paramamosain	Juvenile (no data)	200 300 400	Growth rate and survival highest at 200 ind./m^2, followed by 300 ind./m^2 and 400 ind./m^2.	Toi *et al.*, 2023
S. serrata	Juvenile (3.50–4.26 cm CW; 7.3–11.0 g)	0.5 1.5 3.0	98% 57% 31%	Triño, Millamena & Keenan, 1999
S. serrata	Juvenile (5.2–6.8 cm CW; 40–60 g)	0.5 0.75 1.0	47% 33% 27%	Venugopal *et al.*, 2012
S. serrata	Juvenile (2–8 cm ICW)	4 8	No significant difference in cannibalism and mortality	Mirera and Moksnes, 2014
S. paramamosain	Instar 1 (4.45 ± 1.07 mm CW; 17.1 ± 9 mg)	110 175 230	No significant difference in survival rate	Ut *et al.*, 2007

Note: ICW: internal carapace width; CW: carapace width.

CRABLET TRANSPORTATION AND HARVESTING

Crablets are often harvested and transferred to larger earthen ponds or facilities within 1 month after stocking, as their sizes grow exponentially, and their benthic lifestyle warrants a lot of space. Crablets are commonly transferred in wet conditions, or alternatively in dry or semi-moist condition. In wet conditions, crablets are immersed in water and put in plastic bags filled with oxygen. Shelter in the form of nylon netting can also be included to reduce aggression and cannibalism. A high survival of 88–97 percent was reported when crablets, packed at densities of 50 to 150 ind./bag were transported for a period of 5 hours using the wet method (Sulaeman, Yamin and Parenrengi, 2008). The dry or semi-moist method involves packing the crablets without water into either plastic bags or Styrofoam (polystyrene) boxes with wet cloth or tissues, or seaweeds. Due to the larger surface area and the stackable nature of Styrofoam boxes, higher quantities of crablets can be stocked compared to using plastic bags. When crablets (200 to 300 ind./bag) are transported in the dry or semi-moist condition, over a similar duration of 5–6 hours, in either plastic bags or Styrofoam boxes, survival rates of more than 95 percent can be achieved (Yamin and Sulaeman, 2011).

CONCLUSION

Seed production is a critical and delicate process in the farming of mud crabs. Most of the critical culture parameters such as temperature and salinity have been optimized by researchers and farmers, although slight variations might still exist due to the differences in local adaptation. However, the inconsistency and unpredictably low survival rate during early larval stages of mud crabs is still an issue that hinders the large-scale production of mud crabs in captivity. Close collaboration between industries and research institutes is needed to resolve this longstanding bottleneck. Another major hurdle that still needs attention is the formulation of specific artificial feed for megalopa and crablet stages of mud crabs. The current reliance on either artificial shrimp pellet or fresh feed during nursery phase might not contain the optimal nutrient required by mud crab crablets. Lastly, cannibalism remains as one of the primary causes of mortality during the nursery phase, although size- and sex-grading might help to reduce the cannibalism rate. Future research should investigate the mechanism and promoting factors of cannibalism in mud crabs, and potentially find a solution to mitigate their cannibalistic behaviour.

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Studies on tissue growth in juvenile mud crabs and optimal cholesterol inclusion levels in formulated mud crab feeds

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INTRODUCTION

Mud crab farming in Southeast Asia still predominantly relies on capture-based mud crab juveniles (Allan and Fielder, 2003). The crablets are commonly fed trash fish, which can contaminate the culture medium, increasing the risk of disease outbreaks and contributing to high mortality rates (Linder, 2005). However, the use of trash fish in aquaculture is increasingly unsustainable due to challenges in storage – requiring refrigeration or freezing – and rising costs across many regions. To ensure the sustainable growth of crab farming, the industry must transition to the use of formulated feeds made from selected ingredients sourced locally and internationally.

Crustacean growth relies on the regular moulting of their rigid exoskeletons, a process that requires adequate stored energy and appropriate levels of the hormone ecdysone. Dietary cholesterol plays a critical role in supporting growth and ensuring high survival rates in crustaceans (Sheen, 2000; Holme, 2006; Tao, 2014). Cholesterol is a vital sterol, acting as a precursor for numerous physiologically active compounds, including sex and moulting hormones, adrenal corticoids, bile acids and vitamin D. While most animals can synthesize sterols from acetate, crustaceans lack the ability to produce sterols *de novo* (Sheen *et al*., 1994; Teshima and Kanazawa, 1971).

Most previous studies on mud crab growth have focused on growth rate as measured by increases in fresh weight. Fresh weight changes follow a characteristic pattern through the moulting cycle: rapid and significant increases due to water uptake at ecdysis; moderate gains during the post-moult phase as carapace mineralization and tissue growth occur; and a period of relative stabilization during the intermoult phase, lasting until the onset of the next ecdysis (Heasman, 1980). In contrast, tissue mass increase is a continuous process throughout the moulting cycle (Freeman, 1990). Tissue growth is often measured by increases in dry weight, as tissues lose water proportionally to their gains in dry mass (Passano, 1960).

A comprehensive understanding of juvenile mud crab growth is essential for advancing the formulation of optimized feeds. This paper provides insights into the growth of mud crab juveniles, focusing on tissue growth and the deposition of key nutrients – protein, lipid and ash – during the moulting cycle. Additionally, the study examines the effects of varying cholesterol levels in formulated feeds on the growth and survival of crab juveniles and evaluates specific pellet formulations for soft-shell crab farming.

MATERIALS AND METHODS

Fundamental knowledge on growth of mud crab juveniles

Crab and holding facilities

Juvenile crabs, *Scylla serrata,* were collected from the mangrove habitat surrounding the experimental station in Boulouparis district, New Caledonia. Seventy juvenile crabs were caught using a hand net and transferred to the laboratory and acclimatised into eight circular composite tanks (500 L capacity) for 1 week prior to the beginning of the experiment. The crabs were examined to identify their moult stage using the criteria and methodology described in Heasman (1980). From the collected crabs, 54 were identified as being in intermoult stage and were selected for the experiment. These crabs were randomly and individually assigned to 54 experimental rectangular polyethylene tanks (30 × 20 × 30 cm) covered with black lids. After being dried in soft paper and cotton cloth, each crab was weighed to the nearest 0.01 g and its carapace width was measured to the nearest 0.01 mm.

Each experimental tank was continuously supplied with seawater running from a polyethylene reservoir (2 000 L capacity) at a rate of 0.19 L/min. The water pumped from the lagoon was filtered through a 25 µm net bag into the reservoir. The temperature was automatically controlled using a heater. The temperature in the experimental tanks was measured every 3 hours using an automatic recording probe. During the experimental period, the water parameters were carefully maintained as follows: temperature at 21.5 ± 2.5 °C, salinity at 34.0 ± 1.5 ppt, pH at 7.97 ± 0.09, and oxygen at 4.48 ± 0.16 mg/L.

Diet preparation and composition

The crabs were fed five different experimental diets (SPC-12, SPC-32, SPC-42, SPC-52 and SPC-60) formulated with graded levels of soy protein concentrate (SPC) as the main protein source (Table 1). The diets were produced in the laboratory using the following procedure. The dry ingredients were ground up in a grinder with a 1 mm screen. The meal obtained was mixed with oil and water in a horizontal mixer until the consistency was suitable for pelleting. The mixture was then extruded through a 3 mm die in a meat grinder. Pellets were steamed for 15 minutes and stored at -20 °C before use. The ingredient compositions and proximate nutrient contents of experimental diets are shown in Table 1.

Growth trial

At the beginning of the experiment, the crabs were kept without food for 48 hours and then weighed and measured. The crabs had an initial average body weight of 20.43 ± 9.81 g and average carapace size of 4.92 ± 0.81 cm. Crabs were held individually in each experimental unit. All 54 tanks with individual crabs were assigned to the five different dietary treatments. Thus, 11 tanks were randomly assigned to each treatment (n = 11), except for the treatment with diet SPC-12 (n = 10). The crabs were fed *ad libitum* daily. The daily pre-weighed feed ration for crabs in each tank was given at 06.00–07.00. Three hours after each meal the uneaten feed was siphoned out, dried for 24 hours at 60 °C and weighed.

The leaching rate (dry matter loss of the pellet in the water) was determined by measuring remaining dry matter in a weighed sample of each diet after 3 hours of immersion. Then the amount of voluntary feed intake (VFI) for each crab was obtained following this equation:

$$VFI = dF - L - uF$$

Where: VFI = voluntary feed intake; dF = distributed Feed; L = leaching after 3 hours; and uF = unconsumed feed.

TABLE 1
Ingredients and proximal compositions of five experimental diets

	Experimental diets				
	SPC-12	SPC-32	SPC-42	SPC-52	SPC-60
Composition (%)					
Soy protein concentrate	12.00	32.00	42.00	52.00	60.00
Crab meal	20.00	20.00	20.00	20.00	20.00
Wheat flour	53.50	35.00	25.50	16.00	8.00
Fish oil	4.00	4.00	4.00	4.00	4.00
Soy oil	2.50	1.00	0.50	0.00	0.00
Gluten	5.00	5.00	5.00	5.00	5.00
Dicalcium phosphate	3.00	3.00	3.00	3.00	3.00
Vitamin C[1]	0.25	0.25	0.25	0.25	0.25
Vitamin premix[2]	0.50	0.50	0.50	0.50	0.50
Trace elements[3]	1.00	1.00	1.00	1.00	1.00
Analysis (dry matter basis)					
Crude protein (%)	26.87	35.52	39.69	44.15	49.17
Lipid (%)	4.08	4.80	4.62	4.36	4.43
Ash (%)	13.95	14.54	22.36	21.80	27.43
Gross energy density (MJ/kg^{-1})	17.96	17.26	17.87	18.61	18.44
P/E (g/Mj^{-1})	16.79	20.58	22.13	23.72	25.56

[1] Vitamine C: Rovimix Stay-C 35 from DSM Cie.

[2] Vitamin premix for shrimp from BEC Feed Solutions PTY, LTD. Ingredients: vitamin AD3 1000/200, vitamin B1 98% Thiamine, Mononitrate, vitamin B2 Riboflavin 80%, vitamin B3 99% Niacin, vitamin B5 98% D-Calpan, vitamine B6 98% Pyridoxine, Vitamin B9 97% Folic acid, vitamin D3 500, vitamin E 50 ADD, vitamin K3 43.7%.

[3] Trace eliments from SICA Cie (Goodman Fielder).

During the experimental period, the carapace width, live body weight and date of ecdysis were recorded for each crab after moulting, before being transferred back to the tanks. The exuviae were collected and weighed before and after drying at 80 °C for 24 hours, then kept at -20 °C for energy analysis. The trial was maintained for 81 days. At the end of the experiment, all the crabs were left unfed for 48 hours and then weighed, measured, dried at 80 °C for 48 hours, and kept at -20 °C before biochemical and energy analysis.

Biochemical analysis

The proximate compositions of the diets, faeces, and both initial and final crabs were determined at the *in vivo* laboratory in Viet Nam, following the methods outlined by AOAC (1995). The moisture content of mud crabs and feed was determined by oven drying at 105 °C to a constant weight. Nitrogen content was measured by combusting each sample in pure oxygen, with the nitrogen detected using thermal conductivity detection. The nitrogen content was then converted to equivalent protein content using the factor 6.25 (crude protein percentage = %N × 6.25). Crude lipid content was quantified by solvent extraction with petroleum ether. Ash content was determined by combustion in a muffle furnace at 550 °C for 8–10 hours. The energy content of the diets was determined using a calorimetric bomb (Parr® 6200, USA, calibrated with benzoic acid) at the IFREMER laboratory in New Caledonia.

Definitions, calculations and statistics

Monitoring the moulting – Cumulative moulting or moulting rate (CM in percent) was calculated using the following formula:

$$CM = 100 \times \sum_{i-0}^{n} \frac{Mi}{Cr}$$

Where i = day i; Mi = number of moults on day i; Cr = number of crabs in each treatment.

Growth measurements – Growth parameters of crabs in this study were determined as: tissue growth, tissue gain and nutrient gains (protein, lipid and ash).

Parameters recorded were:

iBW	=	Dry initial body weight.
BWae	=	Dry body weight after ecdysis (15% of fresh body weight of crab estimated from average assessment of 12 crabs that moulted after 1 day).
fBW	=	Final dry body weight.
Tissue growth after ecdysis (% of BWae/day) or during the experiment (% of iBW/day) and tissue gain (% of BWae) were measured based on the increase in dry weight (Passano, 1960).		
Tissue growth after ecdysis	=	100 × ([fBW – BWae] - ash gained) / (BWae × days after ecdysis)
Tissue growth during the course of experiment	=	100 × ([fBW – iBW] - ash gained) / (iBW × days of experiment)
Tissue gain	=	100 × ([fBW – BWae] - ash gained) / BWae)
Protein, lipid or ash gain	=	100 × (protein, lipid or ash retained / BWae)

Use of formulated feed for crab farming in Viet Nam

Two experiments were conducted at the Research Institute for Aquaculture No. 3 in Viet Nam to evaluate the effects of supplemented cholesterol levels and to compare formulated mud crab feed with trash fish. Juvenile mud crabs (*Scylla paramamosain*) used in the trials were sourced from mud crab farms in Khánh Hòa Province. Prior to stocking, crabs in the intermoult stage were selected

Trials on cholesterol supplementation in crab feed

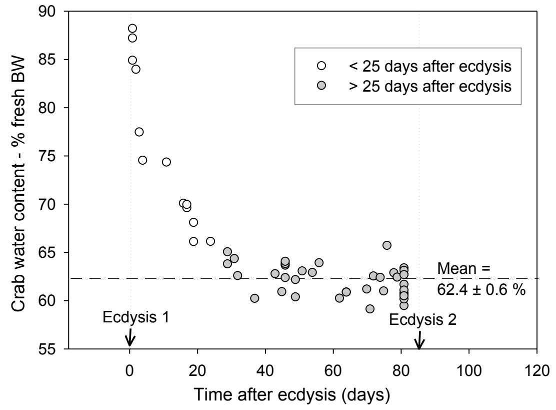
Six treatments of graded cholesterol levels of 0 (control treatment), 0.05, 0.1, 0.15, 0.2 and 0.3 percent (named DC, CH-0.5, CH-1, CH-1.5, CH-2 and CH-3, respectively) were supplemented to the basic crab diet. The nutritional composition of the basic diet was assessed as 44 percent protein, 7.5 percent lipid and 21.3 percent ash, with an energy density of 16.5 MJ/kg.

For each treatment, 60 crab juveniles (*S. paramamosain*) of 60–80 g initial body weight were randomly stocked into 60 boxes in a recirculating aquaculture system during a 30-day experiment, with three replicates for each treatment. At the end of the experiment, the moulting rate (cumulative moulting), moulting duration and survival rate were determined. The moulting rate was calculated as detailed above, while moulting duration (in days) was identified from the first day of the experiment to the day that crab moulted. The survival rate was the percentage of living crabs at the end of the experiment compared to the initial stocking number.

Comparison between crabs fed formulated diet and trash fish

To assess the performance of a formulated mud crab feed for soft-shell crab production, a pelleted feed was compared with trash fish. The trial consisted of two treatments: one using trash fish (small fish and crustaceans) and the other using the most suitable formulated feed previously optimized during the cholesterol supplementation experiment. Each treatment involved 60 individual *S. paramamosain* crabs, with body weights ranging from 60–80 g, distributed across three replicates per treatment. As in the cholesterol supplementation experiment, key parameters were monitored, including moulting rate, moulting duration, survival rate and feed conversion ratio (FCR). The FCR was calculated as the dry matter of the formulated feed or trash fish consumed relative to the crabs' weight gain.

FIGURE 1
Water content of *Scylla serrata* juveniles during a moult cycle



RESULTS AND DISCUSSION

Tissue growth during a moult cycle

The water content of post-moult crabs was 85 percent one day after ecdysis (Figure 1) and then decreased over the next 23 days to reach a baseline of 62.4 ± 0.6 percent of water which then remained relatively constant until the next moult. The tissue gain, measured as the increase in dry organic matter as a proportion of dry body weight after ecdysis (BWae), increased for about 30 days after ecdysis and then remained relatively constant until the next moult (Figure 2a).

The tissue growth rate was the highest 2 days after ecdysis (16.5 percent) and then dropped dramatically during the first 10 days to 3.6 percent. The decrease was slower than the minimum value of 1.3 percent that was recorded before the next ecdysis (Figure 2b). Crab body protein and lipid change during the intermoult cycle showed the same trend as the tissue growth (Figure 3a and Figure 3b) with two distinct phases, i.e. an initial increase followed by a plateau. The initial increase of body protein content started approximately 1 week earlier than the increase of the lipids. Ash gain did not follow the trends of protein and lipids, instead increasing rapidly during the first 5 days after ecdysis and then remaining stable during most of the intermoult period (Figure 3c).

FIGURE 2
Growth of *Scylla serrata* juveniles during a moult cycle
(a) Tissue gain expressed as the % dry BW after ecdysis minus the % BWae. Mean value was determined for crabs after 25 days of ecdysis. (b) Tissue growth rate expressed as the % dry BW after ecdysis/day minus the % BWae/day

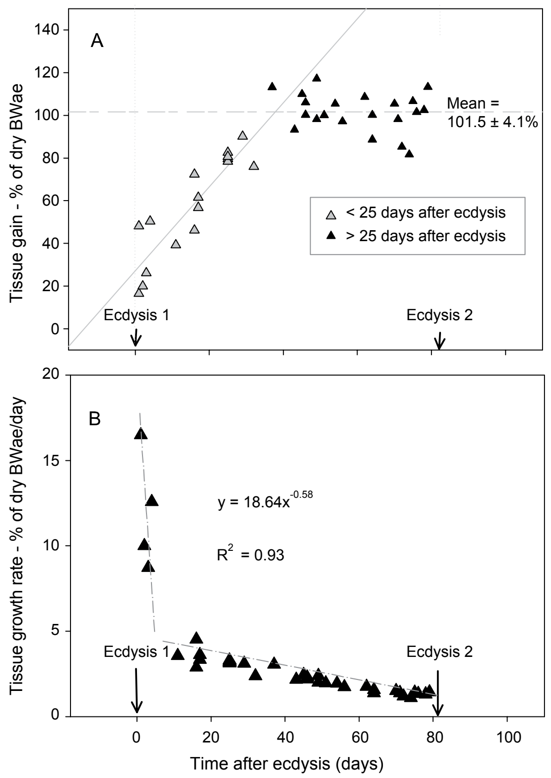


FIGURE 3
Nutrient gains of *Scylla serrata* juveniles expressed as % dry BW after ecdysis during a moult cycle
(a) Protein gain, (b) lipid gain, and (c) ash gain

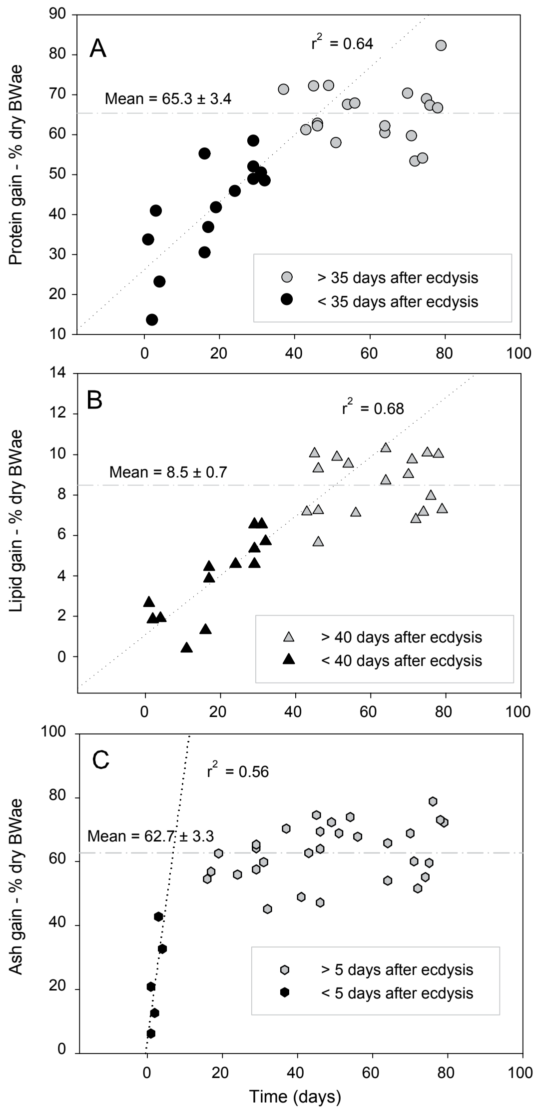
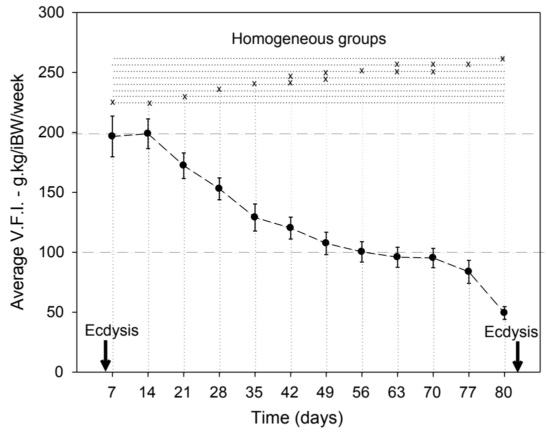


FIGURE 4
Voluntary feed intake of *Scylla serrata* juveniles fed all diets during a moult cycle
Homogenous groups determined from Tukey's Range Test are presented above the curve according to time



Voluntary feed intake and cumulated moult during one moult cycle

Since voluntary feed intake (VFI) was not influenced by diet composition, all data were pooled to analyse feed consumption patterns during the experiment (Figure 4). During the first 14 days post-ecdysis, crabs consumed approximately 200 g/kg of initial body weight (iBW) weekly, equivalent to a daily ration of 0.58 g/ind. Thereafter, VFI gradually declined, reaching lower levels by day 35. Between days 49 and 77, VFI stabilized at a baseline of around 100 g/kg of fresh iBW weekly (0.29 g/ind. daily). In the final 5 days prior to ecdysis, the VFI dropped sharply to 50 g/kg of fresh iBW weekly (0.15 g/ind. daily).

Cumulative moults

The cumulative moults were clearly affected by the VFI levels when all diets were combined (Figure 5). Two groups were identified: a low VFI group (1.05 ± 0.12 percent of iBW consumed daily) and a high VFI group (1.97 ± 0.12 percent iBW daily). Cumulative moults during the experiment were 50 percent and 100 percent in the low and high VFI groups, respectively.

Moulting and survival rates of juvenile crabs fed graded, cholesterol-level-supplemented formulated diets

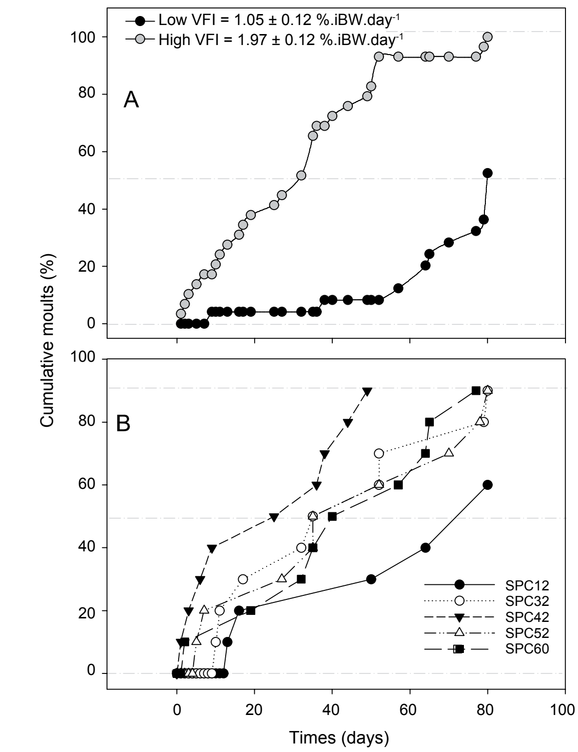
Supplementing cholesterol levels in the diet from 0.05 percent to 0.1 percent significantly increased the moulting rate from 70.32 percent to 90.04 percent ($P < 0.05$) during the 30-day culture period (Figure 6). However, further increase in the supplemented cholesterol levels from 0.1 to 0.3 percent resulted in a significant decrease in the moulting rate, from 90.04 to 73.48 percent ($P < 0.05$). The highest moulting rate, 90.04 percent, was observed in the treatment with 0.1 percent supplementary cholesterol, equivalent to 0.38 percent total cholesterol in the diet, indicating optimal levels for *S. paramamosain* juvenile.

Cholesterol is recognized as an important metabolic precursor for ecdysone biosynthesis in crustaceans (Teshima and Kanazawa, 1971; Watson and Spaziani, 1982; Sheen *et al*., 1994). Additionally, the uptake of cholesterol by the Y-organ is significantly enhanced when the moulting process is initiated (Spaziani and Kater, 1973). This study demonstrated that an increased cholesterol level in the diet can stimulate the excretion of moulting hormones, resulting in higher moulting rates. However, excessive cholesterol in the diet can negatively impact growth and survival in crustaceans (Sheen, 2000), not due to toxicity but rather because of nutrient imbalances (Mercer, 1982).

The survival rates of crabs in the experimental treatments and control group (without supplemental cholesterol) were high, ranging from 70.56 to 75 percent (Figure 6). The control group, which did not receive supplemental cholesterol, had the lowest survival rate (70.56 percent); however, no significant differences were observed between this group and the other treatments (P > 0.05). This suggests that adding cholesterol at various concentrations (0–0.3 percent) to the formulated feed did not significantly affect the survival rate of *S. paramamosain* juveniles. The results indicate that the initial cholesterol level in the control diet (0.28 percent) was already sufficient for crab juveniles to grow and survive. Sheen (2000) reported that for *S. serrata* juveniles, the optimal dietary cholesterol level was 0.51 percent, with the highest survival (93 percent) recorded in juveniles fed a diet containing 0.21 percent supplemental cholesterol. This study also suggested that even at the juvenile stage, *S. serrata* could survive on relatively low levels of dietary cholesterol.

FIGURE 5

Cumulative moults of crab *Scylla serrata* juveniles (% initial crab numbers) according to the voluntary feed intake (VFI) levels (a) and different diets (b)

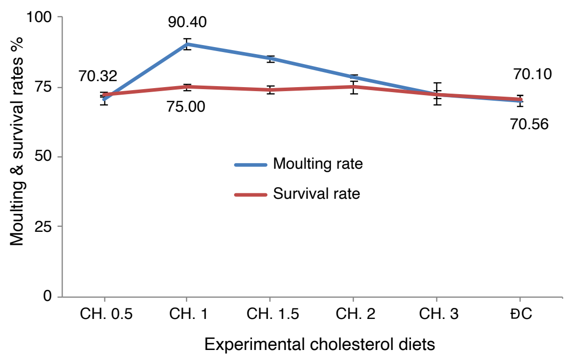


(iBW = fresh initial body weight)

FIGURE 6

Moulting and survival rate of *Scylla paramamosain* juveniles fed diets supplemented with graded cholesterol

Different letters represent statistically significant differences (P < 0.05)



Moulting duration

The results indicate that the moulting duration of crab juveniles was similar among treatments, except for the group fed the diet without cholesterol supplementation (Figure 7). While there were some differences in moulting duration between the treatments, they were not statistically significant, ranging from 22.06 to 27.21 days. However, a significant difference was observed in the control group (0 percent cholesterol supplementation), where crabs had a moulting duration of 29.16 days, which was longer compared to all other treatments. Among the treatments, the group supplemented with 0.1 percent cholesterol exhibited the shortest moulting period of 22.06 days, which was 7 days

FIGURE 7

Moulting duration of *Scylla paramamosain* juveniles fed diets supplemented with graded cholesterol

Moulting rates marked with different letters are statistically significant (P < 0.05)

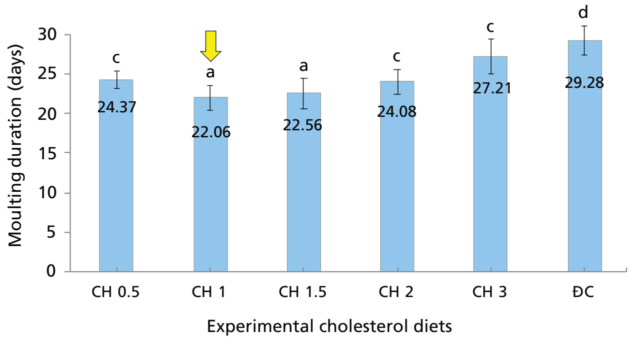


FIGURE 8

Feed conversion rate of *Scylla paramamosain* juveniles fed trash fish and formulated diet

Moulting rates marked with different letters are statistically significant (P < 0.05)

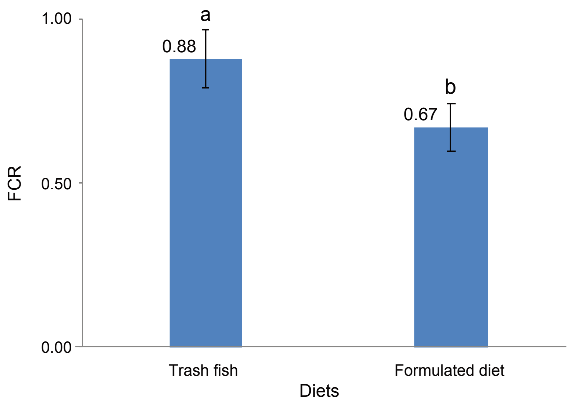
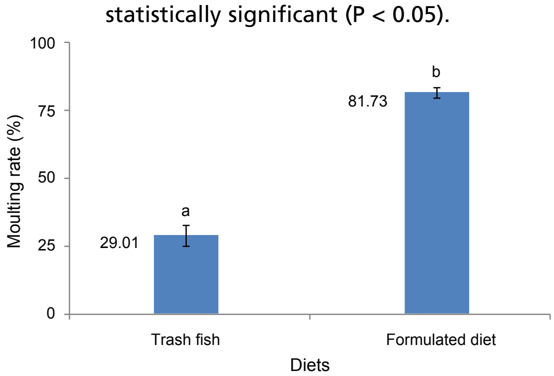


FIGURE 9

Moulting rates of *Scylla paramamosain* juveniles fed trash fish and formulated diet

Moulting rates marked with different letters are statistically significant (P < 0.05).



shorter than the control group fed the diet without added cholesterol.

Comparison of formulated mud crab feed with trash fish

The trial results showed that the FCR of crabs given pellet feeds were significantly lower than those fed trash fish: 0.67 and 0.88, respectively. It is hypothesized that the balanced nutritional profile of the pellets provided a more complete diet than the trash fish (Figure 8). The moulting rate (cumulative moult) of crabs fed pellets (81.73 percent) was 2.8 times higher than those fed trash fish (29.01 percent) (Figure 9). The weight gained after ecdysis was similar for crabs fed pellets (61.41 percent) and those fed trash fish (57.08 percent). In addition, the same trend was seen for survival rates, which were 94.44 percent and 84.44 percent for crabs fed pellets and those fed trash fish, respectively (Figure 10).

These results strongly indicate that a formulated feed can be developed for juvenile mud crabs to replace trash fish. Crabs fed formulated feed had a higher moulting rate, whilst there was no difference in survival rate or weight gained after moulting.

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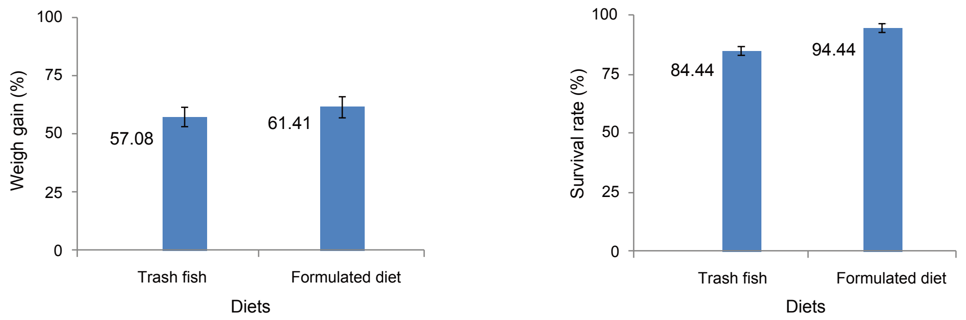
FIGURE 10
Weight gains and survival rates of *Scylla paramamosain* juveniles fed trash fish and formulated diet



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Mud crab feeds and feeding management

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ABSTRACT

Formulated feeds were developed for juvenile mud crab *Scylla serrata* grow-out culture. Currently, there are no commercial feeds available in the market for mud crab farming in pelleted form. Farmers have been relying on fish, molluscs and other aquatic animal by-products (low value fish trimmings, shrimp heads, chicken offal, etc.) or supplementing with feeds formulated for other commercial species to feed the crabs. Three feeding trials were conducted to assess the feasibility of using formulated feed on growth performance of mud crab. In the first feeding trial, commercial feeds of shrimp and grouper were fed for 73 days. The feeds used for either shrimp and grouper had no significant effect on final body weight (g/ind.) and carapace width (CW) of the cultured crab ($p > 0.05$). The total weight gain (in percentage) of mud crabs was less both in the shrimp (55.5 ± 25.0) and grouper (53.4 ± 22.0) feed groups, which were insignificant to each other ($p > 0.05$). Crabs fed shrimp and grouper feed had moulting rates of 65 and 68 percent, respectively, which were not statistically significant ($p > 0.05$). In the second trial, a seafood mix feed (an equal blend of mussels, squid, oyster and trash fish) and formulated feed were provided to the crabs for 60 days. The formulated crab feed included nutrient rich marine ingredients, lecithin, vitamin and mineral premixes, natural pigments (astaxanthin) and gelatine as binder, to supply the necessary nutrients for optimum crab growth and health. The crabs fed with formulated feed showed significantly higher final body weight (g/ind.) and specific growth rate (SGR) ($p < 0.05$) compared to crabs fed the seafood mix. The total weight gain (in percentage) in formulated feed fed group was 576 ± 77 which was significantly higher than the crabs fed with seafood mix (206 ± 45) ($p < 0.05$). Crab shell pigmentation was observed in both feeding trials. Crabs fed with formulated feed containing astaxanthin showed a brown coloured carapace, whereas crabs fed with the other feeds had blue carapace. In the third feeding trial, black soldier fly larvae (BSFL) meal was used to replace fishmeal at 0, 50 and 100 percent in mud crab feed. After a 120-day feeding trial, fishmeal (FM) replacement feed had no effect on weight gain (g/ind.), final weight (g/ind.), SGR, feed conversion ratio (FCR), or protein efficiency ratio (PER) ($p > 0.05$). In conclusion, mud crab could be fed on formulated feed for better growth performance compared to the commercial feed of shrimp, grouper, and seafood mix. Additionally, BSFL could also be used as a replacement of fishmeal in mud crab feed to support growth and health.

INTRODUCTION

Aquaculture production of all mud crab *Scylla* spp., which include the green mud crab (*Scylla paramamosain*), the Indo-Pacific swamp crab (*S. serrata*), the orange mud crab (*S. olivacea*) and the purple mud crab (*Scylla tranquebarica*) was 141 264 t in Southeast Asia in 2021 (FAO, 2023). The major producing countries in the region are Viet Nam (81 144 t), the Philippines (23 112 t) and Indonesia (12 823 t). The majority of farming systems for crabs are extensive, relying on low-value fish or by-products from processing other livestock, such as chicken offal, as feed. Some crab farmers have experimented with commercial feeds designed for other aquatic species, such as shrimp or carnivorous fish, but these efforts have yielded poor results. Furthermore, the use of raw, fresh or frozen food may pose some contamination and disease issues. The use of formulated feeds for crab farming is still incipient, as the demand might not support or justify commercial production by feed manufacturers. Formulated feeds offer several advantages, including providing consistent nutrition, promoting improved growth and moulting, enhancing crab health and shell pigmentation, reducing the risk of contamination and ensuring biosecurity. *Scylla serrata* showed faster growth rate and frequent moulting when fed feeds containing high protein (55 percent) and lipid (15 percent) levels (Shelley and Lovatelli, 2011). Most of the crustaceans, including mud crabs, need to moult and generate a new cuticle under the shell for growth. Chitin is one of the main components of the cuticle (Kaya *et al.*, 2014).

Black soldier fly larvae (BSFL) are a rich source of chitin and have a comparable nutritional profile to fishmeal (Mohan *et al*., 2022). The protein and lipid content of BSFL is 38–57.6 percent and 21.6–28.4 percent, respectively (Liu *et al*., 2017). The BSFL is a rich source of amino acids, however, variations in body composition were observed depending on the culture substrates used (Mohan *et al.*, 2022). While BSFL are widely recognized as an excellent protein source, the complete replacement of FM with BSFL in aquafeed has not yet been successfully achieved (Henry *et al*., 2015). Studies have shown that BSFL can replace 18–36 percent of fishmeal in rainbow trout diets (Sealey *et al*., 2011) and 6.7–12.5 percent of dietary protein in Atlantic salmon diets (Weththasinghe *et al*., 2021).

High inclusion levels of BSFL in aquafeed have been shown to reduce growth performance and protein digestibility (Kroeckel *et al*., 2012; Weththasinghe *et al*., 2021). However, the potential use of BSFL in mud crab diets has not yet been investigated. Therefore, this study aimed to evaluate the feasibility of using commercially available shrimp and grouper feeds, seafood mix, and formulated feeds incorporating BSFL as a substitute for fishmeal in mud crab (*S. serrata*) diets, and to assess their effects on growth performance.

METHODOLOGY

High protein commercial and formulated feeds

An experiment was carried out to test the feasibility of using commercial feeds of shrimp (48 percent crude protein; 6 percent fat) and grouper (44 percent crude protein; 14 percent fat) on the growth performance of *S. serrata*. The commercial feeds were separately ground and extruded through a 2 mm die. Juvenile crabs (initial body weight 14.4 ± 4.7 g; n = 20/treatment) were fed twice a day at 10 percent body weight for 60 days.

A second feeding trial was conducted to determine the growth performance of *S. serrata* using a seafood-mix feed and a formulated feed with gelatine. The seafood-mix feed was prepared by blending mussels, squid, oyster and trash fish in same proportion and adding corn starch as binder. The mixture was cooked in boiling water until it rose to the top of the water. The formulated feed was prepared by mixing the ingredients and adding gelatine dissolved in warm water, mixed and rolled into small cylindrical pellets. The different types of feeds are presented in Figure 1 and the proximate composition of the formulated feed is shown in Table 1. Juvenile crabs (initial body weight 0.54 ± 0.08 g; n = 7/treatment) were fed twice a day at 10 percent body weight for 73 days. The calculated nutritional composition of the seafood mix feed was 14.5 percent crude protein and 2.8 percent fat on “as-is” basis. Feeds were kept refrigerated at 2–4 °C.

During both trials, crabs were housed individually in floating plastic containers within a recirculating aquaculture system. The water quality parameters, including salinity (18 ppt), temperature (27 °C), dissolved oxygen (> 5 mg/L), pH (7.6) and total ammonia nitrogen (≤ 0.2 mg/L) were carefully controlled to ensure they remained within the acceptable range for the species. At the end of both trials, the pigmentation of the crab exoskeleton was observed and recorded.

FIGURE 1
Experimental diets fed to juvenile mud crabs (*Scylla serrata*)
Extruded grouper feed (a), extruded shrimp feed (b), formulated feed with gelatine (c) and seafood-mix feed (d)

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TABLE 1
Formulation and composition ("as-is" basis) of the experimental feed for *Scylla serrata*

Ingredients	%	Ingredients	%
Fishmeal	29.8	Soy lecithin	1.0
Soybean meal (fermented)	18.0	Astaxanthin (pigment)[a]	0.2
Poultry by-product meal	10.0	Vitamin-mineral premix[b]	1.0
Squid liver meal	6.0	**Proximate composition**	**%**
Blood meal	3.0	Crude protein	43.3
Krill meal	2.0	Crude fat	10.0
Fish hydrolysate	5.0	Mineral	13.3
Fish oil	6.0	Total carbohydrates	13.4
Gelatine	10.0	Energy (kcal/kg)	3 922.4
Polychaete meal	8.0		

[a] Carophyll® pink, DSM Thailand.

[b] Vitamin-mineral premix (unit/kg): Vitamin A 3 500 000 IU, Vitamin D3 1 500 000 IU, Vitamin E 75 g, Vitamin K3 15 g, Vitamin B1 12.5 g, Vitamin B2 10 g, Vitamin B6 12.5 g, Vitamin B12 0.01 g, Niacin 50 g, Panthotenic acid 40 g, Biotin 0.5 g, Folic acid 5 g, Vitamin C 100 g, Copper 12.5g, Manganese 15 g, Iodine 0.5 g, Cobalt 0.1 g, Zinc 50 g, Selenium 0.175 g.

Formulated feeds with full-fat black soldier fly larvae protein

Three iso-nitrogenous (crude protein 45 percent) feeds were formulated and fed to *S. serrata* in a completely randomized design. The basal feed with 30 percent FM served as the control (100 percent FM). Two experimental feeds were prepared replacing FM at 50 and 100 percent. The ingredients and formulations are shown in Table 2. Full-fat

BSFL meal and other ingredients were grounded, sieved and homogenously mixed in a Hobart mixer. Around 30 percent warm water was applied to prepare the dough. The pellets were made into sizes of 2.0–2.5 cm in length as shown in Figure 2.

Each feed was fed to three mud crabs with an initial body weight of 34.83 ± 7.90 g and carapace width (CW) of 5.85 ± 0.44 cm to satiation in a recirculating aquaculture system for 120 days. The feeding trial was performed twice with the same experimental set up conditions. The salinity, temperature, pH and dissolved oxygen of the water were 25.0 ± 1.0 ppt, 26.4 ± 1.5 °C, 7.5 ± 0.50, and 4.5 ± 0.72 mg/L, respectively. The ammonia, nitrite and nitrate levels were measured at 0.25 ± 0.10 mg/L, 0.00 mg/L, and 20.00 ± 10.00 mg/L, respectively, which remained within acceptable ranges throughout the study. At the end of the trial, each crab was individually weighed and its CW measured. Likewise, weight gain (g), final weight (g), specific growth rate (SGR; %/day), feed conversion ratio (FCR) and protein efficiency ratio (PER) were determined.

FIGURE 2
Experimental diets fed to juvenile mud crabs (*Scylla serrata*)
Feeds with zero (a), 50 % (b) and 100% (c) BSFL content

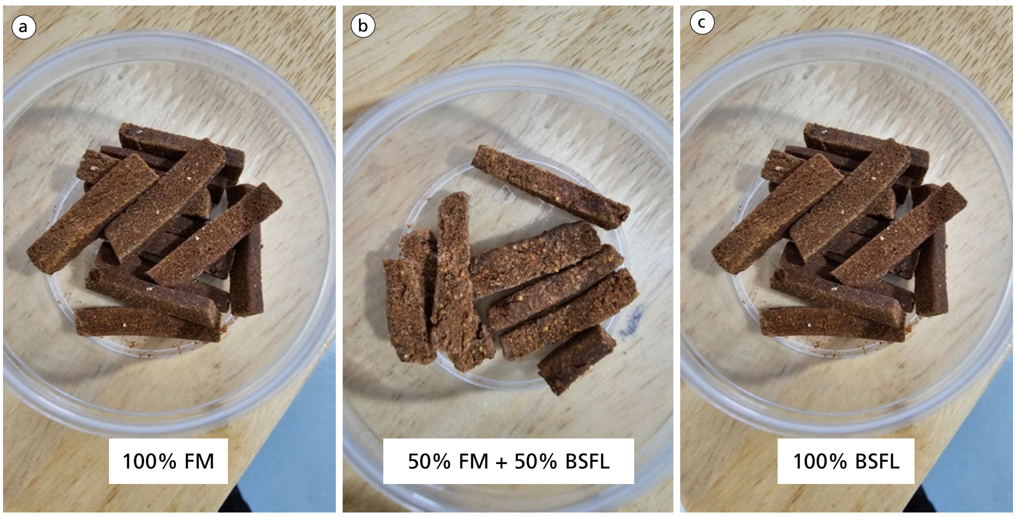


TABLE 2
Ingredients and proximate composition (% as-fed basis) of the experimental feeds with varied levels of fishmeal (FM) and black soldier fly larvae (BSFL)

Ingredients (% of feed)	T1 (100% FM)	T2 (50% FM+50% BSFL)	T3 (100% BSFL)
Fishmeal	30.0	15.0	0
BSFL (microwave-dried)	0	15.0	30.0
Wheat gluten	7.5	10.0	18.0
Squid liver meal	6.0	7.0	8.0
Krill meal	8.0	8.0	3.0
Fish hydrolysate	4.0	4.0	4.0
Fish oil	8.0	1.0	–
Dried yeast	–	1.5	3.0
Lecithin	2.0	2.0	2.0
Gelatine	10.0	10.0	10.0
Ulva meal (seaweed)	2.0	2.0	2.0
Polychaete worms	8.0	8.0	8.0

TABLE 2 (CONTINUED)

Ingredients (% of feed)	**T1 (100% FM)**	**T2 (50% FM+50% BSFL)**	**T3 (100% BSFL)**
Wheat flour	8.0	10.0	5.5
Mineral premix	3.0	3.0	3.0
Vitamin premix	3.0	3.0	3.0
Carophyll pink	0.5	0.5	0.5
Proximate composition (%)			
Crude protein	45.0	44.80	45.20
Crude lipid	14.80	13.10	16.60
NFE[1]	8.60	13.0	12.80
Energy (Kcal)	4 274.10	4 284.70	4 635.70

[1] Nitrogen free extractables.

Statistical analysis

Growth performance data from both feeding trials – the first (shrimp feed and grouper feed) and the second (seafood mix and formulated feed) – were analysed using GraphPad™ Prism 9.3.1 software. Welch's t-test was applied to evaluate the data, with differences between treatments considered significant at a 5 percent probability level.

For the experiment evaluating FM replacement with BSFL, all collected data were analysed using one-way ANOVA in the statistical software SPSS 22 (SPSS Inc., Chicago, United States of America) for Microsoft Windows. Tukey's range test was used to differentiate between means, with significance determined at the 95 percent confidence level.

RESULTS

High-protein commercial and formulated feeds

Growth performance of crabs fed with extruded shrimp and grouper feed, and crabs fed with formulated feed and seafood-mix are presented in Table 3 and Table 4, respectively. The crabs fed with shrimp or grouper feed did not show any significant differences ($p > 0.05$) in the final body weight and final CW, total weight gain and survival rate (Table 3). Total weight gain (percentage) varied between 53.4 ± 22.0 to 55.5 ± 25.0.

TABLE 3

Morphometric parameters and survival rate of *Scylla serrata* after feeding with extruded shrimp and grouper feed for 60 days

Parameters	**Shrimp feed**	**Grouper feed**
Initial body weight (g)	14.4 ± 4.7	22.9 ± 10.7
Initial carapace width (cm)	4.1 ± 0.5	4.7 ± 0.8
Final body weight (g)	22.0 ± 8.0	32.0 ± 15.3
Final carapace width (cm)	4.8 ± 0.6	5.4 ± 0.9
Total weight gain (%)	55.5 ± 25	53.4 ± 22.0
Survival (%)	95	100

Values are mean ± SE, where n = 20.

Weight gain (g/ind.) = final weight (g/ind.) – initial weight (g/ind.).

In the second feeding trial, the final body weight, total weight gain percentage and SGR were significantly higher in crabs fed with the experimental feed compared to the seafood-mix feed ($p < 0.05$) (blend of mussels, squid, oyster and trash fish) as shown in

Table 4. However, FCR, moulting and survival percentage of crabs were comparable ($p > 0.05$) in the two feeding groups.

TABLE 4
Comparison of morphometric and performance parameters of *Scylla serrata* after 73 days feeding with seafood-mix and experimental feed

Parameters	Seafood-mix feed	Experimental feed
Initial body weight (g)	0.54 ± 0.20	0.54 ± 0.17
Initial carapace width (cm)	1.57 ± 0.22	1.57 ± 0.19
Final body weight (g)	1.78 ± 0.83[b]	3.23 ± 0.73[a]
Final carapace width (cm)	2.32 ± 0.39	2.87 ± 0.18
Total weight gain (%)	206 ± 45[b]	576 ± 77[a]
Specific Growth Rate (%/day)	1.47 ± 0.42[b]	2.57 ± 0.34[a]
Feed Conversion Rate	7.1 ± 2.59	3.87 ± 0.96
Moulting (%)	71	86
Survival (%)	71	86

Values are mean ± SE, where n = 7.

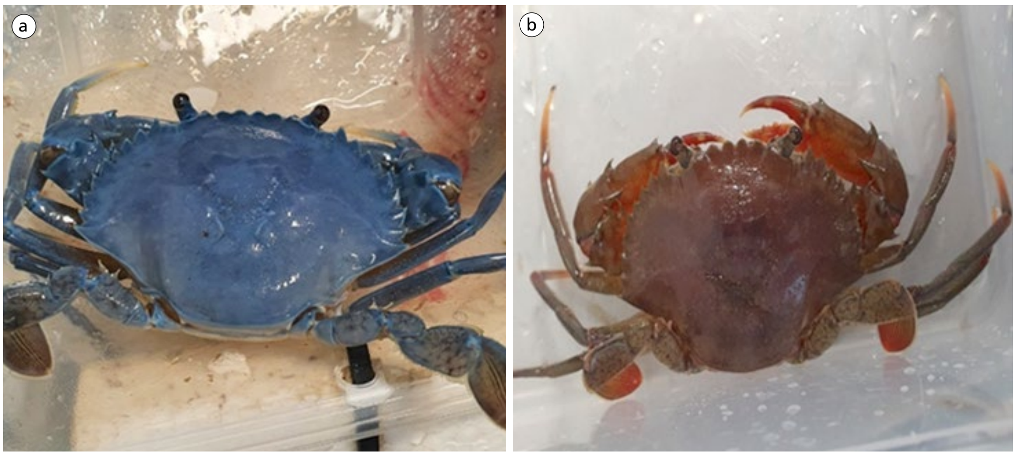
Weight gain (g/ind.) = Final weight (g/ind.) - Initial weight (g/ind.).

Specific growth rate (SGR, %/day) = ([lnW2 - lnW1] / [T2 - T1]) × 100; W1 = Initial weight; W2 = Final weight; T2 - T1 = Culture period (days).

Feed conversion ratio (FCR) = feed intake / weight gain (g/ind.).

Carapace pigmentation varied among crabs fed with the experimental feed and those fed with other tested diets, including commercial shrimp feed, grouper feed, and seafood mix feed. Notably, crabs fed the experimental diet containing astaxanthin exhibited distinct pigmentation, while crabs on all other diets developed bluish carapaces, as illustrated in Figure 3.

FIGURE 3
Colour difference of juvenile *Scylla serrata* fed with seafood-mix (a) and experimental feed (b)



Black soldier fly larvae protein in mud crab diet

After 120 days of the feeding trial, no mortality was observed among the crabs across all feeding groups. Growth performance data are presented in Table 5. Key parameters, including final weight, weight gain, CW, SGR, FCR and PER, showed no significant differences ($p > 0.05$) in crabs fed diets where FM was replaced with BSFL at levels up to 100 percent.

TABLE 5
Growth performance and nutrient utilization of mud crab after 120 days of feeding with fishmeal (FM) replacement diet using black soldier fly larvae (BSFL)

Feed type	Initial weight (g/ind.)	Initial carapace width (cm)	Final weight (g/ind.)	Weight gain (g/ind.)	Carapace length gain (cm)	SGR (%/day)	Consumed feed (g/ind.)	FCR	PER
T1 (100% FM)	25.75 ± 7.71	5.37 ± 0.61	91.86 ± 33.04	66.02 ± 25.48	2.38 ± 0.25	1.05 ± 0.06	98.89 ± 4.78	1.60 ± 0.55	1.47 ± 0.50
T2 (50% FM + 50% BSFL)	36.80 ± 5.55	5.97 ± 0.19	114.26 ± 13.90	77.46 ± 16.67	2.36 ± 0.33	1.03 ± 0.19	111.73 ± 10.84	1.48 ± 0.31	1.55 ± 0.29
T3 (100% BSFL)	37.17 ± 8.88	6.05 ± 0.40	113.55 ± 12.48	76.38 ± 14.50	2.45 ± 0.80	1.06 ± 0.07	119.03 ± 10.11	1.59 ± 0.27	1.42 ± 0.22

Values are mean ± SD, n = 3.

Weight gain (g/ind.) = Final weight (g/ind.) - Initial weight (g/ind.)

Specific growth rate (SGR; %/day) = ([lnW2 - lnW1] / [T2 - T1]) × 100; W1 = Initial weight, W2 = Final weight, T2 - T1 = Culture period (days).

Feed conversion ratio (FCR) = feed intake / weight gain (g/ind.).

Protein efficiency ratio (PER) = weight gain / total protein intake.

DISCUSSION

Diets of 45–55 percent crude protein and 9–15 percent lipid appear to support optimal growth in *S. serrata* crablets (Shelley and Lovatelli, 2011). Catacutan (2002) reported that a formulated feed with 32–40 percent protein and either 6 percent or 12 percent fat is conducive to optimal growth in mud crabs. In another study, Catacutan (2017) reported better conversion ratios and specific growth rates in feed containing higher protein levels (48 percent). In the present study, crabs fed on formulated feed with 43 percent crude protein and 10 percent crude fat presented a higher percentage weight gain compared to the commercial shrimp feed, commercial grouper feed or seafood-mix feed. The results showed that faster weight gain and frequent moulting can be achieved with feeds containing higher protein and lipid levels. Nevertheless, feed conversion ratio was still poor (3.87 ± 0.96) in crabs fed with formulated feed as compared to previously reported values of 1.2–2.1:1 for juvenile crabs (Shelley and Lovatelli, 2011).

Mud crabs have been reported to efficiently digest a variety of plant-based and terrestrial animal ingredients (Catacutan *et al.*, 2003), expanding the range of raw materials that can be used to develop nutrient-rich and more sustainable crab feeds. However, mud crabs are messy eaters, handling feed with their chelae and often leaving significant amounts of uneaten feed behind. To minimize feed wastage, the use of an effective binder is essential. From a nutritional perspective, protein-based binders such as zein, wheat gluten, or gelatine are preferable to polysaccharide-based binders like agar, alginate or carrageenan (Holme, Zeng, and Southgate, 2009).

Observations of mud crabs feeding in the wild, such as their consumption of marine worms, suggest that they may feed more efficiently on tubular, "spaghetti-like" feeds (Shelley and Lovatelli, 2011). Based on this insight, gelatine was used in the formulated feeds to enable the creation of cylindrical pellets measuring 4–5 cm in length. These pellets were stable, easier for the crabs to handle, and minimized feed waste. The inclusion of marine ingredients enhanced the feed's attractiveness, while the addition of astaxanthin was critical for promoting natural shell pigmentation.

Formulated feeds offer consistent and balanced nutrition, supporting improved growth, better health, and vibrant shell coloration – a key factor influencing the marketability of crabs.

The use of BSFL in *S. serrata* feeds during the 120-day feeding trial demonstrated that BSFL can serve as a viable alternative protein source, as it had no adverse effects on crab health or survival. Previous studies have shown that BSFL can promote positive growth and improve the health status of several aquatic species (Mohan *et al.*, 2022).

While no significant differences were observed in growth performance or FCR between the control and BSFL-incorporated experimental feeds, the results suggest that insect protein in the feed supports healthy growth due to its essential amino acid profile. Consequently, fishmeal can be safely replaced with full-fat BSFL in formulated feeds for mud crabs.

In conclusion, mud crabs can benefit from feeding on formulated diets, which improved growth performance compared to commercial shrimp, grouper feeds or seafood-mix. Additionally, BSFL can be used as an alternative protein source in mud crab feeds, promoting growth and enhancing overall health. However, further research is needed to ensure that crab health and growth performance are not negatively impacted when fed pelleted diets containing BSFL over longer periods. In this study, while the crabs were gradually conditioned to accept formulated pellets over 2–4 weeks, they exhibited varying feeding behaviours. Some crabs responded immediately to the pellets, while others took longer to start eating or consumed the feed more slowly. Additional research is needed to better understand these feeding behaviours and optimize the adaptation of crabs to formulated feeds.

RECOMMENDATION

Given the declining wild fish stocks, there is an urgent need to prioritize fish for human consumption rather than using it for fishmeal in aquaculture. To reduce reliance on fish, aquaculture feeds must shift towards alternative ingredients that do not compete with human nutrition. Formulated feeds for crabs should incorporate more terrestrial plants, microalgae, animal by-products, invertebrates and single-cell proteins. Further research is needed to determine optimal inclusion levels based on factors such as digestibility, growth, gut health, immune response and production cost. Additionally, it is crucial to include appropriate binders, lipids, sterols and pigments in the feed, as these are essential for promoting growth, successful moulting and maintaining overall health (Kanazawa, 2001; Suprayudi, Takeuchi and Hamasaki, 2012).

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Prophylactic treatment for mud crabs

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ABSTRACT

There are no commercial mud crab production farms in Singapore but there are a few companies such as local importers and wholesalers that utilize "water crabs" for crab fattening. As imported mud crabs are coming from various sources including wild-caught and cultured, there is a risk of them carrying pathogens causing disease that would significantly impact the farming operations. The current prophylactic treatment given to imported mud crabs is a formalin (40 percent formaldehyde) bath (150–200 ppm) for 30 minutes. The present study was done to identify an environmentally friendly prophylactic treatment for mud crabs for companies that are engaged in mud crab fattening, grow-out and soft-shell crab production, or for crabs used in hatchery research. In this preliminary work, comparative analysis of five different treatment modalities were studied: formalin, formalin in combination with oxolinic acid (OXO), sodium percarbonate (SPC) and OXO, SPC and oxytetracycline (OTC), and a commercial organic water conditioner for invertebrates (Mangrozyme™). Improvements in the treatment outcome were observed among the SPC/OXO and SPC/OTC experimental groups.

INTRODUCTION

Singapore is the world's second-largest importer of live mud crabs, following China, with annual imports exceeding 3.3 million kg of live and chilled mud crabs, and an average daily consumption of 10 t. A variety of pathogens – including viruses, bacteria, parasites, and fungi – can potentially affect mud crab broodstock, posing significant biosecurity risks and potentially impacting hatchery operations. Shell disease and fouling organisms are common issues among mud crab broodstock, which are sourced from diverse locations. Previous investigations into mud crabs with shell disease identified pathogens such as *Vibrio* species (*V. parahaemolyticus*, *V. harveyi*), as well as other bacteria including *Pseudoalteromonas lipolytica*, *Priesta megaterium* and *Bacillus amyloliquefaciens* (AIC, unpublished data).

Diseases in *Scylla serrata* continue to cause significant mass mortalities and substantial economic losses for farmers worldwide (Chen *et al*., 2011). Of the four viral diseases reported in mud crabs – white spot syndrome virus (WSSV), muscle necrosis virus, mud crab reovirus (MCRV) and baculovirus – MCRV is particularly pathogenic. MCRV has been implicated in numerous outbreaks and severe economic losses in open pen culture systems. Furthermore, MCRV has been associated with sleeping disease (SD) in *S. serrata* (Weng *et al*., 2007; Zhang *et al*., 2013).

Proper broodstock handling, as well as hatchery and nursery culture operations, require stringent hygiene and biosecurity measures to achieve consistently high larval survival rates. While existing procedures for incoming adult crabs, such as short-term formalin baths, are recommended, they may not provide comprehensive protection. Although Singapore does not have commercial mud crab production farms, a few farms and importers engage in sorting water crabs from the catch for fattening or soft-shell crab production. Implementing effective treatment protocols during crab conditioning is a critical first step in ensuring farm biosecurity. This study evaluated a comprehensive prophylactic treatment for incoming mud crabs, focusing on the effectiveness of non-formalin approaches compared to current standard practices.

METHODOLOGY

In this preliminary investigation a total of 30 samples of *S. serrata* including 23 females and 7 males from the same source, were divided into five experimental groups as follows:

GP-I:	**Standard protocol formalin 150 ppm for 30 minutes.**
GP-II:	**Formalin at 100 ppm for 1 hour daily for 2 days, followed by an oxolinic acid (OXO) treatment 15 ppm (1.5 g/100 L) – 1 hour daily for 5 days.**
GP-III:	**Sodium percarbonate (SPC) 45 g + citric acid (16 g/100 L) – 1 hour daily for 2 days, followed by OXO treatment as in GP-II.**
GP-IV:	**SPC treatment as in GP-III for 2 days, followed by oxytetracycline (OTC) 20 ppm (2 g/100 L) – 1 hour daily for 5 days.**
GP-V:	**Commercial Mangrozyme^{TM} for invertebrates treatment – 10 ppm daily for 7 days.**

Six crabs were allocated to each experimental group (Table 1). The average body weight (BW) and carapace width (CW) of crabs were 252.56 ± 10.86 g and 11.02 ± 1.7 cm, respectively. The mud crabs were maintained in 25 ppt salinity water at room temperature (26–27 °C) with a dissolved oxygen content of > 5 mg/L. Unionized ammonia and nitrite levels were < 1 ppm and < 0.1 ppm, respectively. The doses of SPC, OXO and OTC are derived from AIC's treatment protocols for marine fishes for ectoparasites and bacterial pathogens. The usual treatment course is 5–7 days for bacteria, with intermittently spaced treatment for fish parasites extending for 14 days. The farms follow an appropriate withdrawal period post-treatment regime to comply with the maximum residue level (MRL) of drugs in randomly sampled fishes.

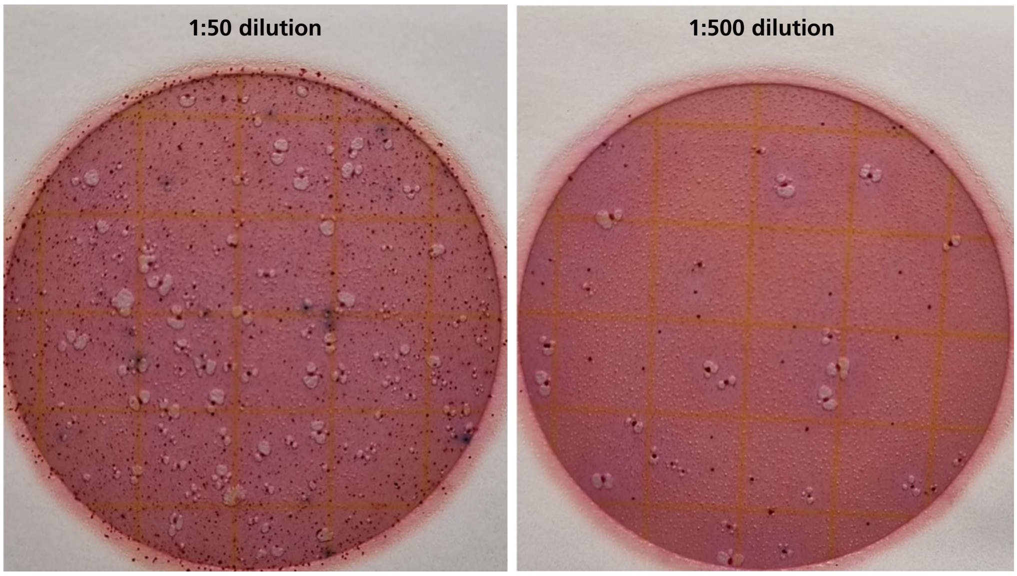
Water from each treatment tank was analysed for total coliform and *Escherichia coli* count using the 3M Petrifilm aerobic plate count method (Figure 1) post-treatment 3 (T3) to compare microbial load in respective crab holding tanks.

TABLE 1
Experimental groups (GP) of mud crabs and prophylactic treatment (T) modalities

		GP-I	GP-II	GP-III	GP-IV	GP-V
	Baseline crab sampling					
Day 0	T1	Formalin	Formalin	SPC	SPC	MangrozymeINV
Day 1	T2	–	Formalin	SPC	SPC	MangrozymeINV
	Day 1 sampling					
Day 2	T3	–	OXO	OXO	OTC	MangrozymeINV
Day 3	T4	–	OXO	OXO	OTC	MangrozymeINV
	Day 3 sampling					
Day 4	T5	–	OXO	OXO	OTC	MangrozymeINV
Day 5	T6	–	OXO	OXO	OTC	MangrozymeINV
Day 6	T7	–	OXO	OXO	OTC	MangrozymeINV
Day 7		Day 6 sampling				

SPC: Sodium percarbonate; OXO: Oxolinic acid; OTC: Oxytetracycline.

FIGURE 1
Total coliform and *Escherichia coli* count determination in 3M Petrifilm aerobic count plate, showing colonies at two different water sample dilutions



Sedation or stunning followed by various euthanasia methods, such as spiking nerve centres or using a clove oil bath, has been employed in different studies to ensure the humane killing of mud crabs. In this study, mud crabs were sedated in a saltwater ice slurry for 15 minutes. Haemolymph samples were collected from the base of the swimming legs using a 1 ml insulin syringe (29 gauge × 12.7 mm) and immediately transferred to anticoagulant tubes containing a solution of 400 mM NaCl, 25 mM EDTA, 30 mM sodium citrate, 25 mM citric acid, 150 mM dextrose (pH 5.0).

After haemolymph collection, the mud crabs were euthanized using 300 mg/L AQUI-S for 30 minutes. The crab shells were then opened for gross observation of internal organs and gill parasites. Tissue samples from the hepatopancreas, gills, gut and heart were dissected, homogenized and preserved through ultralow freezing. Portions of the homogenates were plated on selective and enrichment agar media for microbiological analysis, including TCBS (thiosulfate citrate bile salt sucrose agar), BHI (brain heart infusion agar), MA (marine agar) and TSA (tryptic soy agar). The remaining homogenates were divided for DNA and RNA extractions and stored at -80°C for molecular analysis.

Gill tissue DNA extracts were screened for WSSV using an IQ2000 WSSV PCR kit following the manufacturer's protocol. Positive PCR results were identified by the presence of 333 bp and 630 bp bands during agarose gel electrophoresis, visualized using gel red staining.

MCRV was screened from RNA extracts of hepatopancreas and gut tissue samples collected from mud crabs representing the five experimental groups. In brief, cDNA was generated by reverse transcription reaction, followed by PCR using forward primer (5'-TCAGTGTCTTCAGCTTTAGGTTG-3') and reverse primer (5'-TCTCTTGAGGCCTAGATTCG-3') with cycling conditions involving initial denaturation at 95 °C for 2 minutes followed by 35 cycles of 10 seconds at 95 °C (denaturation), 30 seconds at 61 °C (annealing), 30 seconds at 72 °C (elongation) and a final elongation for 5 minutes at 72 °C. The PCR-amplified products were analysed by agarose gel electrophoresis and Gelred staining and visualization in a Syngene G:BOX imaging system. Positive PCR produced a predicted 483-bp amplicon.

RESULTS

The average baseline total coliform and *E. coli* count determined in experimental tanks was observed to be 3 000 CFU/ml. More than 1-log reduction in water bacterial load was observed among experimental groups III and IV during Day-3 sampling as shown in Table 2 below.

TABLE 2
Coliform and *Escherichia coli* count in experimental tank water sampled on Day-3 of the experimental study

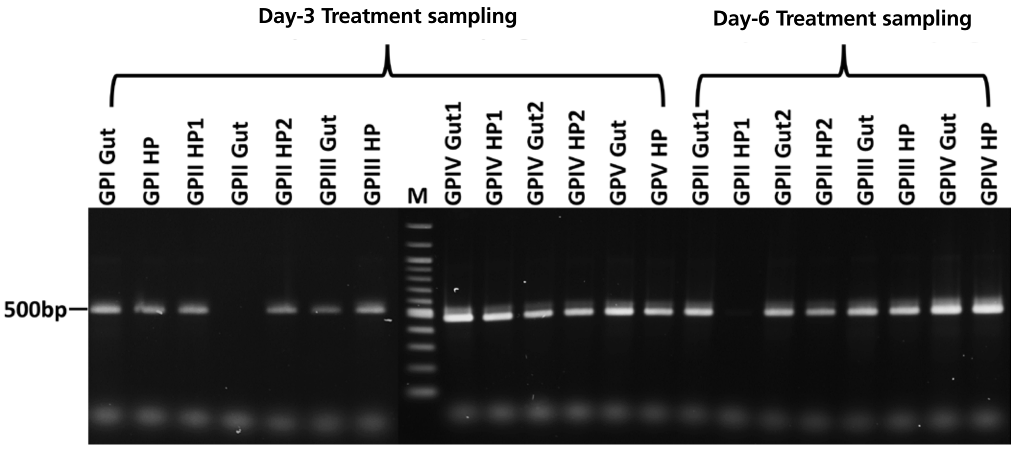
Experimental tanks	Coliform count (CFU/ml)	*E. coli* count (CFU/ml)
GP-I	5 000 ± 424	2 100 ± 141
GP-II	1 550 ± 353	430 ± 28
GP-III	360 ± 56	125 ± 35
GP-IV	255 ± 35	65 ± 7
GP-V	4 950 ± 212	1 500 ± 282

In GP-I, 100 percent of the microbes identified were pathogenic, including 94.7 percent *Vibrio* isolates of which *V. parahemolyticus* contributed 52.6 percent. GP-V bacteria isolations were 81.9 percent pathogenic with *Vibrio* bacteria contributing 63.7 percent (Table 3). GP-III and GP-IV showed the lowest isolation of pathogenic microbes at 71.1 and 50 percent, respectively. The total *Vibrio* isolates were 42.7 and 25 percent, with corresponding *V. parahaemolyticus* of 21.4 and 12.5 percent, respectively. GP-II isolates were 66.9 percent pathogenic with *Vibrio* contributing 58.4 percent of these.

TABLE 3
Pathogenic and non-pathogenic bacterial isolates identified from different prophylactic treatment groups

Bacterial isolates	GP-I (%)	GP-II (%)	GP-III (%)	GP-IV (%)	GP-V (%)
Pathogenic bacteria					
Vibrio parahaemolyticus	52.6	16.7	21.4	12.5	36.4
Vibrio campbelli	10.5	0.0	0.0	12.5	9.1
Vibrio alginolyticus	10.5	8.3	7.1	0.0	9.1
Vibrio panuliri	10.5	0.0	7.1	0.0	0.0
Vibrio ponticus	5.3	0.0	0.0	0.0	0.0
Vibrio harveyi	5.3	16.7	0.0	0.0	0.0
Vibrio sinaloensis	0.0	16.7	0.0	0.0	9.1
Vibrio mediterranei	0.0	0.0	7.1	0.0	0.0
Proteus vulgaris	5.3	0.0	7.1	0.0	0.0
Enterococcus sp.	0.0	8.3	7.1	12.5	0.0
Pseudomonas sp.	0.0	0.0	7.1	0.0	0.0
Photobacterium ganghwense	0.0	0.0	0.0	0.0	18.2
Oceanimonas sp.	0.0	0.0	7.1	12.5	0.0
Non-pathogenic bacteria					
Shewanella algae (warm water - soil and water)	0.0	25.0	0.0	25.0	9.1
Shewanella aquamarine (probiotic)	0.0	8.3	0.0	0.0	0.0
Shewanella rhizosphaerae	0.0	0.0	7.1	0.0	0.0
Tenacibaculum mesophilum	0.0	0.0	7.1	25.0	0.0
Staphylococcus kloosii	0.0	0.0	14.3	0.0	0.0
% *Vibrio* isolates of the total bacteria remaining after each treatment	94.7	58.4	42.7	25.0	63.7

FIGURE 2
RT-PCR analysis of mud crabs sampled on days 3 and 6 post-treatment showed positivity for mud crab reovirus in all experimental groups



Baseline reovirus testing of mud crabs showed positive results in the hepatopancreas and negative in the gut samples. However, hepatopancreas and gut samples from two crabs in each of the five experimental groups sampled on Day-3 showed positive results for reovirus infection (Figure 2). All gill samples tested were negative for WSSV both in baseline and in Day-3 sampling.

DISCUSSION

Vibriosis is an important disease in the culture of portunid crabs, and one which can infect all stages of crabs (Coates and Rowley, 2022). Vibriosis is known to cause severe economic losses and is responsible for mass mortality in shrimp, fish and shellfish (Novriadi, 2016). Antibiotics and other chemicals have been used for treatment and prevention of vibriosis. However, drug-resistant strains may develop with the constant use of antibiotics. As Singapore emphasizes a clean and green environment for aquaculture, chemicals that are hard to remove from the environment are discouraged. Sodium percarbonate and citric acid powder are ecofriendly cleaning products that also act as disinfectants. Citric acid is a weak organic acid found commonly in citrus fruits. When mixed with sodium percarbonate which acts against bacteria and mould, the chemical reaction results in the formation of carbon dioxide (CO_2) and water which are environmentally friendly. Prophylactic treatment involving SPC and oxolinic acid recorded a higher survival rate during the holding period, and with a more than 90 percent reduction in water microbial load during the treatment phase. The advantage of SPC application lies in its faster activity peaking between 15 and 45 minutes and leaves no traces of chemical impact to the environment. The by-products are hydrogen peroxide, CO_2 and water.

Oxolinic acid is a synthetic quinolone antibiotic authorized in veterinary medicine for use in finfish, calves, pigs and poultry. It is active against gram-negative and gram-positive bacteria (more so against the former) and has been used for prophylaxis and therapy for rainbow trout (Roger and Austin, 1983). It is a synthetic antibacterial agent used in the treatment of fish diseases in many countries. According to a study on the retention of oxolinic acid and oxytetracycline residues in fish and sediments from five fish farms after chemotherapy (Bjorklund, Rabergh and Bylund, 1991), the absorption of oxolinic acid into the treated fish was faster than that of oxytetracycline. The former was also excreted faster with only 0.05–0.2 µg/g in the fish sediments for 5 days after the treatment of the fish. On the other hand, OTC concentrations of 0.8–6.3 µg/g remained at that level in the fish sediments.

OTC is one of the most used antimicrobial agents approved for aquaculture to control and treat bacterial diseases (USFDA, 2008; Olatoye and Afisu, 2013). While the safety, efficacy, and withdrawal period of OTC have been established for certain temperate fish species, there is a lack of comprehensive studies on its use in tropical fish. Optimization is required for tropical fish species, including considerations for the treatment method (oral administration through feed or immersion), as well as its impact on fish behaviour, growth, histopathology and tissue residue levels.

In contrast, Mangrozyme™ did not demonstrate a significant impact at a 10 ppm dose when used in mud crab treatment. This outcome differs from earlier trials conducted with *Litopenaeus vannamei* (whiteleg shrimp), where both prophylactic (10 ppm for 5 days) and disease challenge rescue protocols (100 ppm for 1 day followed by 4 days at 20 ppm) significantly reduced cumulative mortality rates during a 7-day observation period. In these shrimp trials, 44 percent protection was achieved compared to an 84 percent mortality rate in the control group (unpublished data) when challenged with *Vibrio parahaemolyticus*. Additionally, ammonia levels were notably lower in the prophylactic-cum-rescue group (0.75 mg/L) compared to the control group (6.0 mg/L). Further studies are needed to determine the optimal dosing of Mangrozyme™ for prophylactic treatment in mud crabs.

Reovirus is a highly virulent pathogen that causes significant mortality in mud crabs (*Scylla* spp.), with clinical symptoms including loss of appetite, lethargy, loose gills, enlarged hepatopancreas and shell discoloration (Weng *et al*., 2007). Currently, there are no available treatments for controlling this pathogen. Histopathological analysis of infected mud crabs has revealed atrophied hepatopancreas, tissue degeneration, and viral inclusions in the hepatopancreas, gills and muscles (Sravani *et al*., 2024).

To mitigate the impact of MCRV, stringent biosecurity measures are essential in aquaculture settings. Regular monitoring of MCRV in polyculture farms is crucial for early detection and intervention. A practical, non-lethal screening method involves collecting small volumes (< 50 µL) of hemolymph from broodstock to test for MCRV using quantitative RT-PCR. This approach enables the identification and selection of MCRV-free breeding crabs for stocking in culture facilities.

Mud crabs are known carriers of WSSV and typically remain asymptomatic. Natural WSSV infections have been documented in a few studies involving both wild-caught and farmed mud crabs at various growth stages (Jithendran *et al*., 2011). Although vertical transmission of WSSV from wild broodstock has been proposed, this phenomenon has not been extensively studied or well-documented.

It is critically important for shrimp farmers to understand whether mud crabs act as reservoirs of WSSV capable of transmitting the virus to farmed shrimp. This concern is particularly relevant in regions where monoculture or polyculture of mud crabs is widely practiced alongside shrimp farming. Addressing this knowledge gap is essential to mitigate the risk of WSSV outbreaks and safeguard shrimp aquaculture systems.

RECOMMENDATION

Further studies involving a larger sample size of mud crabs in treatment groups are needed to validate the promising results observed with prophylactic treatments using sodium percarbonate and oxolinic acid. These studies should aim to determine the optimal dosage and duration of the treatment regimen for effective disease control. Additionally, investigating the gut microbiota and immune responses of treated and untreated mud crabs could provide valuable insights into the treatments' broader physiological and immunological impacts.

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Value chain, processing and international trade in soft-shell mud crab

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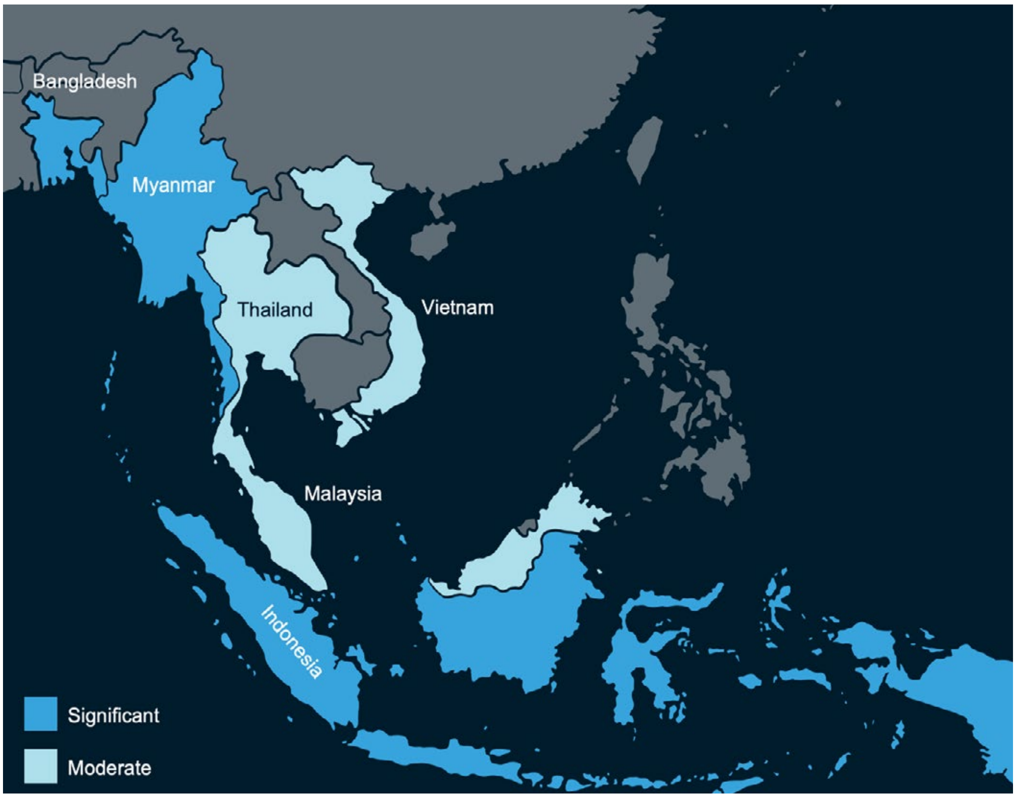
ABSTRACT
Soft-shell crab is a high-value, specialty seafood that is prized for its soft, edible shell, which allows consumers enjoy the same delicate white crab meat without the hassle of breaking apart the otherwise-hard shell. What used to be a niche product, soft-shell crabs have become a mainstay in many Japanese restaurants around the world. Its consumption is expected to increase, buoyed by the continued growth of the Japanese restaurant sector and the adoption of soft-shell crabs in other cuisines. The major markets for soft-shell crabs include the United States of America (which alone imports about one third of the global supply), various Asia-Pacific countries and Europe. The increasing demand for soft-shell crabs and their high value-added potential has led to a rapid proliferation of soft-shell crab farms in recent years, especially in Myanmar, Indonesia and Bangladesh, which together produce most of the product available in the international market. The soft-shell crab value chain, starting from the capture of seed stock to farming and processing then export, poses a unique set of challenges that limits production and increases the cost of this specialty seafood product. These challenges include: the long distances that seed stock must be transported over to farms, leading to significant stress and mortality; the reliance on extensive culture methods due to the cannibalistic nature of crabs; and the labour-intensive process of monitoring and harvesting newly moulted crabs during the short window of opportunity before their shells harden. Therefore, there are many opportunities for innovations to increase the efficiency of soft-shell crab production and further expand this industry.

OVERVIEW OF THE GLOBAL SOFT-SHELL MUD CRAB INDUSTRY
Most soft-shell mud crabs (*Scylla* spp.) available in the global market today come from Southeast Asia, wherein Myanmar, Indonesia and Bangladesh are the main producing countries (Figure 1). Commercial scale soft-shell mud crab production is thought to have started in Thailand, which developed the extensive farming system comprised of floating rafts and plastic baskets that is still in use today in many other countries. Thailand was the global leader of soft-shell crab production by volume in the 1990s to 2000s. However, the soft-shell crab industry in Thailand gradually declined due to the diminishing wild mud crab population. The industry continues to operate in Thailand but is reliant on mud crabs imported from its neighbouring countries Myanmar and Viet Nam. For example, the soft-shell crab farms along the western coast of Thailand, notably Ranong, source an estimated 80 percent of the mud crabs from the Tanintharyi region of Myanmar.

The technology for soft-shell crab farming was later transferred from Thailand to the southern region of Myanmar in the early 2000s and extended to other parts of the country. The industry in Myanmar saw a rapid expansion in the past decades due to the

FIGURE 1
Overview of the main Southeast Asian countries exporting soft-shell mud crabs
Most soft-shell crabs currently available in the international market comes from Myanmar, Indonesia and Bangladesh.



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

abundance of natural mud crab resources and is currently one of the largest exporters of soft-shell crabs in the world. About 50 percent of its soft-shell crabs are exported to the Asia-Pacific (APAC) market (such as China, Hong Kong SAR, Japan, Singapore, and Taiwan Province of China); the United States of America is the single largest importer (35 percent), whereas the European market's share is relatively small given that Myanmar only received European Union export authorization in 2018. Soft-shell crab production is currently stable in Myanmar, but the country needs to invest in sustainable practices to secure the long-term sustainability of this food sector.

From Myanmar, soft-shell crab farming continued to spread westwards from its Rakhine region into the adjacent Cox's Bazaar in eastern Bangladesh, where it was first established in 2011. However, the number of farms in eastern Bangladesh saw a massive decline of 80 percent between 2014 to 2017, attributed to poor linkage to global value chains and shortage of seed supply (Lahiri *et al*., 2021). On the other hand, soft-shell crab farming seems to have taken hold in the Sundarbans in southwestern Bangladesh, where there are 350–400 farms in operation. At present, about 70 percent of the soft-shell crabs produced in Bangladesh are exported to Australia and Japan (Md. Mojibar Rahman, personal communication). In contrast to Thailand, Myanmar, and Bangladesh, farming methods in Indonesia have evolved distinctly, utilizing the limb autotomy-moulting method described below. Despite these differences, Indonesia remains a significant player in the global soft-shell crab industry. Soft-shell crab farming is practised in other parts of Southeast Asia including Viet Nam, Malaysia and the Philippines, but not at the same scale.

MOULTING METHODS

Natural moulting vs. limb autotomy

Crustaceans, including crabs, need to shed their hard-shells (a natural process called "moulting") to grow (Waiho *et al*., 2021). Natural moulting is the primary method used in major soft-shell crab producing and exporting countries such as Myanmar, Thailand and Bangladesh. Limb autotomy, or the deliberate removal of a crab's claws or legs, is used to induce moulting as part of the crab's natural survival mechanism for regenerating lost limbs (Figure 2). This method is widely practiced in Indonesia to accelerate the moulting process, reducing holding times, minimizing mortality during captivity, and improving turnaround time. Furthermore, as declawed crabs cannot eat well, farmers often forego feeding, significantly lowering farming costs. The origin of this practice in Indonesia, as opposed to other countries, is not clear. However, the notable commercial benefits likely incentivize its continuation, despite ethical concerns. Research has shown that the limb autotomy method yields lower-quality crabs, with reduced post-moult body size and weight, missing limbs, or regrown limbs that are smaller, particularly the claws (Fujaya *et al*., 2020) (Figure 2). In contrast, naturally moulted soft-shell crabs exhibit fuller white meat content and more appealing physical characteristics.

In the soft-shell crab market, many importers and distributors have come to appreciate the differences between natural vs. artificial moulting, which they tend to advertise in their product packaging or websites. In comparison, soft-shell crabs produced by limb autotomy have been colloquially referred to as "balloon crabs", describing the absence of meat inside the normal looking exterior. These "balloon

FIGURE 2
Comparison of the physical appearance of soft-shell crabs produced by natural moulting vs. limb autotomy
The dorsal (a) and ventral (b) views of a naturally moulted soft-shell crab compared to crabs subjected to partial or full limb autotomy resulting in soft-shell crabs with either limbs of smaller sizes (c) or completely missing limbs (d).

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crabs" are also prone to bursting when deep fried in hot oil (the most common cooking method for soft-shell crabs), which can be dangerous to food preparers. Despite the lower quality of soft-shell crabs produced by limb cutting, the lower cost of goods compared to naturally moulted crabs is attractive for countries with lower costs of living and price-sensitive consumers. As a result, the market is currently segmented into the higher-quality and higher cost naturally moulted crabs vs. the lower-quality and lower cost crabs produced by limb cutting. Naturally moulted soft-shell crabs (especially from Myanmar and Bangladesh) have greater market share in countries such as the United States of America and in the European Union whereas Indonesian origin soft-shell crabs have a considerable market share in the Asia-Pacific.

SOFT-SHELL CRAB VALUE CHAIN

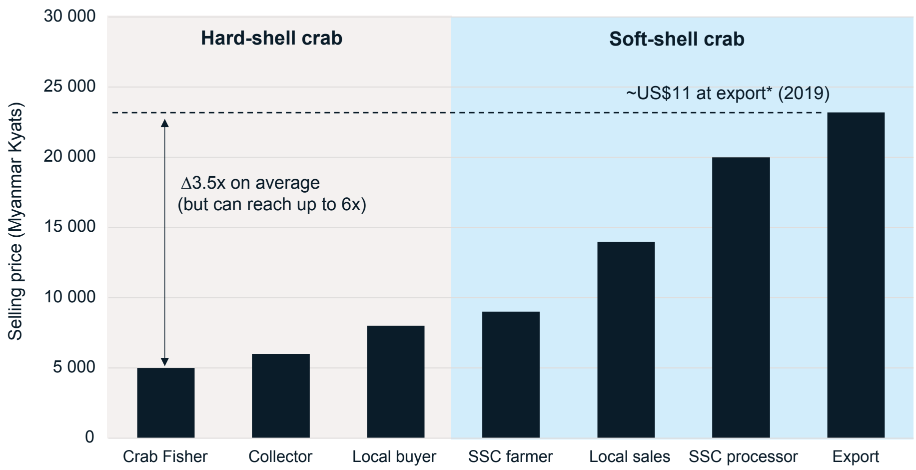
Soft-shell crabs have high value-added potential, which on average can be exported at 3.5-times of the unit price of hard-shell crabs sold by fishers. The overall process of soft-shell crab production requires a well-organized network of stakeholders, starting with the fishers involved in the capture and tie-up of hard-shell crabs from the wild, which are subsequently accumulated at the village or township level then sold, with the facilitation of domestic live-crab traders, to soft-shell crab farms (Figure 3 and Figure 4). Soft-shell crabs are then transported to processing facilities to be graded, sized, cleaned, individually wrapped and frozen within hours after harvest before the new shells harden. Due to the narrow window of opportunity for the soft-shelled state, processing facilities should ideally be directly adjacent to or near to the producing farms.

Delays in harvesting or processing the soft-shell crabs result in lower quality products with a tougher, paper-like skin. Additionally, soft-shell crabs received at the processing facility should still be alive and are visually inspected for the appearance and colouration of their shells and, more importantly, whether there are any broken or missing legs. Lower quality products are usually sold at discounted prices to the domestic market, to be consumed in local restaurants or hotels. During processing, export-grade soft-shell crabs can be prepared as either "whole clean" products, with the undesirable parts of the crab removed (e.g. gills, apron or abdominal flap, antennae,

FIGURE 3

Cost of goods in the soft-shell crab value chain in Myanmar in 2019

Values assume an exchange rate of 2 100 MMK (Myanmar Kyats) to 1 USD



* Export price represents the average of Whole Round and Whole Clean prices across different sizes.

Source: Adapted from Robalino, J.J., Russell, A.J.M. & Soewarno, N. 2019. Myanmar Ayeyarwady Delta: Bio-based value chain analysis for sustainable mangrove restoration. Seoul, The Global Green Growth Institute.

FIGURE 4
Overview of the stakeholders and corresponding activities in the soft-shell crab value chain

Function	Input supply / production	Collection	Domestic trade (Live Crabs)	Soft-shell crab farming	Processing	Export or local sales
Stakeholders	Crab Fishers	Collectors	Traders	Soft-shell crab farmers	Seafood processors	Seafood processors
Activities	▪ Capture ▪ Tie up	▪ Collect at village or township level ▪ Determine sizes ▪ Weigh ▪ Overnight storage in boxes ▪ Package ▪ Store in ponds	▪ Clean ▪ Determine size ▪ Tie up ▪ Weigh ▪ Package ▪ Store (river or boxes) ▪ Organize transport	▪ Soft-shell crab farming	▪ Sort based on size ▪ Process and freeze ▪ Package	▪ Export ▪ Local sales and distribution

Source: Adapted from García, V. 2021. Impact of COVID-19 on the mud crab value chain in Rakhine State, Myanmar. Yangon, Myanmar, Mercy Corps' Market Analysis Unit.

claw pins), or "whole round" in which the entirety of the crab remains intact. Many countries importing soft-shell crabs have basic requirements for an active HACCP (Hazard Analysis and Critical Control Point) food safety management system. Other countries, especially in the European Union, have additional food safety requirements in the form of GFSI (Global Food Safety Initiative) recognized standards such as the BRCGS (Brand Compliance Global Standard), IFS (International Featured Standard), or ISO (International Organization for Standardization) 22000.

After processing, the ready-to-cook, individually quick frozen (IQF) soft-shell crabs are typically packed into 1 kg cardboard boxes and are ready to be exported. Most of the soft-shell crab products available in the market are shipped frozen because of the transient nature of the soft-shelled state. Exported products need to adhere to a complex set of requirements such as product labelling, food testing and proper documentation, which varies depending on the importing country.

SOFT-SHELL CRAB CONSUMPTION

The most common method of cooking soft-shell crabs is deep frying, which turns the edible shell into a thin, crispy layer that contrasts with the juicy white crab meat on the inside. Other regions may have different cooking methods, such as pan-frying in the East Coast of the United States of America or steaming in parts of southern China. The most popular ways to prepare soft-shell crabs in Japanese cuisine is either in sushi rolls ("spider rolls") which are thought to have been invented by Vancouver-based Chef Hidekazu Tojo in the 1970s (Harowitz, 2017), or as tempura (coated in a light flour batter then deep-fried) (Figure 5a and Figure 5b). The appetite for soft-shell crabs grew and it became a mainstay of many Japanese restaurants in the United States and eventually spread to other Japanese restaurants around the world.

There are an estimated 187 000 Japanese restaurants outside Japan as of 2023, reflecting a 20 percent increase since 2021, according to a survey by the Japanese Ministry of Agriculture (Verdict Food Service, 2023). This growth in the Japanese restaurant sector is expected to sustain global demand for soft-shell crabs. Additionally, their adoption in other cuisines is further driving demand. For instance, Thai restaurants in the Republic of Korea have creatively replaced hard-shell mud crabs with soft-shell crabs in dishes like Thai stir-fried crab yellow curry (*phu phat pong karee*; Figure 5c). In Japan, the country's first burger chain, DomDom, introduced a soft-shell crab burger to its menu in 2020 (Japan Today, 2020; Figure 5d). As restaurants and consumers become more

FIGURE 5
Popular ways of preparing soft-shell crabs
Spider rolls (a) and tempura soft-shell crabs (b) are currently the mainstay menu items in many Japanese restaurants around the world, whereas soft shell crab burgers (c) and Thai soft shell crab curry (d) are starting to gain more popularity.

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familiar with soft-shell crabs, there will likely be more creative ways to incorporate this ingredient in different recipes and cuisines.

Depending on the type of cuisine or restaurant and consumer preferences, soft-shell crabs are sold in different sizes. For example, soft-shell crabs served as entrées presented as the whole crab are typically larger whereas those used in Japanese sushi rolls are typically smaller. Sizes for whole clean soft-shell crabs, which are mostly exported to the United States of America and Europe, follow the nomenclature set by the American soft-shell blue swimming crab industry, which has a long history dating back to the mid-1800s. Soft-shell crab production in the United States of America was reported to have started in New Jersey around 1855, and by 1905 the products were being exported to Europe (Hungria *et al.*, 2017). Whole clean, soft-shell crab sizes include "super colossal" (6 pieces/box), "colossal" (7 pieces/box), "super-whale" (8 pieces/box), "whale" (9–10 pieces/box), "jumbo" (12 pieces/box), "prime" (14 pieces/box) and "hotel" (18 pieces/box).

Whole round sizes are mostly applicable to the Asia-Pacific market and follows a set of weight ranges (e.g. "100/200" referring to 100–200 g) for the individual soft-shell crab pieces. Overall, product sizes for soft-shell crabs in the market are standardized and well established.

FUTURE PERSPECTIVES ON THE SOFT-SHELL CRAB MARKET

Global consumption of soft-shell crabs is expected to grow, driven by the increasing number of Japanese restaurants and the diversification of preparation methods (see Figure 5). A SWOT analysis of the soft-shell crab value chain is shown in Figure 6. Unlike hard-shell crabs, soft-shell crabs are more convenient to eat, as their edible shells reduce mess and waste. However, they are primarily served in restaurants because deep frying, the most common cooking method, involves excessive oil and is less convenient for home preparation.

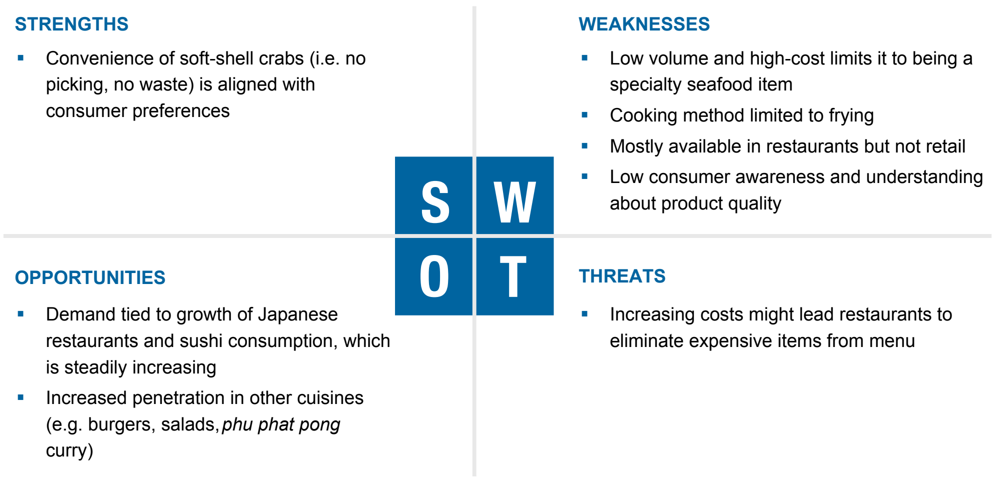
Home consumption could see modest growth with the rising popularity of air fryers – compact convection ovens offering a healthier, more convenient alternative to deep frying. As of March 2023, nearly 60 percent of U.S. households own air fryers (Lucas, 2023). To capitalize on this trend, manufacturers should conduct market research to develop value-added products, such as air fryer-compatible tempura soft-shell crabs or meal kits.

Soft-shell crabs remain a specialty seafood item due to their high cost and limited supply compared to other proteins like fish (e.g. cod, salmon) and shrimp. Innovations on the supply side to increase yields and reduce costs could broaden their appeal and drive greater adoption.

Consumer misconceptions may also hinder the popularity of soft-shell crabs, with many people unfamiliar with the natural moulting process. Anecdotal evidence suggests that some incorrectly believe soft-shell crabs are a distinct species or that their shells are chemically treated to become soft. Raising awareness and educating consumers about the product's natural origins could be key to boosting consumption.

In summary, the soft-shell crab market represents a fascinating niche with unique challenges and opportunities, offering a commercially attractive space for future innovation and growth.

FIGURE 6
SWOT analysis for the soft-shell crab industry



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Quality standard of mangrove crabs

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ABSTRACT

The handling, storage, and transportation of mangrove or mud crabs must be managed effectively from capture to its destination to ensure the delivery of high-quality, marketable crabs to consumers. In many crab producing countries, established national quality standards for locally produced mud crabs are lacking. While traders and exporters often strive to meet the quality requirements of importing nations, the absence of comprehensive domestic guidelines highlights a significant gap in the industry. The quality of crabs is evaluated based on the fullness of meat by palpation, relative weight to size, and overall appearance. Crabs exhibiting mechanical injuries, oozing haemolymph or bleeding, bubbling or frothing at the mouth, or displaying weak movements are excluded from final packing and transportation. When crabs are kept out of water for several days, ammoniacal excreta accumulate in their gills, resulting in an unpleasant odor. Prolonged storage also causes the crab muscles to become emaciated, making the limbs prone to detachment. To maintain their quality, crabs should not be held for more than three days after harvest.

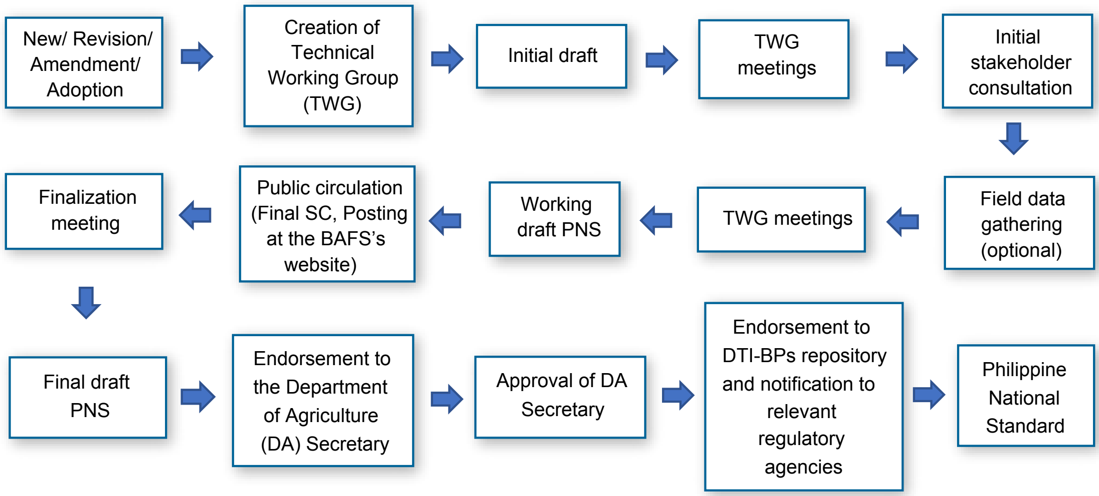
In the Philippines, the Bureau of Agriculture and Fisheries Standards (BAFS) under the Department of Agriculture (DA) is tasked with developing and promoting standards to ensure food safety, product quality, workers' health and welfare, environmental management, and the global competitiveness of Philippine agriculture and fishery products. BAFS has established Philippine National Standards (PNS) for various crab products, including live, fresh chilled, and fresh frozen mangrove crabs (product standard), soft-shell crabs (product standard), chilled or frozen crabs (code of practice), and the Code of Good Aquaculture Practices. These standards outline food safety and quality requirements for different crab product forms, aiming to protect consumer health while ensuring global competitiveness. The PNS developed by DA-BAFS are aligned with regional and international standards, particularly those set by the Association of Southeast Asian Nations (ASEAN) and Codex Alimentarius.

INTRODUCTION

Active and healthy mangrove crabs command a good price in the market. However, crabs must be handled, stored and transported properly to maintain their quality from the time they are caught until they reach their final destination. High quality crab satisfies the end consumers and commands higher prices for traders.

In the Philippines, the Bureau of Agriculture and Fisheries Standards (BAFS) of the Department of Agriculture (DA) is mandated to develop and promote standards to ensure food safety, quality, workers' health and welfare, environmental management, and global competitiveness of Philippine agriculture and fishery products. BAFS, in collaboration with relevant government and research agencies, academic institutions, and stakeholders, developed the Philippine National Standards (PNS) for live, fresh chilled and fresh frozen mangrove crabs (product standard), soft-shell crabs (product standard), chilled or frozen crabs (code of practice) and the Code of Good Aquaculture

FIGURE 1
Process for the development of product quality standards
(Philippines National Standards – PNS)



Practices for shrimps and crabs. These PNS for crabs describe the food safety and quality requirements for various crab product forms to safeguard the health of consumers and secure globally competitive products.

The process for the development of a safe and quality standard is shown in Figure 1. New or existing standards that need amendments or updating are proposed to BAFS and then a technical working group (TWG) is formed composed of representatives from relevant government agencies, academia, research institutions, private sector and civil society organizations. The TWG is created through a Special Order signed by the DA Secretary. The PNS draft is formulated and discussed in a series of TWG meetings and stakeholder consultations that are conducted both physically and online before the draft is endorsed to the Secretary of the DA for approval. The draft is also posted on the BAFS website to elicit comments from relevant stakeholders and provide transparency on the standards development process. The approved PNS can be used to support the development of relevant policies and laws by concerned government agencies. Regulators, legislators and other government representatives refer to standards to protect consumers and business interests.

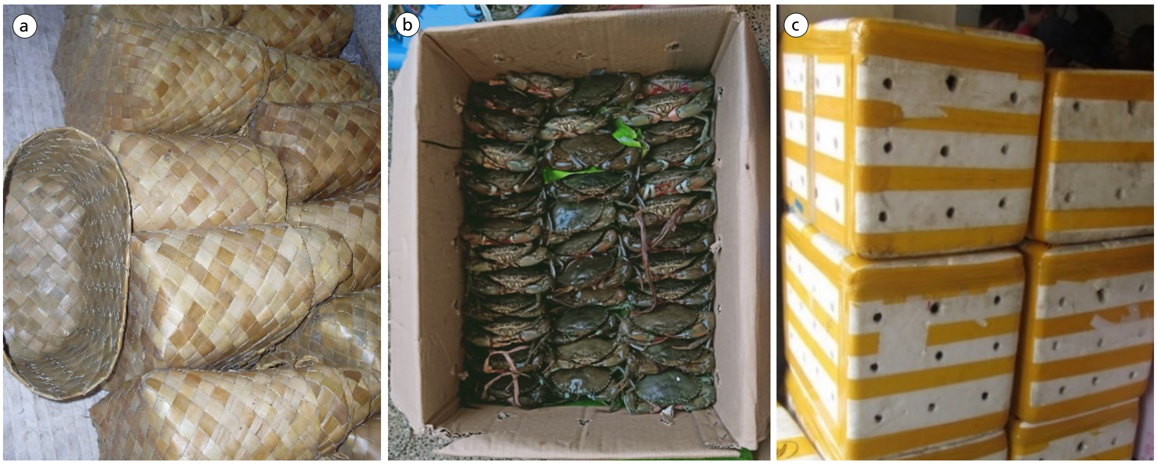
BAFS develops PNS which are harmonized with the regional and international standards – in particular the ASEAN and the FAO/WHO Codex Alimentarius standards, respectively. Harmonization with the international standards is one of the basic principles in the development of national standards that aim to protect consumers' health and facilitate fair practices in food trade (https://bafs.da.gov.ph). The DA-BAFS conducted the most recent review of existing PNS related to fisheries in 2023. This review aimed to re-evaluate and verify whether the provisions of the older PNS remain relevant to current regulatory and market requirements. If necessary, PNS are revised or amended every five years to incorporate updates that enhance consumer product safety and ensure compliance with evolving standards. Additionally, the review seeks to align product specifications with current market demands, ensuring that the standards remain practical and competitive.

In many mangrove crab-producing countries, there remains a lack of documented or established national quality standards for mangrove crabs. While traders and exporters often adhere to the quality requirements of importing countries, these standards should also be applied domestically to protect consumer health and uphold the business interests of all stakeholders. Additionally, exporting countries must ensure compliance with the standards established in the Philippines, further promoting consistent quality and safety across markets.

POST-HARVEST QUALITY OF CRABS

Crabs are typically transported to trading centres immediately after harvest from culture ponds or fishery collection sites. They are carried in woven baskets, sacks, cartons, polystyrene boxes or crates, lined with clean, damp cloth or leaves to maintain their freshness and prevent damage during transit (Figure 2). These are then classified according to species, sex, body size and weight, maturity, completeness of limbs, and presence of deformities (Figure 3) (The Mangrove Crab Technical Committee 2018, 2021).

FIGURE 2
Some containers used for the transportation of live crabs
Locally crafted baskets (a), carton (b) and polystyrene boxes (c)



Quality grading

The quality of crabs is assessed by examining the meat fullness through palpation and comparing their weight relative to their size (Figure 4). A firm carapace indicates fullness of meat. Crabs showing signs of mechanical injuries, oozing haemolymph or bleeding (Figure 5), bubbling or frothing at the mouth, or exhibiting weak or sluggish movements are excluded from the packing process (Figure 6). When crabs are kept out of water for extended periods, ammoniacal excreta accumulate over time. If unwashed, this accumulation in the gills can cause an unpleasant odour (The Mangrove Crab Technical Committee 2018, 2021). To prevent this, crabs are thoroughly washed and cleaned to remove body wastes and eliminate off-odours. Prolonged storage of crabs can also lead to muscle emaciation. Without feeding, their glycogen reserves are depleted, forcing them to use major energy sources such as lipids, carbohydrates and proteins. This results in

FIGURE 3
Crabs are classified according to species, sex, body weight, maturity and completeness of limbs upon arrival at the trading centre or consolidator

muscle atrophy, weight loss, and easily detached limbs, significantly reducing their market value. To preserve quality, crabs should not be stored for more than three days after harvest.

Packing

There are several containers used for packing and transporting crabs depending on the destination, mode of transport and size of crabs. Polystyrene boxes with ventilation holes are commonly used for air transport. Carton boxes with ventilation holes are utilized for road transport. Chunks of ice are wrapped in paper and placed in the container to maintain cool condition during transport.

PHILIPPINE NATIONAL STANDARD

Currently, several approved Philippine National Standards (PNS) pertain to mangrove crabs. The following excerpt is taken from the Bureau of Agriculture and Fisheries Standards (BAFS) PNS:

- *Live, fresh chilled, and fresh frozen crabs – Product standard [BAFS-DA, 2023 (PNS/BAFS 177:2023 - ICS 67.120.30)]*

In 2016, the PNS for Live Mangrove Crab [BAFS-DA, 2016 (PNS/BAFS 177:2016)] was developed by a TWG led by the Bureau of Agriculture and Fisheries Standards. This standard was created to establish a common understanding of key aspects related to live mangrove crabs, including: the scope of the standard; product and process descriptions; essential composition and quality factors; food additives; contaminants; hygiene and handling practices; packaging and labelling requirements; methods of sampling, examination and analysis; definitions of defects; and lot acceptance criteria. The standard covered all four species of mangrove crabs: *Scylla serrata*, *Scylla olivacea*, *Scylla tranquebarica* and *Scylla paramamosain*.

In 2023, the standard was amended and reissued as *Live, Fresh Chilled, and Fresh Frozen Crabs – Product Standard* (PNS/BAFS 177:2023 - ICS 67.120.30). This

FIGURE 4
Meat fullness of a mud crab is checked by pressing the sides of the carapace

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FIGURE 5
Haemolymph oozing from the crab

©The Mangrove Crab Technical Committee 2018

FIGURE 6
Bubbles (foaming) produced from the mouth of an adult mud crab

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updated version effectively cancelled and replaced the 2016 standard for Live Mangrove Crab. Key changes introduced in the 2023 revision include:

- expanded the scope to include all commercially available crab species;
- added fresh chilled and fresh frozen product forms to the scope;
- updated Normative References and Terms and Definitions;
- enhanced microbiological safety requirements, including the addition of *Shigella* and *Vibrio cholerae*;
- revised size classification of live mangrove crabs to align with the Department of Trade and Industry regulations;
- updated labelling requirements to reflect current standards; and
- included Maximum Residue Limits (MRL) for veterinary drug residues in crabs.

The scope of the new PNS version applies to crabs that are marketed either live, fresh chilled, and fresh frozen. This includes species of mangrove crab (*Scylla*), crucifix crab (*Charybdis*), and blue swimmer crab (*Portunus*) (Figure 7) of the family Portunidae, stone or king crab-related species of the family Lithodidae and other species of marine and freshwater crabs which have similar morphological structures and features. The PNS provides a common understanding on: description of the product; essential composition and quality factors; processing aid; hygiene and handling; presentation, packaging and labelling; methods of sampling, examination and analysis; definition of defectives; and lot acceptance.

The final crab product should conform to the quality requirements as shown in Table 1 and Table 2. The size classification with consideration of the existing ordinances is shown in Table 3.

FIGURE 7
Selected crab species included in the Philippine National Standards that are marketed either live, fresh chilled and fresh frozen
Mangrove crab (a), crucifix crab (b) and blue swimmer crab (c)

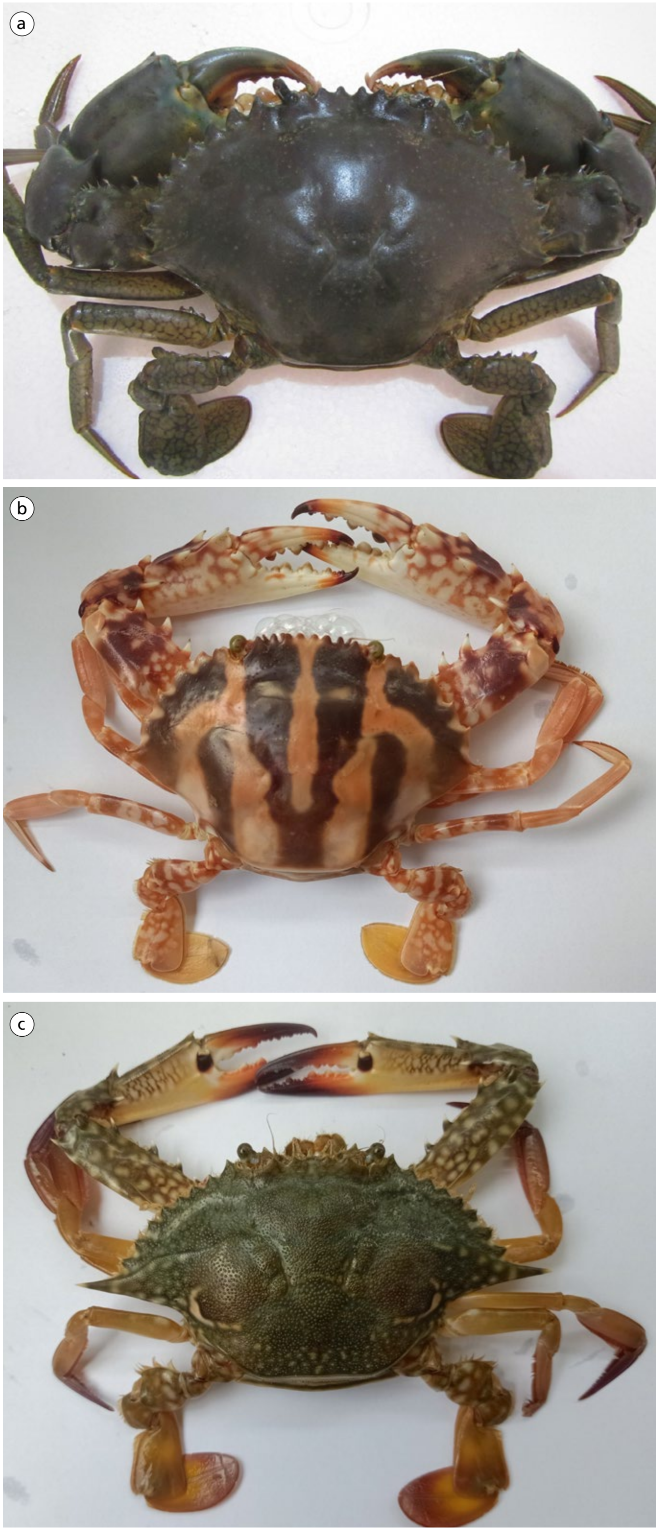

TABLE 1
Microbiological safety requirements for frozen raw crab

Microbiological parameter	n	c	m	M	Source
Aerobic Plate Count (APC)/ Standard Plate Count (SPC) Colony Forming Unit (CFU)/g	5	3	10^6	10^7	FDA-DoH, 2022
Escherichia coli, Most Probable Number (MPN)/g	5	3	11	460	FDA-DoH, 2022
Salmonella/25 g	5	0	Absent		FDA-DoH, 2022
Staphylococcus aureus, CFU/g	5	2	10^3	10^4	FDA-DoH, 2022
Vibrio parahaemolyticus, MPN/g	5	1	10^2	10^3	FDA-DoH, 2022
Vibrio cholerae/25 g	Absent				BFAR-DA, 2001a
Shigella/25 g	Absent				BFAR-DA, 2001b

n = number of sample units selected from a lot of food to be examined.
c = maximum allowable number of marginally accepted samples.
m = acceptable level of microorganisms determined by specific method.
M = level which when exceeded in one or more samples cause the lot to be rejected, as this indicates potential health hazard or imminent spoilage.

TABLE 2
Maximum levels of heavy metals

Heavy metal	Maximum level (mg/kg)	Source
Lead	0.3	BAFS-DA, 2022
Mercury	0.5	BFAR-DA, 2001
Cadmium	0.5	BFAR-DA, 2001

TABLE 3
Size classification of live mangrove crabs

Crab size class	Body weight (g)			
	Scylla serrata		Other *Scylla* species	
	Male	Female	Male	Female
Oversize	> 1 000	> 700	> 500	> 400
Large	701–1 000	501–700	401–500	301–400
Medium	501–700	401–500	301–400	200–300
Small	200–500	200–400	200–300	–

Source: BAFS-DA (Bureau of Agriculture and Fisheries Standards - Department of Agriculture). 2023. Live, fresh chilled and fresh frozen crabs – Product standard (PNS/BAFS 177:2023).

As per Executive Order No. 1016, Resolution No. 1, Series of 2013, Annex A – List of prohibited and regulated products for export issued by the Department of Trade and Industry–Inter-Agency Committee, live mangrove crabs (*S. serrata*) of less than 200 g body weight (10 cm carapace length) are prohibited for export. Soft-shell crabs are not included since these are traded in frozen form.

- *Chilled or Frozen Crabs – Code of Practice [BAFS-DA, 2022 (PNS/BAFS 328:2022 - ICS 67.120.30)]*

This PNS covers crabs marketed as live, fresh-chilled, or fresh-frozen. It applies to species such as mangrove crabs (*Scylla*), crucifix crabs (*Charybdis*), blue swimmer crabs (*Portunus*) from the family Portunidae, stone or king crabs from the family Lithodidae, and other marine and freshwater crab species with similar physical characteristics.

The PNS outlines and details the requirements for facilities, hygiene practices, handling procedures, and processing methods for chilled and frozen crabs. It also addresses labour, community, and other social considerations related to the industry. Furthermore, the PNS discusses potential hazards and defects associated with the processing of chilled and frozen crabs.

- *Fresh frozen soft-shell crab – Product standard [BAFS-DA, 2022 (PNS/BAFS 235:2022 - ICS 67.120.30)]*

This 2022 PNS supersedes and replaces PNS/BAFS 235:2017, which had previously been amended. The original standard on Soft-Shell Crab was developed by BAFS in 2017. However, in 2021, the Integrated Services for the Development of Fisheries and Aquaculture, Inc. (ISDA, Inc.) proposed updates to address evolving food safety and quality requirements. These updates include provisions on microbiological limits, maximum levels of heavy metals, and maximum residue limits of veterinary drugs, as well as revised standards for size classification, quality, and sensory attributes to align with current regulatory and market demands. The key updates in this version are as follows:

- exclusion of blue swimmer crab in the scope;
- amendment of size classification;
- updating of microbiological safety requirements and maximum level of heavy metals;
- inclusion of quality and sensory attributes of raw soft-shell crab; and
- inclusion of maximum levels of veterinary drug residues.

The PNS applies to all the mangrove crab species presented as fresh frozen whole soft-shell crab or fresh frozen dressed soft-shell crab intended for further processing for human consumption.

There are only three size classifications for the soft-shell crabs as shown in Table 4. Table 5 describes the quality and sensory attributes of fresh frozen whole and fresh frozen dressed soft-shell crabs.

TABLE 4
Size classification of whole soft-shell crabs (preferably hatchery-reared crabs)

Size	Body weight (g)	Source
Large	> 150	BAFS-DA, 2022
Medium	121–150	
Small	100–120	

Source: BAFS-DA (Bureau of Agriculture and Fisheries Standards – Department of Agriculture). 2022. Fresh frozen soft-shell crab - Product standard (PNS/BAFS 235:2022 - ICS 67.120.30).

TABLE 5
Quality and sensory attributes of raw soft-shell crabs

Descriptive parameters	Product forms	
	Fresh frozen whole Soft-shell crabs	Fresh frozen dressed Soft-shell crabs
Appearance	• Natural characteristic of the species. • Complete body parts with the appendages intact. • Shell firmly attached to the body. • Absence of deformities in the carapace and appendages or any mechanical damage.	• Natural characteristic of the species. • With one or more body parts removed or cut.
Texture	Soft-shell with firm meat.	
Odour	No unpleasant odour (e.g. No ammonia-like odour, muddy smell, or any odour uncharacteristic of the species.)	

Source: Adapted from BAFS-DA (Bureau of Agriculture and Fisheries Standards - Department of Agriculture). 2022. Fresh frozen soft-shell crab – Product standard (PNS/BAFS 235:2022 - ICS 67.120.30).

The PNS defines and describes several key aspects, including the product and process definition, essential composition and quality factors for both raw and final products, food additives, contaminants, hygiene and handling practices, packaging and labelling requirements, methods of sampling/examination/analysis, definition of defects, and criteria for lot acceptance.

- *Code of good aquaculture practices for shrimp and crab [BAFS-DA, 2017 (PNS/BAFS 197:2017 - ICS 65.150)]*

The Code of Good Aquaculture Practices (GAqP) for Shrimp and Crab provides guidelines to prevent or mitigate risks associated with hazards during aquaculture production, harvesting, and post-harvest handling of shrimp and crab, while ensuring aquatic animal health and welfare. It is applicable to various aquaculture farms and operations, including hatcheries, nurseries, and grow-out farms for shrimp and mangrove crab. The code incorporates practices from the ASEAN Good Aquaculture Practices for Shrimp Farming and the Good Aquaculture Practice Farmers Guidance Workbook developed by BFAR under the European Union Trade-Related Technical Assistance programme. It addresses key aspects of aquaculture production, including food safety, animal health and welfare, environmental sustainability and socioeconomic considerations.

- *Establishment of traceability system for cultured finfishes and crustaceans — Guidelines [BAFS-DA, 2022 (PNS/BAFS 338:2022 - ICS 67.120.30)]*

This document serves as a guide in establishing a traceability system for cultured crustaceans and finfishes that are marketed live, fresh chilled, or fresh frozen. This covers operations from aquaculture inputs procurement, hatchery, nursery, grow-out, marketing, post-harvest to end-product distribution, which correspond to the different stages of the supply chain. The supply chain is further illustrated in Annex A of the PNS (Generic supply chain for cultured finfishes and crustaceans).

PRODUCT STANDARDS IN THAILAND

- *Soft-shell mud crab – Thai Agricultural Standard 7021 (TAS 7021, 2010)*

The Thai Agricultural Standards Committee (TAS) has established a quality and safety standard for soft-shell mud crabs to ensure consumer acceptance and enhance competitiveness in the global market. Thailand exports soft-shell crabs to destinations such as Australia, China, and the United States of America. The TAS standard outlines the quality requirements for soft-shell crabs traded either fresh or frozen, addressing key aspects such as product types and quality (minimum requirements) and classification, sizing, product origin, packaging, contaminants and veterinary drug residues, food additives, hygiene, labelling, official inspection and certification marks, as well as methods of analysis and judgment criteria.

Notably, the TAS includes a greater number of size classifications for soft-shell crabs compared to the PNS, as detailed in Table 6.

TABLE 6
Size classification of soft-shell mud crabs used in Thailand

Size	Body weight (g/ind.)	Quantity (ind./kg)
Special extra large	> 200	3–4
Extra large	> 150–200	5–6
Large	> 120–150	7–9
Medium	> 100–120	9–10
Small	70–100	> 10

Source: TAS (Thailand Agricultural Standard). 2010. Soft-Shell Mud Crab (TAS: 7021-2010). National Bureau of Agricultural Commodity and Food Standards, Ministry of Agriculture and Cooperatives.

The levels of microbiological parameters identified by TAS in Table 7 is similar to the microbiological safety requirements for frozen raw crab in the Philippine National Standards (see Table 1).

TABLE 7
Microbiological criteria for soft-shell mud crab used in Thailand

Parameter	n	c	m	M
Total viable counts	5	3	5×10^5 CFU/g	10^7 CFU/g
Escherichia coli	5	3	11 MPN/g	500 MPN/g
Staphylococcus aureus	5	2	10^3 CFU/g	10^4 CFU/g
Salmonella spp.	5	0	Not found in 25 g	

n = number of sample units for inspection from each lot.
c = maximum number of samples for which a quantity of microorganisms higher than the level specified is allowed.
m = quantity of microorganisms allowable in the sample.
M = quantity of microorganisms found in the sample and is the reason for rejection of the lot.
CFU/g = colony forming unit per gram.
MPN/g = most probable number per gram.
When M is not specified, m and c shall be used as the criteria.

Source: TAS (Thailand Agricultural Standard). 2010. Soft-Shell Mud Crab (TAS: 7021-2010). National Bureau of Agricultural Commodity and Food Standards, Ministry of Agriculture and Cooperatives.

PRODUCT STANDARDS IN MYANMAR

In 2018, Myanmar established technical regulations for the export and import of fishery products, aligned with sanitary and phytosanitary requirements. These regulations were developed through a collaborative effort involving the European Union, Deutsche Zusammenarbeit, Myanmar's Department of Fisheries (DOF), and the Trade Development Program. The scope of these technical regulations (Myanmar DOF, 2018) covers the following:

- *Fishery Sector Operators – All entities involved in the production of fishery products intended for export for human consumption, including:*
  - Primary production and associated activities, such as hatcheries, aquaculture farms, feed mills, and feed importers or distributors.
  - Fishing operations, including fishing vessels, carrier vessels, ice factories, landing sites, auction halls, collection stations, and vehicles transporting fishery products.
  - Establishments for handling and processing fishery products.
  - Independent cold storage facilities and warehouses used for storing fishery products intended for export.

- *Importers of Fishery Products – All operators in Myanmar importing fishery products for domestic distribution or for further processing before export.*
- *National Competent Authority – The designated authority responsible for developing enforcement and compliance programmes to verify and document that all operators adhere to these regulations.*

The technical regulations apply to all fishery products, including crabs, but specifically exclude the production, handling, export or import of live bivalve products.

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Hard-shell mangrove crab farming

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ABSTRACT

Mangrove crabs are grown in earthen brackish water ponds, pens or cages depending on the site and type of culture system. Farming involves the long-term culture of crablets to market size for 3–5 months, short-term culture (fattening) of lean crabs for 15–30 days, or soft-shell crab production for 3–4 weeks for each batch. In the grow-out culture of mangrove crabs for hard-shell production, polyculture of juvenile crabs to market size with one or two other commodities in the pond is commonly practised to maximize the utilization of the pond and enhance financial returns. These may include fish species such as milkfish, siganid, tilapia, mullet, and spotted scat; seaweeds; molluscs such as clams and oysters; and shrimps. Fattening of crabs for 1–2 weeks in communal or individual culture systems is done by some farmers to add value to lean crabs. In the communal culture system, several lean crabs are stocked in pond compartments, pens or cages. Pens and cages are set up in ponds, estuaries, mangroves, sheltered coastal waters, shallow lagoons or bays. In the individual culture system, crabs are stocked individually in compartmentalized bamboo cages, perforated polyethylene containers or other improvised containers. Indoor vertical farming utilizing the recirculating aquaculture system is also carried out for crab fattening. Likewise, aquasilviculture or silvofisheries, which is the integration of the culture of crab and other brackish water animals with the mangroves, is practiced in some coastal areas. An area ranging between 500–2 000 m^2 in a flooded mangrove swamp is enclosed using bamboo or polyethylene netting. The occurrence of diseases, abnormalities, and cannibalism are significant challenges in crab culture, posing serious threats to its economic viability. These can be mitigated by using good quality seedstocks, following good aquaculture practices, and by implementing effective strategies to minimize cannibalism.

INTRODUCTION

Mangrove or mud crab (*Scylla* spp.) farming has long been established in the Philippines (Quinitio, 2017). Initially, crab culture started unintentionally, with wild seedstocks accidentally entering shrimp and fish culture ponds. Due to their suitability for cultivation and ability to reach marketable size in shrimp or fish ponds, farmers began intentionally stocking wild juvenile crabs at low densities alongside other commodities. Currently, the majority of crablets used for farming are sourced from the wild, with only 10–15 percent originating from hatcheries. Among the three *Scylla* species commonly found in the country—*Scylla serrata*, *Scylla olivacea* and *Scylla tranquebarica* – *S. serrata* is the preferred species for both hatcheries and grow-out farms due to its larger size and ease of cultivation.

Mangrove crabs are raised in earthen brackish water ponds, pens or cages, depending on site availability and the chosen culture system. Farming practices include long-term culture, where juvenile crabs are grown to market size over 3–5 months; short-term culture, or fattening, which enhances the condition of lean crabs in 15–30 days; and soft-shell crab production, which takes approximately 3–4 weeks per batch. Crab fattening can be performed using either communal or individual culture systems. In communal systems, stocking density is kept low to mitigate the crabs' natural cannibalistic behaviour (The Mangrove Crab Technical Committee 2018, 2021).

CULTURE OF CRABS IN EARTHEN POND

Pond preparation – such as drying, liming, removing unwanted species, flushing and applying fertilizers – is a common practice among many crab farmers. Proper preparation is crucial, as the soil condition of the pond significantly impacts the quality of the culture water. Therefore, thorough pond preparation is essential before stocking crabs or other aquatic species. However, a small number of farmers fail to adhere strictly to standard preparation practices, often due to the additional costs involved or the limited availability of necessary supplies, such as lime, in their area.

Stocking

Initial stocking density in crab culture is low (800–1 000 ind./ha) compared to cultured shrimp due to their cannibalistic behaviour. The duration of culture depends on the initial size of crab juveniles at stocking. The larger the juveniles at stocking, the shorter the duration of culture. Polyculture of juvenile crabs to market size with one or two commodities (usually fish) in the pond is commonly practiced maximizing the utilization of the pond. Herbivore (milkfish or siganid) or omnivore (tilapia) fish (Figure 1) are grown together with crabs. A combination of three species is also practiced but a lower stocking density is used for each commodity. Although growing shrimps (*Penaeus monodon*) alongside crabs is generally discouraged due to their shared susceptibility to similar diseases, such as white spot syndrome virus (WSSV), some farmers still practice this combination to capitalize on the high market value of both commodities. During the colder months (December-February), when WSSV is prevalent, the stocking density of crabs is typically reduced to mitigate disease risks. Juvenile crabs, stocked at 800–1 000 ind./ha, are often cultured alongside milkfish fingerlings (1 000–2 000 ind./ha) or saline tilapia (1 000–2 000 ind./ha). Additionally, seaweeds such as *Gracilaria* (Figure 2), which provide shelter, are sometimes grown with crabs in ponds where salinity levels are favourable (20–28 ppt) (Trono, 1988).

In some cases, farmers adopt high stocking densities for mangrove crabs but thin the population after 1–2 months to reduce competition and cannibalism. Polyculture practices vary by region: in Bangladesh, *S. olivacea* are raised alongside tilapia or spotted scat (*Scatophagus*) in brackish water ponds; in India, mud crabs are cultured with mullet, tilapia, shrimp, oysters, clams or seaweeds. In Viet Nam, *Scylla paramamosain* is polycultured with shrimp in mangroves or integrated with rice farming systems (Vu Ngoc Ut, personal communication).

To prevent crab escapes, especially in ponds with low dykes, some farmers install barriers made of bamboo or polyethylene netting as additional safeguards.

FIGURE 1
Fish such as milkfish (a), siganid (b) and tilapia (c) are cultured with mangrove crabs

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Feeding management

The major food items for crabs are fish of various species, variety of molluscs including small bivalves, cracked telescope snails or freshwater snails from rice fields, boiled corn and formulated feeds (Figure 3). Farmers prefer fish as feed for crabs because of the ease in preparation and all parts of the fish are consumed. When fish and molluscs are not available, the crabs are fed boiled corn and animal entrails to reduce feed cost. Crabs are fed daily at 10 percent of their body mass at the start of the culture period and reduced gradually to 3 percent as they grow to market size (The Mangrove Crab Technical Committee 2018, 2021). However, many farmers feed their crabs to satiation. Feeding frequency varies from 1–2 times daily. Feeding trays are fixed in such a way to monitor feeding consumption and condition of the cultured animals. When crabs are co-cultured with milkfish, "lab-lab" – a complex mat of benthic algae, microorganisms, detritus, and other organic matter that forms on the bottom of ponds – is allowed to grow abundantly after application of fertilizer prior to stocking. This mat serves as natural food for milkfish sometimes also floating as patches on the surface of the pond (Fortes and Piñosa, 2010) (Figure 4).

FIGURE 2
Seaweed, *Gracilaria*, is sometimes grown with mangrove crabs, which also serves as shelter

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FIGURE 3
Bivalves and other molluscs fed to mangrove crabs
Small bivalves (a), telescope snails (b), and freshwater snails from rice field (c)

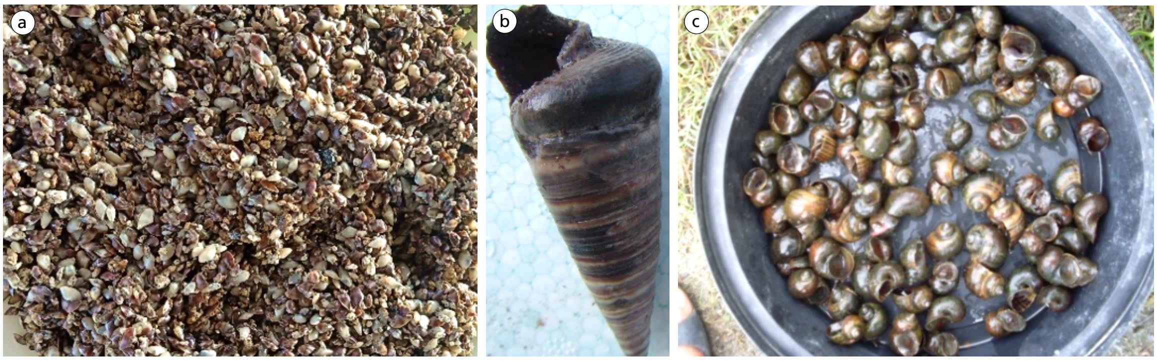

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FIGURE 4
Lab-lab grown in ponds as food for milkfish

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Water management

Water is changed during spring tide or whenever necessary. Water depth in the pond is maintained above 50 cm. The condition of the crabs and water are monitored regularly. Optimal water

TABLE 1
Optimum water parameters for the culture of mangrove crabs and fish

Water parameters	Value
Temperature	27–31 °C
Salinity	20–30 ppt
Dissolved oxygen	5 ppm
pH	7.5–8.5
Hydrogen sulphide	0.004 ppm
Unionized ammonia	0.10 ppm
Nitrite	0.01 ppm
Organic matter	1–10%
Transparency (Secchi disk)	20–30 cm

Source: The Mangrove Crab Technical Committee 2018. 2021 *The Philippines recommends for mangrove crab*. Department of Science and Technology – Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (DOST-PCAARRD). Los Baños, Philippines.

parameters are maintained as much as possible by the farmers (Table 1). However, farmers that do not have a dissolved oxygen meter, pH meter, test kits or nearby laboratories where they can send the samples for analysis rely solely on their observations based on several years of experience or by using alternative simple and inexpensive tools or kits.

Harvesting

Market size starts at 350 g for *S. serrata* or 200 g for *S. olivacea* and *S. tranquebarica.* However, the desired weight for *S. serrata* is 500 g or above in both local and international markets. Immature female crabs are increasingly being harvested, provided they are sufficiently heavy. In ponds or compartments, some crabs exhibit faster growth and can be harvested earlier than scheduled. Periodic harvesting of market-sized crabs reduces competition for food and space, as well as the incidence of cannibalism, allowing the smaller crabs to grow faster. Partial harvesting is typically carried out using baited traps, which are set and retrieved after several hours or the following day. Alternatively, during low tide, the pond is partially drained, and as new water enters at high tide, large crabs swimming toward the incoming water near the pond gate are scooped out.

Total harvesting is conducted once crabs and fish have reached market size. In most polyculture systems, fish are harvested ahead of the crabs. Fish are usually gathered during water exchange, as they tend to swim against the current and can be collected in the catching pond or canal system using a seine net. For a complete harvest, the pond is fully drained, and crabs and any remaining fish are collected manually. Undersized or underweight crabs are either sold at lower prices or restocked in separate pond compartments, cages, or pens for further culture or fattening.

Emergency harvesting may occur when high crab mortality is observed, often due to white spot syndrome virus (WSSV) or other causes, necessitating immediate action to minimize losses.

FATTENING OF CRABS IN PONDS, PENS AND CAGES

Often, 20–40 percent of the harvested crabs are found to have missing claws or walking legs, be underweight (lean), or far too small. These crabs are deemed unsuitable for the export market and are considered of low value in the domestic market. This issue becomes more pronounced when crabs are stocked at higher densities. To address this, some farmers engage in fattening or further culturing these crabs for 1–2 weeks, either communally or individually, to enhance their market value. Lean crabs that are diseased cannot undergo the fattening process and are excluded by farmers from subsequent cultivation efforts.

Communal and individual culture systems

In communal culture system, several lean crabs are stocked in a pond compartment, pen or cage. Pens and cages are set up in ponds, estuaries, mangroves, sheltered coastal waters, shallow lagoons or bays. The cages may be floating or fixed (Figure 6). Crabs are sometimes stocked at higher density, depending on their size, because moulting frequency lessens as crabs increase in size. Crabs are harvested when fattened and replaced again with lean but active crabs whenever available.

In other countries, crabs for fattening remain tied until they are harvested in communal culture system to prevent cannibalism (Figure 5). In this way, retrieval of crabs becomes easy. Feeding is not impeded by cheliped immobilization; however, the holding period is generally short (about 1 week).

In the individual culture system, crabs are stocked separately in compartmentalized bamboo cages, perforated polyethylene plastic containers (like those used for soft-shell crabs but larger, designed for fattening), or other improvised containers such as plastic crates, gallon containers or baskets (Figure 6). To optimize pond space, these cages or containers are mounted on polyvinyl chloride (PVC) or wooden frames and placed within the pond, which may also house fish. This arrangement allows fish to graze on filamentous algae growing on the walls of the cages or boxes, contributing to pond ecosystem management.

FIGURE 5
Tied crabs stocked in cage for fattening in communal culture system

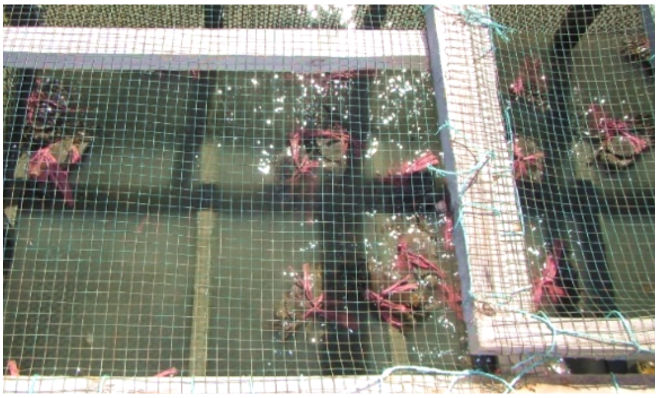

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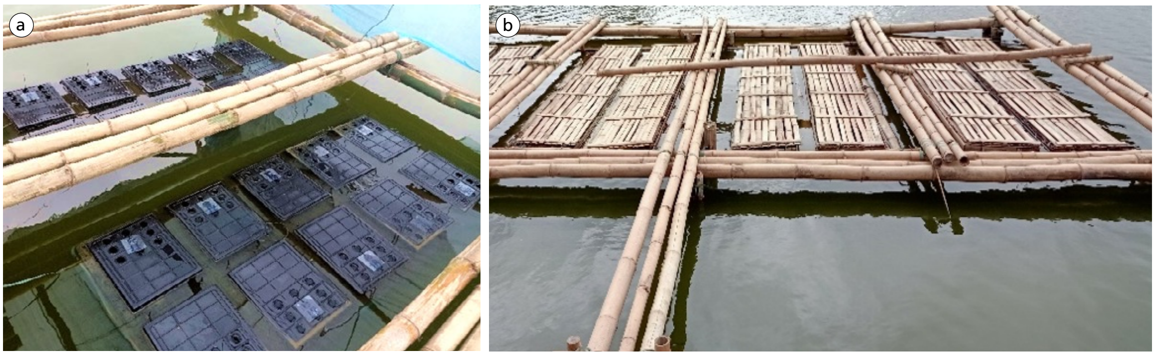
FIGURE 6
High density polyethylene (plastic) boxes (a) and compartmentalized bamboo cages (b) positioned in pond used for crab fattening in individual culture system



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Crabs are also cultured in containers within indoor vertical farming systems that utilize recirculating aquaculture systems (RAS). Some farmers modify RAS setups using locally available materials to reduce costs, as purchasing a complete RAS setup can be very expensive.

Feeding and water management

Crabs are fed with fish, molluscs, or other affordable protein sources readily available in the area. The feed is prepared to match the size of the crabs' mouths and is designed not to fall through the holes at the bottom of the containers. Feeding is conducted once or twice daily to satiation, with uneaten food removed from cages or pens before the next feeding to maintain water quality.

Adequate water flow is essential, particularly when using cages, as it ensures proper oxygenation and waste removal. To maintain optimal water circulation, periodic inspections and cleaning of the cages are necessary to prevent the accumulation of filamentous algae and other organisms that could obstruct water flow.

Harvesting

Harvesting is easier in the communal and individual culture systems because the crabs are confined in smaller compartments or containers. Fattened crabs are selected, tied, washed and classified before being brought to trading centres where the crabs are further classified based on their quality.

FIGURE 7
Mangroves enclosed with net for the culture of mangrove crabs as in aquasilviculture

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AQUASILVICULTURE

Aquasilviculture or silvofisheries, integrates mud crab farming and other aquatic species with mangrove ecosystems (Figure 7) (Takashima, 2000; Fitzgerald, 2000). In this system, the flooded areas within mangroves are enclosed using bamboo or polyethylene pens ranging in size from 500 to 2 000 m². The enclosures may be rectangular, square or irregular in shape, depending on the distribution of mangroves in the area.

To facilitate feeding, monitoring and sampling, catwalks or narrow bamboo walkways are constructed in the middle of the pens. In some setups, overhang nets are installed at the top edges of the pens to prevent escapes. Approximately 20 percent of the total pen area is designated as canals to retain water during low tide, ensuring a continuous water source for the crabs.

Pens are ideally located in the lower part of the intertidal zone, where water remains even during low tide. This is crucial because insufficient water levels during low tide can negatively impact crab moulting and feeding. This setup is particularly suitable for crab fattening, as the culture period is short (2–3 weeks). Additionally, the shorter duration minimises moulting frequency, allowing for higher stocking densities during the fattening process.

Although aquasilviculture has been adopted by many coastal communities, numerous challenges have been reported (Dieta and Dieta, 2014). Many projects struggled to succeed, particularly when aquasilviculture was used for long-term culture, raising crabs from juveniles to market size. The extended culture period increased the crabs' exposure to predators and the likelihood of cannibalism, resulting in significantly reduced yields for farmers.

Additionally, some aquasilviculture projects were established in unsuitable locations, including areas with inappropriate mangrove species. Selecting the right mangrove species is crucial for a successful site, as crabs require continuous submersion during culture. However, certain mangrove species cannot tolerate prolonged submersion of their aerial roots, leading to mangrove mortality – particularly in areas where low dykes are built to retain water during low tide.

For example, *Rhizophora* species are typically found near flooding tides and rely on branching stilt roots for oxygen and stability (Smithsonian Institution, 2024). These roots suspend the trunk above water and feature lenticel openings that enable oxygen uptake even when submerged. Similarly, mangrove genera like *Avicennia*, *Laguncularia* and *Sonneratia* have pneumatophores – specialized aerial roots growing from cable roots – that help the trees access oxygen in waterlogged conditions (Smithsonian Institution, 2024).

Pens are best constructed in areas with mature mangroves that provide adequate shade and protection against strong winds and typhoons, ensuring both the health of the mangroves and the success of crab farming.

Feeding and water management

Algae, leaf litter, detritus, snails and other invertebrates are available in mangroves that can serve as food for crabs aside from the food actively provided by the farmer (fish, molluscs, etc.). Feeding is done once a day during high tide.

Water exchange is maintained by ensuring a consistent flow of water in and out of the pen. Any debris that accumulates around the pen, obstructing water flow, is promptly removed. Canals are regularly maintained to ensure a minimum water depth of 0.5 m. To prevent erosion caused by tidal fluctuations, some farmers install bamboo frames around the canals or ditches, providing additional stability and protection against water currents.

Harvesting

Selective harvesting is commonly practiced in aquasilviculture when market-sized crabs are identified. Once the majority of the crabs have reached the desired size and are fully fattened, a total harvest is carried out. This is done by deploying multiple baited crab traps or by manually handpicking the crabs during low tide.

Problems encountered

The most common problems in aquasilviculture are the presence of predators that enter the pens and prey on the cultured crabs, as well as the issue of poaching. Predators of mangrove crabs include other species of crabs such as *Thalamita* spp., *Varuna litterata*, and carnivorous fish like the Asian seabass, grouper, snapper and sea snake fish. Newly moulted crabs are often the most vulnerable. Therefore, it is advisable to stock larger-sized crabs to reduce the frequency of moulting. Predators can be effectively removed during low tide to minimize losses. However, poaching – whether through the use of crab traps or handpicking – is a common issue in setups that are not consistently monitored or guarded by the farmer.

DISEASE AND HEALTH MANAGEMENT

The health and condition of crabs are closely monitored for any signs of disease, abnormal behaviour, or unusual appearance. This proactive approach ensures that necessary remedial measures can be implemented promptly to address any issues. The use of quality seed stock and adherence to good aquaculture practices are essential to preventing diseases and abnormalities that can compromise the economic viability of crab farming. The following are common diseases and abnormalities observed in grow-out ponds (The Mangrove Crab Technical Committee 2018, 2021):

- *White Spot Syndrome Virus (WSSV)* – Caused by a rod-shaped double-stranded DNA virus from the genus *Whispovirus* (Leu and Lo, 2008), WSSV can decimate entire crab populations. It is prevented by avoiding the polyculture of crabs with shrimp. Some farmers also avoid crustacean culture during colder months.
- *Bacterial shell disease* – This disease is caused by gram-negative, rod-shaped bacteria such as *Vibrio*, *Pseudomonas*, *Aeromonas* or *Spirillum*, which digest chitin following mechanical injury. Overcrowding and poor water quality exacerbate the problem. Prevention involves maintaining optimal water quality and avoiding overstocking.
- *Hematodinium infection* – This parasitic dinoflagellate infects the haemolymph or haemocoel, damaging major organs and causing mortalities of up to 50 percent (Li *et al.*, 2008; Li, Li and Huang, 2021). Proper pond preparation and strict biosecurity measures are critical for mitigating this infection.
- *Shell fouling* – A mixture of filamentous bacteria, algae, protozoans, and debris causes shell fouling. This issue typically resolves after moulting.
- *Stalked barnacle infestation* – Stalked barnacles from the genus *Octolasmis* colonize the gill chambers (Figure 8). In large numbers, they can impair oxygen and carbon dioxide exchange, negatively affecting the crabs. Prevention and control measures remain unknown.
- *Acorn barnacle infestation* – Barnacles from the genus *Balanus* adhere to the crabs' shells. They can be removed by scraping or naturally eliminated after moulting.

FIGURE 8
Stalked barnacles, Octalasmis (arrow), colonizing the gills of the mangrove crab

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FIGURE 9
Rusty colour of the ventral side of the mangrove crab due to acid sulfate soil in the pond

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FIGURE 10
Albinism in juvenile mangrove crab

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- *Black gills or gill fouling* – Caused by poor environmental conditions such as high organic load and heavy siltation, this condition can be prevented through proper pond preparation, including sludge removal, and by maintaining good water quality to prevent silt accumulation that clogs the gills.
- *Rusty discoloration* – The ventral side of the crab develops a rusty appearance (Figure 9) due to low soil pH. This can be prevented by applying lime during pond preparation to neutralize acid sulphate soils.
- *Albinism* – This condition, likely a nutritional disorder, is characterized by whitish discoloration on the body or legs (Figure 10). Providing feeds rich in vitamins C and E can prevent or reverse albinism.

Thus far, reoviruses which have been detected in India and caused mass mortalities in mangrove crabs (Shanmuganathan Kandan, personal communication) has not been detected in the Philippines.

MARKETING

Live mud crabs are sold to buying stations or traders, or directly to the consumers, including seafood restaurants or exporters. From the buying stations or traders, the bulk of the crab stocks are sold to exporters. Crabs are exported to China, China, Hong Kong SAR, Republic of Korea, Singapore, and Taiwan Province of China.

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Towards sustainability in soft-shell crab production

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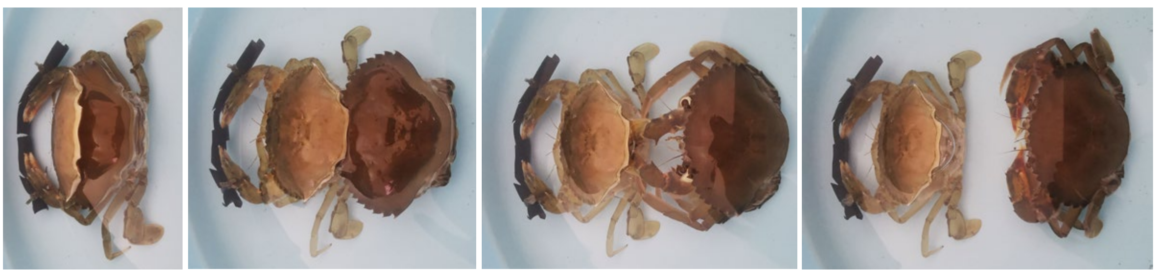
ABSTRACT

Sustainability in soft-shell crab production necessitates the implementation of effective management practices and practical solutions to address critical challenges essential for the industry's continuous progress. Key initiatives include securing the supply of intermoult crabs through advancements in hatchery technologies and grow-out operations, providing a strong foundation for achieving sustainability. Employing a mangrove-friendly extensive polyculture approach not only supports crab grow-out but also fosters mangrove reforestation and community engagement. Stocking pre-moult crabs communally enhances operational efficiency by streamlining routine tasks and reducing manpower needs. Integrating *Caulerpa* sp. in recirculating aquaculture systems offers dual benefits: cost-effective nutrient-rich water treatment and the production of commercially valuable seaweed as a secondary crop. Additionally, adopting proper post-harvest handling procedures minimizes stress-induced mortality in crabs, improving overall yield. Finally, exploring alternative feeds such as selected insect species and fish provides sustainable options for meeting the nutritional demands of soft-shell crab production. Together, these initiatives contribute to the long-term viability and environmental stewardship of the industry.

INTRODUCTION

Soft-shell crab, distinguished by its pliable and expandable exoskeleton (Figure 1), represents a natural life stage of the crab and has been consumed for over 150 years in the United States of America (Oesterling, 1995). Over time, its popularity has grown, making it a highly sought-after seafood worldwide, particularly in regions such as Australia, China, Japan and Southeast Asia. Renowned for its unique, flavourful taste, soft-shell crab is prepared using various culinary methods, including grilling, baking, sautéing and deep-frying. Widely perceived as a healthy seafood choice, it is a rich source of minerals, high in protein, and contains relatively low lipid levels (Gao, 2023).

FIGURE 1
Moulting process leading to the formation of a soft-shell crab



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Despite its global appeal, the potential demand for soft-shell crabs remains under-realized, primarily due to limited supply and inadequate marketing efforts. In Malaysia and much of Southeast Asia, soft-shell crab production predominantly involves the *Scylla* species – *S. paramamosain*, *S. olivacea*, *S. serrata* and *S. tranquebarica*. Collectively known as mud crabs, these species are often referred to as mangrove crabs for more market-friendly branding.

Soft-shell shedding operations typically utilize juvenile hard-shell or intermoult crabs as raw material. These crabs are cultured until they moult, after which the newly moulted individuals are promptly harvested and marketed as soft-shell crabs (Figure 1).

However, the soft-shell crab industry currently faces several challenges that hinder its growth and sustainability. A key issue is the unpredictability of raw material supply, driven by export restrictions on wild-caught juvenile intermoult crabs imposed by neighbouring countries and declining harvests from local fisheries. Additionally, the single-crab stocking systems used in moulting operations are labour-intensive and operationally inefficient. The industry also faces significant post-harvest and post-stocking mortality rates, which reduce overall yield. Furthermore, there is a lack of effective measures for recycling nutrient-rich water and food waste, which impacts environmental sustainability. Rising feed costs compound these issues, further straining production viability. Addressing these challenges is essential to unlocking the full potential of the industry.

SEAWEED-BASED RECIRCULATING AQUACULTURE SYSTEM FOR CRABLET HATCHERY PRODUCTION

The ability of hatchery technologies to produce crablets in the desired quantity and quality at specific times is fundamental to the sustainability of crab aquaculture. This approach is particularly critical for soft-shell crab moulting operations, which demand consistent, year-round supplies of intermoult crabs as raw materials. By reducing dependency on wild-caught crabs, hatchery production enhances the stability and sustainability of the industry.

Hatchery technologies offer several advantages that make them indispensable for modern crab aquaculture. They allow for species-specific production, ensuring that the desired crab varieties are cultivated efficiently. The quality of crablets is ascertainable, providing uniform and predictable results that are critical for market demands. These technologies also enable predictable production volumes, which can be scaled and scheduled according to specific needs. Additionally, they provide an avenue for selective breeding programmes, paving the way for genetic improvements and better-performing crabs.

Compared to traditional larval rearing methods that depend on periodic water exchanges, a seaweed-based recirculating aquaculture system (RAS) offers significant improvements in larval performance (Figure 2). The continuous water treatment maintains superior water quality, which directly enhances larval survival rates. Additionally, *Artemia* has been shown to outperform enriched rotifers as a feed source, resulting in significantly higher survival rates among larvae.

In the hatchery, newly hatched Z1 larvae of *S. paramamosain* are stocked at a density of approximately 200 ind./L. During their initial growth stages, larvae are fed the umbrella stage of *Artemia*. As the larvae develop, a combination of the umbrella stage *Artemia* and particulate feeds is introduced to support their nutritional needs. Harvesting of C1 crablets typically begins 21 days after stocking. Survival rates average around 10 percent and can reach a maximum of 20 percent (Figure 3). This optimized approach not only improves the consistency and quality of crablet production but also aligns with the industry's broader goals of sustainability and reduced reliance on wild stocks.

FIGURE 2
Seaweed-based RAS enabled larval rearing tanks

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FIGURE 3
Hatchery-produced C1 *Scylla paramamosain* crablets

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MANGROVE-FRIENDLY EXTENSIVE CRAB POLYCULTURE

Hatchery-reared crablets are raised to marketable sizes using a mangrove-friendly extensive polyculture system, a practice also widely adopted in Viet Nam. Degraded mangrove habitats are restored by replanting mangrove trees and constructing and dividing the area into culture ponds. The intricate root systems of the mangroves, along with other vegetation, create ideal shelters for the crabs (Figure 4). These ponds support the polyculture of crabs alongside other co-cultured species of fish and shrimp.

The ponds are connected to the sea through gates, allowing natural tidal flows to replenish the ecosystem. This tidal exchange fosters the growth of natural food sources such as bivalves, gastropods and polychaete worms, which benefit the crabs. Depending on the crab stocking density and the natural productivity of the ponds, supplementary feeding may be provided but is often optional.

Crablets are stocked either monthly or bi-monthly, ensuring a consistent supply for the culture system. Harvesting, on the other hand, is conducted daily, typically using traditional net traps. Alternatively, the crabs' natural behaviour of swimming toward water flow can be leveraged to optimize and streamline the harvesting process.

While most grow-out farmers prefer cultivating large hard-shell crabs weighing over 250 g, producing smaller crabs of approximately 120 g for soft-shell crab production also offers distinct advantages (Figure 5):

FIGURE 4
Mangrove-friendly polyculture of hatchery-produced crablets

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FIGURE 5
Crabs (120 g) grown from hatchery-produced C1 crablets

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- *Faster turnover of crab stock* – Smaller crabs take only 2–3 months to reach 120 g, compared to 5–6 months needed to produce crabs weighing 250 g.
- *Higher stocking density* – Smaller crabs require less space, allowing for a higher stocking density. More shelter options can be accommodated to minimize stress and competition.
- *Improved survival rates and yield* – Shorter culture periods mean fewer cycles of moulting, during which crabs are highly vulnerable. The survival rate ranges from 20–50 percent depending on various factors including cannibalism, predation and poaching.

This grow-out system, characterized by its simplicity and low operational costs, presents a viable economic opportunity for fishers and local communities. Participation in grow-out operations can be further incentivized through buyback arrangements, where soft-shell shedding operators supply crablets to participants and subsequently purchase the marketable-sized crabs from them. This mutually beneficial arrangement fosters economic engagement while reducing entry barriers for local stakeholders.

SEAWEED-BASED RAS SYSTEM FOR COMMUNAL SOFT-SHELL MOULTING

Crabs in the intermoult stage exhibit natural cannibalistic behaviour and are typically housed in isolation within boxes, either in pond-based or indoor soft-shell shedding systems. Alternatively, crabs can be stocked communally by restraining their chelipeds to prevent injury (Figure 6).

Cheliped restraint can be achieved through various methods. One common technique involves immobilizing the dactylus (the movable tip of the cheliped) with a plastic fastener which is then secured to the lower section of the propodus. With chelipeds restrained, crabs can be stocked communally at high densities, exceeding 100 individuals in a culture tank measuring approximately 75 × 300 m, or around 43 ind./m^2.

Each tank is equipped with water inlets and outlets located at opposite ends. Nutrient-rich water discharged from the tanks is treated using seaweed within a recirculating aquaculture system (RAS) before being reused (Figure 7).

FIGURE 6
Communal stocking of crabs with restrained chelipeds

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FIGURE 7
Shedding system using communal stocking in a seaweed-based RAS facility

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Early pre-moult crabs are identified by the formation of new bristles which is seen as a red line on the margin of the paddle segments of the swimming legs (Figure 8). Late pre-moult crabs are characterized by a splitting gap along the posterior margin of the carapace (Figure 9). Once detected, they are transferred to a shedding (or moulting) tank containing water of reduced salinity. Deprivation of external sources of calcium

FIGURE 8
Early pre-moult crab with a red line on the margin of the paddle segments of the swimming leg

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FIGURE 9
Late pre-moult crab with a splitting gap of the carapace

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ions slows the mineralization and hardening processes of the newly formed exoskelton (shell) of the soft-shell crab.

The ability to monitor the entire stock held within the culture tank at any one time significantly simplifies routine tasks by:

- *Facilitating efficient transfer* – The detection and transfer of pre-moult crabs from the culture tank to the shedding tank can be streamlined. These tasks, along with the harvesting of soft-shell crabs from the shedding tank, can be performed three to four times daily, significantly reducing the workload and requiring fewer workers compared to systems where crabs are stocked individually.
- *Streamlined feed management* – Leftover feed, if any, can be removed collectively, simplifying tank maintenance and ensuring cleaner conditions.
- *Enhanced monitoring* – The communal stocking system provides ongoing insight into the general health and appetite of the crab population. This allows for timely corrective actions and precise adjustments to feeding rates as needed, ensuring optimal growth and wellbeing.

An important benefit of communal stocking is the ability to easily identify pre-moulting female crabs by the presence of a coupling (intermoult) male crab. This facilitates the large-scale harvesting of pre-moult crabs, commonly referred to as "double-shell crabs", which can be marketed as a viable alternative to traditional soft-shell crabs.

Furthermore, manpower can be efficiently scheduled to accommodate peaks in moulting activity, which typically occur 3–5 days before the full moon and new moon, aligning with the waxing gibbous phase and the waning crescent phase of the lunar cycle, respectively. This ensures sufficient labour is available during these critical periods, optimizing productivity.

Water quality maintenance using a seaweed-based RAS system

Water quality in a soft-shell crab shedding system must be regulated to remain within optimal parameter ranges.

Mangrove crabs demonstrate adaptability to a broad salinity range of 5–30 ppt. However, they cannot tolerate a salinity of 0 ppt and typically perish within 5 days under such conditions. Interestingly, they can survive indefinitely when provided with an adequate mud substrate, which likely acts as a reservoir of essential minerals necessary for their physiological needs.

Seaweed has proven to be an effective, natural, and cost-efficient method for wastewater treatment. In soft-shell crab shedding systems, species such as *Caulerpa* sp.,

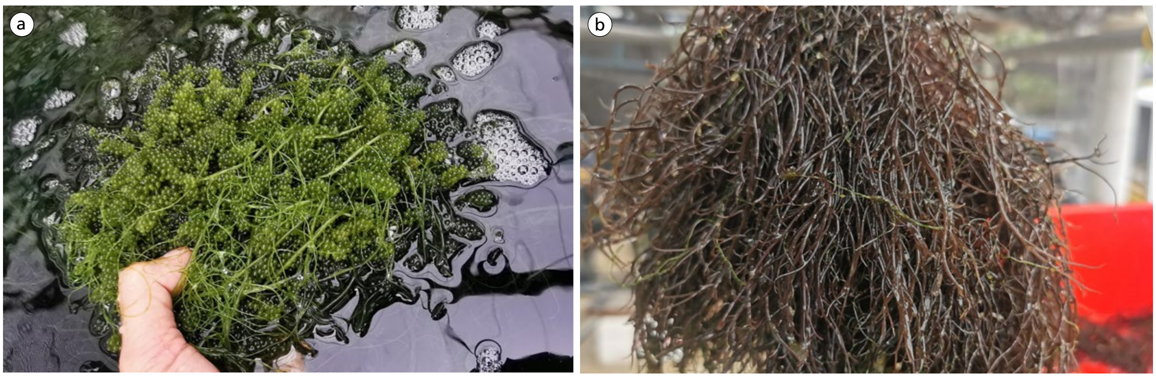
Environmental parameter	Desirable values
Salinity	15–25 ppt (or 30 ppt, if *Caulerpa* spp. is used in the RAS)
pH	7.5–8.3
Temperature:	28–30 °C
Dissolved oxygen	> 5 ppm
Ammonia	< 0.5 ppm
Alkalinity	120 ppm

Gracilaria sp. and *Chaetomorpha* sp. are effective in maintaining near-negligible concentrations of ammonia, nitrite and nitrate, respectively, in the culture water (Figure 10).

Caulerpa spp. (*C. lentillifera* and *C. racemosa*), commonly referred to as sea grapes, are widely consumed raw in salads across Southeast Asia and East Asia. Their high commercial value and potential as a functional food make them highly attractive candidates for aquaculture. These species are particularly well-suited for integration with recirculating aquaculture systems (RAS) in soft-shell crab production.

Moreover, seaweed species and their associated microbiomes are known to synthesize a variety of antimicrobial compounds. These bioactive substances play a significant role in mitigating the proliferation of potential pathogens, contributing to a healthier culture environment (Pérez, Falqué and Domínguez, 2016).

FIGURE 10
Caulerpa sp. (a) and _Gracilaria_ sp. (b) used as an effective water treatment component in a recirculating aquaculture system



Minimizing mortality of crabs

One key advantage of locating the crab grow-out operation in proximity of a soft-shell shedding facility is the increased efficiency of post-harvest transfers and handling. This proximity significantly reduces post-stocking mortality, which can be as high as 40 percent when crabs are sourced from external distributors, compared to an average of < 10 percent for crabs supplied from in-house grow-out ponds.

When sourcing crabs from distributors, it is critical to ensure proper handling, transportation and holding practices, along with minimizing transfer times. Recommended guidelines for post-harvest crab handling are detailed in a report by the Australian Fisheries Research and Development Corporation (Poole *et al*., 2008). The report highlights that the time of emersion (crabs out of water) during delivery and handling contribute to stress and reduced survivability due to the following factors:

- *Respiratory metabolic stress* – Crabs are unable to obtain sufficient oxygen during emersion.
- *Ammonia accumulation* – Toxic levels of ammonia build up within the crab's system.
- *Dehydration* – Loss of water exacerbates physiological stress.
- *Physical handling disturbances* – Handling shocks negatively impact the health of the crabs.
- *Airflow exposure* – Air currents can exacerbate dehydration.
- *Temperature fluctuations* – Sudden changes in temperature increase stress levels.

To mitigate these risks, it is recommended to incorporate a recovery phase in the live mud crab distribution chain. This involves submerging the crabs in aerated water for 2–3 hours post-delivery to allow the excretion of accumulated ammonia. Subsequently, the crabs should be held in fresh seawater tanks to facilitate full recovery before further processing or stocking.

In soft-shell shedding systems, organic waste must be managed effectively to prevent the proliferation of disease-causing organisms. Uneaten feed should be promptly removed to avoid overloading the seaweed-based RAS water treatment system. Regular cleaning of the culture tanks with freshwater is essential to remove biofilm buildup and minimize organic waste accumulation, ensuring a healthier shedding environment.

Feeds and feeding

Sardines and trash fish (by-catch comprising juveniles of various fish species) are commonly used as feed in soft-shell crab production. They are often delivered fresh or frozen at -18°C. Frozen supplies need to be defrosted and washed with clean freshwater before being cut into a suitable size.

The feeding rate for crabs should align with their appetite and can range from 10 percent of their body weight every two days to 10 percent of their body weight daily or until satiation. A decline in appetite or cessation of feed intake may indicate either a pre-moulting phase or compromised health in the crab.

The use of sardines and trash fish as feed is increasingly unsustainable due to their declining availability, rising costs, and competition with human consumption. As an alternative, formulated pellet feeds are being developed and evaluated for their effectiveness in supporting growth, survival and moulting performance in crabs (Lwin, 2018). Protein sources derived from plants and organisms lower in the trophic food chain are particularly promising, as they can be produced using food waste, contributing to sustainability.

Preliminary trials have demonstrated the viability of using black soldier fly pupae (*Hermetia* sp.), crickets (*Gryllus* sp.), and guppy fish (*Poecilia* sp.) as cost-effective and sustainable feed options in soft-shell crab production. Whole feed items are preferable over cut feed to minimize nutrient leaching, which can degrade water quality within the culture system.

SHORTENING THE INTERMOULT PERIOD

Several methods are available for inducing moulting in crabs, all of which aim to bypass the intermoult stage by triggering hormonal changes that initiate the moulting process, or ecdysis.

A comprehensive review of these moulting inducement techniques is provided by Khor *et al.* (2021). The ideal moulting induction method should be cost-effective, practical, and easy to implement. It should result in minimal or negligible mortality, with no compromise in weight and size gains. Additionally, the method must ensure limb completeness and adhere to humane treatment standards.

Shortening the duration of the intermoult stage is desirable as it will increase the stock turnover and the production rate of soft-shell crabs, thus realizing higher profits. A shorter intermoult stage will also result in lower production costs. However, it is imperative that moult induction does not impart any negative effect on the nutritional composition, texture and taste of the softshell crab.

A blind taste test comparing fried softshell crabs produced using natural moulting and induced moulting by unilateral ablation showed that 75 percent of respondents preferred the former which they described as the better-tasting product, having more meat and a firmer texture (Figure 11 and Figure 12). The remaining 25 percent of the respondents were not able to discriminate any differences, and none preferred the latter.

FIGURE 11
A succulent, golden-crisp fried soft-shell crab

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FIGURE 12
Soft-shell crab halves with full meat content

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Consumer taste preferences for naturally moulted softshell crabs is a compelling reason for shedding operators to reconsider the use of moult inducement methods. Instead, shedding operators may prefer to focus on using a natural approach to shortening the intermoult stage of crabs by the improvement of natural growth rates through the continuous optimization of culture conditions, feed and feeding practices.

CONCLUSION

Soft-shell crab production offers both lucrative opportunities and the potential for sustainability. While current challenges exist, they can be addressed through strategic interventions and continuous improvements:

- Development of crab hatchery and grow-out operations
  - Reduces dependency on the unpredictable supply of wild crabs, which are often harvested using unregulated fishing practices.
  - Supports the production of crablets and their grow-out through an extensive polyculture approach, which not only promotes the replanting of mangrove trees in degraded brackish areas but also involves local communities in the process.
  - Provides greater control over the quantity, quality, and timing of crab supplies throughout the year.
- Optimization of soft-shell shedding systems
  - Communal stocking of intermoult crabs improves operational efficiency and reduces manpower requirements, enhancing overall system performance.
- Application of nature-based solutions
  - Implements simple, sustainable and cost-effective solutions, such as the use of seaweed in recirculating aquaculture system water treatment, contributing to healthier and more efficient systems.
- Improved post-harvest handling and husbandry practices
  - Reduces stress on crabs through improved handling and care, enhancing survival rates and product quality.
- Development of sustainable, cost-effective feeds
  - Supports the recycling of food waste to produce organisms at lower trophic levels, offering a more sustainable feed source for crab farming.
- Development of new markets and marketing strategies
  - Expands market opportunities and promotes the industry through effective marketing, ensuring sustained demand and profitability.

These approaches not only addresses key challenges in soft-shell crab production but also fosters a more sustainable and profitable industry.

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Advancing mud crab farming: precision aquaculture and future tech needs

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INTRODUCTION

To date most mud crab aquaculture has been undertaken by small- and medium-sized enterprises with limited capital investment. With demand outstripping the supply of mud crabs, resulting in overfishing of wild stocks, the farming sector is beginning to attract significant corporate interest. Greater capital investment will likely transform the sector from one that is experience-based to one that is data-driven and knowledge-based, following larger more established aquaculture sectors such as marine shrimp and salmonids. As such, new trends in precision aquaculture will be utilized by and adapted to the needs of the mud crab farming sector, whilst some species-specific tools will also need to be developed.

This paper identifies both current and future technological needs of the mud crab farming sector. Its purpose is to stimulate debate around the needs of the sector; to share its requirements and opportunities they present for investors, aquaculture technology suppliers and the R&D community to support the growth of the nascent mud crab aquaculture sector.

PRECISION AQUACULTURE

Precision aquaculture introduces control-engineering principles (Antonucci and Costa, 2019) to the sector and the ability to better monitor, control and document biological processes (Føre *et al*., 2018). This approach includes the Internet of Things (IoT), which can be incorporated into decision support and farm management systems (O'Donncha and Grant, 2019) to service aquaculture. A precision aquaculture ecosystem reduces the need for subjective, experience-based decisions and replaces it with a data-driven, evidence-based approach (Pounds, 2021).

While farm management software for hard-shell crabs has many similarities to those developed for prawns or shrimp, systems for soft-shell crabs (SSC) need to be specifically developed as the flow of raw materials between both production units is different.

PRECISION AQUACULTURE IN MUD CRAB HATCHERIES AND NURSERIES

Water quality

Maintaining stable water quality parameters is considered critical for successful mud crab larval culture. Monitoring of water quality parameters from multiple tanks via sensors, linked via controllers to a digital dashboard are now common in fish farming, is similarly required for mud crab hatchery systems. Key parameters include temperature, salinity, pH, ammonia, nitrite, dissolved oxygen and ozone (in recirculating aquaculture systems).

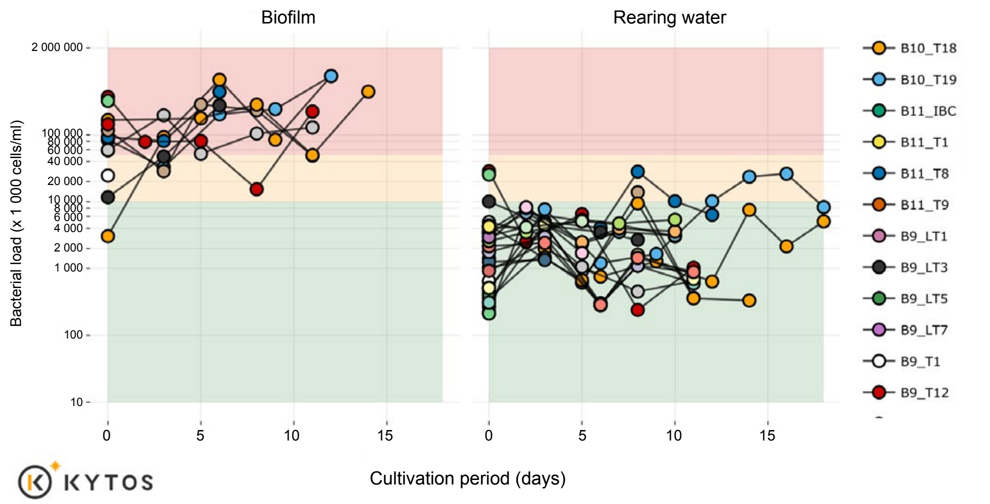
Depth and height sensors can be used to monitor water levels throughout the different components of a hatchery system and provide alarms to alert staff to any issues regarding low water or overfilling situations.

Microbiome management

It is well documented that the main factor negatively impacting the survival of mud crab larvae is bacterial in nature (Shelley, 2008; Dan and Hamasaki, 2015; Waiho *et al.*, 2018) and that the prophylactic use of antibiotics in hatchery protocols (Azam and Narayan, 2013) has underpinned much of the early successes in mud crab larval rearing. The use of probiotics, coupled with improved water quality management technologies, such as UV and ozone disinfection, now support improved control of bacteria in mud crab larval rearing. However, a detailed understanding of the microbiome of mud crab larval systems is still in its infancy. Technologies such as microbiome fingerprinting (e.g. Kytos) (Figure 1), next-generation sequencing (NGS) microbiome profiling (e.g. Luminis) and (almost) real-time monitoring of bacteria and fungi (e.g. Bactiquant) can now be used to examine relationships between bacterial numbers, types of bacteria, bacterial diversity, water quality and larval survival. This will enable hatchery operators to modify their feeding, disinfection and water management to optimize results and potentially make timely interventions to improve larval productivity.

FIGURE 1

A mud crab microbiome reading showing higher bacterial numbers in tank biofilm compared to rearing water



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Recent analysis of the microbiome of shrimp larval systems has indicated that probiotic dosing can be targeted to specific problems within the microbiome of tanks, resulting in improved production (Kytos, personal communication, 2023). As mud crab larvae are very prone to bacterial infections, such an approach will likely benefit mud crab larval production.

Feed management

Feeding of mud crab larvae is almost entirely manual. Automated larval feeding systems using pneumatic, peristaltic and mechanical technologies are now available to provide both dry and live feeds to larval tanks. Feeding regimens can then be established based on the optimal frequencies, times and quantities of feed required, without the need for consideration of staff rosters and work shifts. This will reduce labour required for feeding, prevent potential overfeeding of larvae and reduce the chances of human error. Such systems enable multi-tank systems to be linked through controllers and actuators, with different feeding programmes available for each tank.

Larval and live feed counting

In the same way that quantity of fish in cages can now be assessed using visual and Artificial Intelligence (AI) systems, there is a need to accurately count larvae during culture. At present counting larvae is based on taking a few random water samples from a tank and extrapolating the total number of larvae based on crude volumetric assumptions. However, this is inherently inaccurate as mud crab larvae exhibit schooling behaviour and move around tanks in response to various stimuli, resulting in uneven distribution within the tank. Obtaining accurate counts will enable hatchery operators to modify feeding regimens and water quality management to optimize survival.

PRECISION AQUACULTURE IN POND FARMING

Water quality

A variety of automated and semi-automated sensing systems are already being used in the pond aquaculture of shrimp and fish. To ensure the correct levels of oxygen are maintained in ponds, oxygen readings can be linked to the actuation of paddle wheels or other aeration devices, feeding programmes and alarms (e.g. Pond Master by Oxyguard).

Critical water parameters for mud crab and tropical shrimp farming are the same. In that sector, AI and IoT technology are already being combined with aquaculture expertise to improve shrimp farm management (e.g. AquaEasy).

Feed management

Automated feeders can be utilized to distribute feed more evenly in grow-out ponds. In addition to feeders operating based on quantity and time (e.g. eFishery), it is likely that feeding algorithms can be determined for feeding based on acoustic feedback. Such systems are already being used in shrimp farms where intelligent sound filtering algorithms measure the feeding intensity of farmed shrimp in variable noise environments, together with passive acoustic sensors (e.g. AQ1). Such systems can maximize growth, reduce feed use, improve food conversion ratios (FCRs), reduce labour costs, and potentially improve the environment by avoiding overfeeding, where excess feeds will harm the environment.

Stock control

Technologies to count shrimp going into ponds, like fish counting technology (e.g. Sincere Aqua), and technology for estimating the biomass of shrimp in the pond (e.g. Minnowtech), are already facilitating stock monitoring in the shrimp sector. With minor modifications, the same technologies can be utilized for mud crabs. One of the most difficult aspects of managing mud crab farming is to monitor the number of crabs in a pond during grow-out. At present, capture, tag and recapture techniques, combined with weighing a subsample of stock can be used, but this can stress and potentially damage stock through multiple trapping events. This is hard to justify and costly from a farm labour perspective. Other technologies that could potentially be incorporated into mud crab stock monitoring are remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs) which make use of infrared or reduced light visual sensing systems similar to those being utilized to sense, count, and size fish in salmon farming.

PRECISION AQUACULTURE IN SOFT-SHELL CRAB PRODUCTION

Work is already in progress with regard to the use of IoT in soft-shell crab production, with water quality sensors, motion sensors and feeding systems being developed to create “smart” farming systems (Pitakphongmetha, Suntiamorntut and Charoenpanyasak, 2021). Work on automated production systems for SSC was first highlighted in a patent awarded to Watermark Seafoods in 2004 (Patent WO, 2004/016077 A1), a "*System for harvesting crustaceans*". An automated robotic camera, linked to software on image analysis was utilized to sense when a crab had moulted; this would then lead to the harvest of the SSC from its individual basket. A system based on this patent, incorporating RAS technology, was built in Brisbane (Australia) and operated for a few years in the early 2000s.

Over the last 20 years huge advancements in robotics, sensors and AI indicate that a new system using similar technologies could be cost effective for future SSC farming and would result in less labour requirements compared to the current labour-intensive floating, or vertical, SSC systems.

With the floating SSC systems operating in countries such as Myanmar (Figure 2), basic data collection usually consists of records of SSC harvested per day and mortalities noted and removed. The average duration of each crab staying in the box is not recorded. To improve data recovery from the process, a bar code system could be employed. This would allow greatly improved collection of data, including time from stocking to harvest or to mortality for each individual crab as well as feed used. In addition, different fishers or traders supplying crabs for SSC could be traced. Some work in Myanmar has already identified that there can be significant differences in the survival rate of crabs from different suppliers, related to differences in logistics as well as handling and packing. This level of information could be considered in certification systems that require blockchain data to underpin traceability of products for specific markets.

FIGURE 2
Floating soft-shell crab culture system in Myanmar

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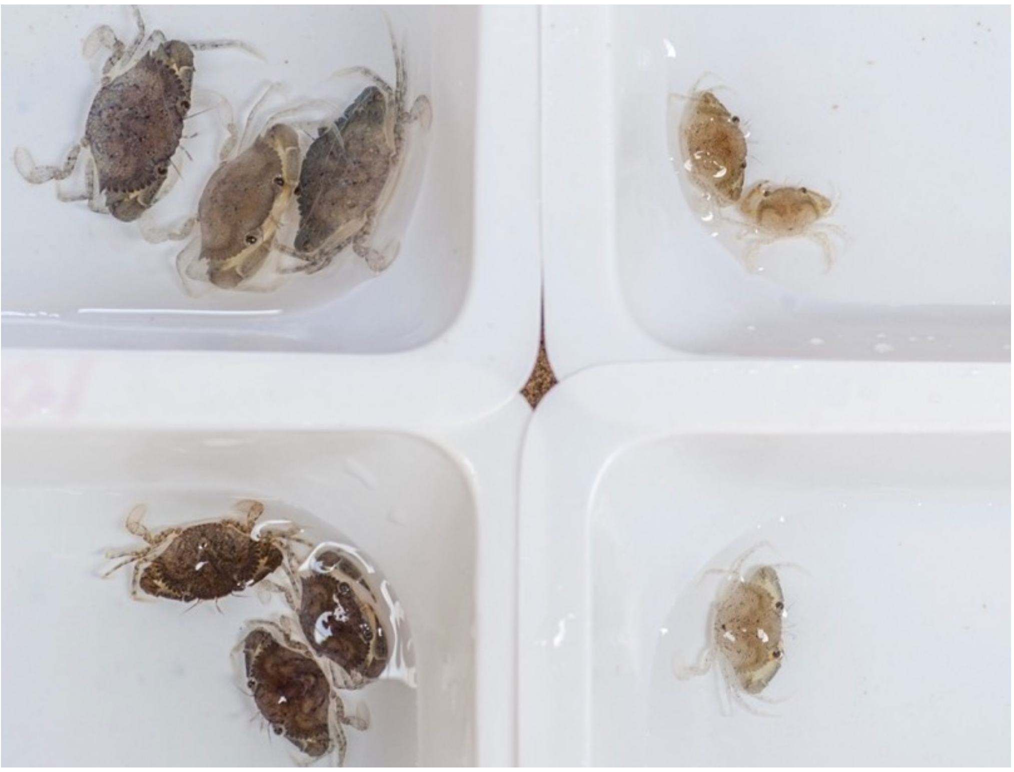
PRECISION AQUACULTURE IN POST-HARVEST PROCESSING

Currently, the "fullness" of mud crabs and their quality grading are based on manual physical testing. Attempts have been made in recent years to use near-infrared spectrometers (NIRS) and AI to grade live crabs based on their meat content. As customers are prepared to pay a premium price for mud crabs that are full of meat (not lean), a portable instrument that can quickly and cheaply provide this information will likely become a standard tool for fishers, farmers, wholesalers and end users. Commercialization of this technology is anticipated soon from work being undertaken in Australia and Singapore (National Mud Crab Industry Reference Group, 2012.).

Grading to prevent cannibalism

As in the early stages of fish culture, there is significant variation in growth within each cohort of crablets (Figure 3). As such, grading of crabs by size during the nursery phase prior to stocking in ponds, presents an opportunity to minimize cannibalism by reducing the size variability within each pond. At present, there is no machine that can be used specifically to grade crablets. Grading is most likely best applied between systems, such as in moving from nursery to juvenile ponds, around C4 (15 mm carapace width [CW], 0.4 g body weight [BW]), to C5 (20 mm CW, 1.0 g BW)]. Similarly, grading could also be useful when harvesting crabs from juvenile ponds for either soft-shell production or hard-shell farming at approximately C10 (85 mm CW; 77 g BW). Grading can be done by weight, size, or both.

FIGURE 3
Variation in size of crablets produced from one nursery batch of *Scylla serrata*



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Grading to separate sexes

If male and female crabs are not separated prior to reaching sexual maturity in the pond, mating will result in energy used mostly for reproduction, rather than somatic growth, which is more important from a farming perspective as crabs are sold primarily by weight. Whilst visual sorting by sex is possible from as early as C6, waiting until C10 means that crabs can be more easily sorted. Also sorting at this size corresponds to the size at which crabs can be harvested to be put into SSC systems or into grow-out ponds for hard-shell farming.

Technologies that can be used in automating sex grading of mud crabs include robotics combined with AI and visual recognition software. To simplify the handling process and stress involved with it, anaesthetics (e.g. Aqui-S) could be used to slow down the crabs' activity to make them easier to handle.

FIGURE 4
Packing frozen processed soft-shell mud crab in Myanmar

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Grading by weight prior to packing

Technology for grading by weight is readily available from a range of food processing equipment suppliers. These can enable accurate sorting of both SSC (Figure 4) and hard-shell mud crabs. Relatively high-speed grading enables live products to be harvested, graded and shipped in the shortest time possible, with minimal stress.

Packing

All live mud crabs are tied with string or vines to keep their claws tight against their body and minimize the risk of injuring other crabs during transit and food service staff handling them. This is a time-consuming and labour-intensive operation. In the future, packing of crabs could be mechanized if methods to make the crabs less active can be established (e.g. cooling or anaesthetics). Crabs could then be packed without tying within a tight mesh bag, or similar design to hold them securely during transport.

FROM PRECISION AQUACULTURE TO AI AGENTS FOR MUD CRAB AQUACULTURE

"An AI agent perceives its environment through sensors and acts upon that through actuators" (Nguyen, 2023). Agents can be software alone or combined with hardware. Commonly known examples of such systems that are already available for the public include Siri and Alexa. In aquaculture, an example of a simple agent is a system that controls the operation (switching on or off) of aerators in a pond in response to oxygen levels measured by sensors. This is already commonly used in fish and shrimp aquaculture.

A software agent for mud crab aquaculture would aid technicians and farmers, similar to having on hand a consultant or extension support worker but has the additional skill of knowing the current water quality parameters, feed levels, and such via sensors and has access to all the historic data from the aquaculture facility. In addition, the agent may have historic data from other farms to support its analysis.

Such an agent can either be used to make autonomous decisions or provide options for a farmer or technician to consider.

Agents could take autonomous action, via pumps, heaters, feeders, or other parts of the hatchery, nursery or farm through actuators, some of which may be incorporated or linked to robotic tools. AI agents can be incorporated into farm management systems, helping to improve productivity, reduce waste and optimize environmental performance and profitability. Recently, Bill Gates (2023) said in reference to AI personal assistants: "Agents are smarter. They're proactive – capable of making suggestions before you ask for them." He also predicted such systems would be commonly used within the next 5 years.

Aquaculture, including the mud crab farming sector, will need to embrace both precision aquaculture and innovations in AI and IoT to successfully compete in the increasingly high technology game of protein production.

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Technological innovations in mud crab aquaculture

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ABSTRACT

With the advent of advanced genetics and genome sequencing techniques, as well as computer and data science technologies, innovations to improve mud crab farming have become more accessible for field application. This paper discusses several novel science-based tools such as CrabADAPT, CrabSNP (single nucleotide protein), CrabMOLT, CrabMAP and "Alinmango", that have been developed by academic and research institutions to help make mud crab seed production and farming less challenging, thus enabling the growth of a sustainable mud crab industry.

INTRODUCTION

For years, the mud crabs or *Scylla* spp. have been produced through very conventional techniques starting with the use of wild-sourced seedstock; identification of juvenile crab species using morphology-based methods; nursery rearing in net cages within pond systems and farming of juvenile in earthen or concrete ponds; crab fattening; and polyculture of crabs in brackish water ponds and pens. In 2012, the Department of Science and Technology (DOST) in the Philippines supported the implementation of several research studies that focused on addressing known gaps in mud crab aquaculture such as limited seedstock supply, poor larval survival, cannibalism, accurate species identification at the juvenile stage, feed development, disease management, among others – with the purview that novel, more advanced techniques (software applications, IoT, genetics and genomics, and gene editing) can be developed through research and later validated in the field for widespread adoption by crab farmers. This paper describes the various novel science-based technologies aimed at improving mud crab production.

CONSTRAINTS IN SUSTAINABLE MUD CRAB PRODUCTION

The supply of crablets still remains limited despite of the efforts to domesticate mud crabs and enable the production of hatchery-bred seedstock (Figure 1). Various sizes of crablets sourced from the wild are still widely used for farming and in some areas, these are usually a mix of the three *Scylla* species found in the Philippines. Hence, crab collectors, traders and buyers need to be familiar with traditional identification methods which include examining the spines of chelipeds, claws, frontal spines, colour and markings (Quinitio *et al.*, 2018), while some consider the carapace width and size, carapace texture, or behaviour patterns like walking movement (Orario *et al.*, 2021).

Although the collection of wild crab seedstock remains a common practice, identifying the early life stages of the preferred *Scylla* species, *S. serrata*, poses significant challenges for the untrained eye. This difficulty arises from the diverse and

FIGURE 1
Juvenile crabs used as seedstock in mud crab aquaculture

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nuanced morphological and meristic characteristics used to differentiate species. Adding to the complexity, the morphological features of crablets are often ambiguous, making accurate identification even more challenging.

Beyond the need for species-specific identification, the nursery rearing of crab instars presents its own set of difficulties, including high rates of cannibalism, insufficient nutrition, and suboptimal environmental conditions (Syafaat *et al.*, 2021). Effective strategies for proper nutrition and health management are critical for improving growth and survival rates in this stage. Similarly, in grow-out culture systems, the development of low-cost diets and alternative feed ingredients is essential for reducing costs while maintaining productivity and sustainability in mud crab aquaculture.

ADVANCED TECHNOLOGIES IN MUD CRAB AQUACULTURE

Crabifier

This is a mobile application for juvenile crab species identification. With the advent of computer-based technologies, an automated and a quicker method of species identification for discerning differences in *Scylla* species has been developed via a mobile-based system known as "Crabifier". This is a scientifically sound alternative to the traditional species identification method practised by crab collectors, traders and farmers.

"Crabifier" is an android-based mobile application that uses convolutional neural networks to analyse the shape of the crablets' dorsal carapace to distinguish previously identified subtle morphological differences (Vince Cruz-Abeledo, Ting and Ablan-Lagman, 2018; Vince Cruz-Abeledo *et al.*, 2021). The "Crabifier" identification tool (Figure 2a) makes use of genetic barcodes based on ITS-1 PCR products unique to the species of individual crabs as well as image analysis of the crown or the reference frontal lobe spine shape (Vince Cruz-Abeledo, Ting and Ablan-Lagman, 2018). The "Crabifier" can be downloaded for free onto any android phone and used in the field (Figure 2b). The collector takes individual photos of juvenile mud crabs caught from the wild and the application identifies the species.

IMPROVED NURSERY REARING USING NUTRITIONAL INTERVENTION

Nutrigenomics

Crab nursery rearing is commonly conducted outdoors in concrete tanks, lined ponds, or net cages placed within brackish water ponds, where natural food sources are readily available. Alternatively, indoor tanks can be employed to enhance seedstock production, with biofloc technology offering potential benefits, as it has proven effective in shrimp farming. However, its application for mud crabs remains unexplored (Syafaat *et al.*, 2021).

Feeds tailored specifically for crab farming can be developed based on the species' nutrient requirements. Conventional feed formulation methods have demonstrated

FIGURE 2
Android based "Crabifier" App used in juvenile crab species identification (a) and demonstrated on its use to target users (b)

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success in improving the growth and survival of mud crabs. However, studies show that diets entirely replacing natural feeds with commercial or specially formulated feeds often underperform compared to diets combining natural and formulated feeds or those relying solely on natural feeds such as trash fish, squid, molluscs, shrimp, or slaughterhouse by-products (Millamena and Quinitio, 2000; Djunaidah *et al*., 2003; Alava *et al*., 2007).

Advanced approaches such as nutrigenomics are now being explored to develop more efficient feeds and feed additives. Nutrigenomics, defined by Alhoshy *et al*. (2022), examines the effects of nutrients and dietary bioactive compounds on gene expression. It focuses on interactions between these nutrients and the genome at the molecular level, which in turn influences cellular responses and mediates gene expression.

Preliminary research on local raw materials such as Bermuda grass (*Cynodon dactylon*), water hyacinth (*Eichhornia crassipes*) and banana peels (*Musa acuminata*) – all containing β-glucan, a known immunostimulant – has been conducted by the Practical Genomics Laboratory of De La Salle University, Philippines, in collaboration with the Southeast Asian Fisheries Development Center's Aquaculture Department (SEAFDEC/AQD) (Castillo, 2022; Joaquin, 2022) (Figure 3).

One study revealed that a diet containing 0.5 percent Bermuda grass for crab juveniles increased nitric oxide (NO) concentration, glutathione peroxidase (GPX) activity, prophenoloxidase (proPO), and superoxide dismutase (SOD) mRNA expression levels. These markers indicated improved immune response (Figure 4) (Castillo, 2022). Similarly, incorporating water hyacinth

FIGURE 3
Bermuda grass (*Cynodon dactylon*) used as raw material for crab diet

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FIGURE 4
Preparation of 0.5 percent *Cynodon dactylon* crab diet

©B. Joaquin

hot-water extract into juvenile crab diets significantly enhanced catalase (CAT) activity and prophenoloxidase (proPO) gene expression due to the presence of β-glucan in the extract. Both Bermuda grass and water hyacinth contain β-glucan, which triggers a cascade of immune defence mechanisms in crabs (Joaquin, 2022).

Such findings underscore the potential of nutrigenomics to expedite the identification of feed ingredients containing bioactive compounds. These compounds, when incorporated into crab diets, could not only enhance immune defence but also positively influence growth, reproduction and overall development.

INFORMATION TECHNOLOGY INNOVATIONS AND GENETICS

Mud crab research projects on genomics ramped up when funds from the Philippine Department of Science and Technology (DOST) became available in 2017 under a programme entitled "Harnessing emerging technologies for mangrove crab culture and resource management: 'omics approaches, web-based and mobile computing technologies". DOST included *Scylla* spp. in the list of priority aquaculture commodities for research and development, others being tilapia, milkfish, shrimps, prawns, mussels and oysters. This is the reason why innovations such as the "Crabifier", nutrigenomics-based evaluation of potential feed ingredient-immunostimulants, genetic characterization of crab populations and selective breeding came to the fore. Apart from these technology advancements, other projects included the following (Romana-Eguia *et al.*, 2019):

- CrabADAPT is a study investigating the genetic adaptability of specific mud crab (*Scylla serrata*) populations to wider temperature ranges and climatic anomalies. A key finding from this research emerged from comparative transcriptome profiling of the heat stress response in *S. serrata* populations sampled from three Philippine sites with distinct climate profiles.

  The study revealed that western Philippine mangrove crab populations, such as those in Bataan, exhibited a higher number of differentially expressed (DE) genes in response to heat stress compared to eastern populations, such as those in Cagayan and Bicol. This suggests that crabs from eastern regions, particularly Cagayan, possess broader thermal tolerance and a greater capacity for acclimation than their western counterparts.

  These findings have significant implications for aquaculture and stock management practices. For instance, crab farmers and hatchery operators could prioritize using stocks from eastern Philippine populations, which are likely to perform better under fluctuating and extreme thermal conditions, thereby enhancing the success of breeding and farming operations in the face of climate change (Shrestha *et al.*, 2021).

- CrabSNP is a study focused on identifying single nucleotide polymorphism (SNP) variants linked to adult-sized immature female mangrove crabs and identifying genome markers potentially associated with these phenotypes. This research is particularly relevant because immature female mangrove crabs fetch a premium price in the Philippine market.

  One aspect of the investigation examined the effects of temperature stress on fatty acid-specific proteins and the expression of heat shock protein 70 (HSP70) in various *S. serrata* sex phenotypes. However, the study found no significant differences in fatty acid profiles, protein levels, or HSP70 expression that could be attributed to sex phenotype (Lilagan, 2018).

  These findings suggest that factors other than sex phenotype influence these molecular responses, highlighting the need for further research to uncover the mechanisms behind phenotypic variations and stress responses in *S. serrata*.
- CrabMOLT is a study which investigated optimal salinity and temperature combinations that favoured frequent moulting. If crabs moult frequently this is an indication that the crab might belong to a fast-growing stock. Here, the ratios of a moult-promoting hormone (ERK) to a moult-inhibiting hormone were established for the different moulting stages of the mud crab.
- CrabMAP is an environmental guide map designed to identify suitable culture environments for mud crab farming. Using Geographic Information System (GIS) technology, it categorizes coastal sites based on their temperature profiles, including areas with high temperature fluctuations and elevated temperature levels, high temperature fluctuations with occasional low-temperature spikes, and low temperature fluctuations with minimal temperature spikes. This detailed mapping provides crucial information for farmers, helping them adopt climate-smart practices in mangrove crab aquaculture. By selecting sites best suited to the thermal tolerance of their stock, farmers can enhance productivity and build resilience to climate variability.
- "Alinmango" is a computer technology-based innovation that provides some data on major mud crab source sites and the environmental fluctuations that the crabs experience in each of these areas.
- Recent studies have explored the molecular mechanisms underlying *S. serrata*'s response to white spot syndrome virus (WSSV) infection using metagenomic and transcriptomic approaches. Conducted by the Marine Science Institute of the University of the Philippines in collaboration with SEAFDEC/AQD, this project aimed to characterize the microbiome and transcriptome profiles associated with the progression of WSSV infection. WSSV is a significant pathogen that affects crustaceans, particularly shrimps and crabs.

  The study revealed that in WSSV-infected mud crabs that survived the infection, viral loads increased at 48 hours post-injection (HPI), peaked at 72 HPI, and subsequently decreased to levels similar to uninfected crabs by 96 HPI, maintaining these levels through 144 HPI. This suggests that *S. serrata* can reduce WSSV viral loads during the late stages of infection, indicating a degree of resistance to the virus. These findings also highlight the potential role of mud crabs as carriers of WSSV.

  To further investigate the host's response, RNA sequencing (RNA-seq) was used to analyse the transcriptome of *S. serrata*. Pairwise differential expression analyses were conducted on genes expressed in the gills and hepatopancreas, comparing infected and non-infected crabs at various time points post-injection. The results provided valuable insights into the molecular mechanisms of the host's response to WSSV at the holobiont level, encompassing both the microbiome and the host (Ravago-Gotanco, 2023).

These findings have practical implications for selective breeding programmes aimed at improving the resilience and quality of mud crab seedstock and adult crabs. By integrating genomics-based research, future efforts can better address challenges related to WSSV resistance and enhance sustainable aquaculture practices.

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Enhancing post-harvest survival of crabs within the Australian mud crab fishery supply chain

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INTRODUCTION

The market of mud crab (*Scylla* sp.) in Australia is built on the sale of live product. This is grounded around two key areas: "quality", based on meat content (fullness) and shelf life, based on an assessment of the mud crab's post-harvest survival; and "liveliness", with greater liveliness a proxy for anticipated shelf life.

The industry along the supply chain continually have disputes around these two parameters. Over time industry players developed tests to assess these parameters, but all are subjective and there was no industry standard, although a number of broadly accepted techniques are used. Over the past 20 years or more, the industry, in collaboration with Australian government researchers, has sought to work towards a more objective science-based approach to these tests by better understanding the parameters that lead to, or can determine, meat content and liveliness, and how that can be consistently measured.

This paper explores the 25-year journey of improving quality, post-harvest survival, and vitality within the supply chain of the Australian mud crab fishery.

MUD CRAB SUPPLY CHAIN BACKGROUND

In Australia, mud crab is the basis of a highly valuable resource for commercial, recreational and indigenous interests. Within the commercial sector, there are two major areas of dispute along the supply chain. These relate to the meat content of mud crabs (i.e. the fullness) and the liveliness of mud crabs (i.e. the shelf life of the crab – with liveliness being a proxy for expected shelf life). Liveliness is the term that is used in the crab industry and it relates to a range of factors, including a rapid response to stimulus.

Over time the industry had developed some general methods for testing both aspects that were generally accepted but were subjective and open to dispute. Over more than 20 years, catchers, supply chain partners, consumers and researchers have been working to improve methods to determine fullness and improve the assessment of quality and liveliness.

Mud crabs are often harvested from remote coastal locations in the northern half of Australia – often with harsh environmental conditions and limited, if any, infrastructure – and in less remote areas along eastern Australia. The majority of remote crab fishers work from outboard powered dinghies and semi-permanent land-based camps where the live crabs are stored prior to transport to market. Those operating in less remote area will generally have a home base they return to daily.

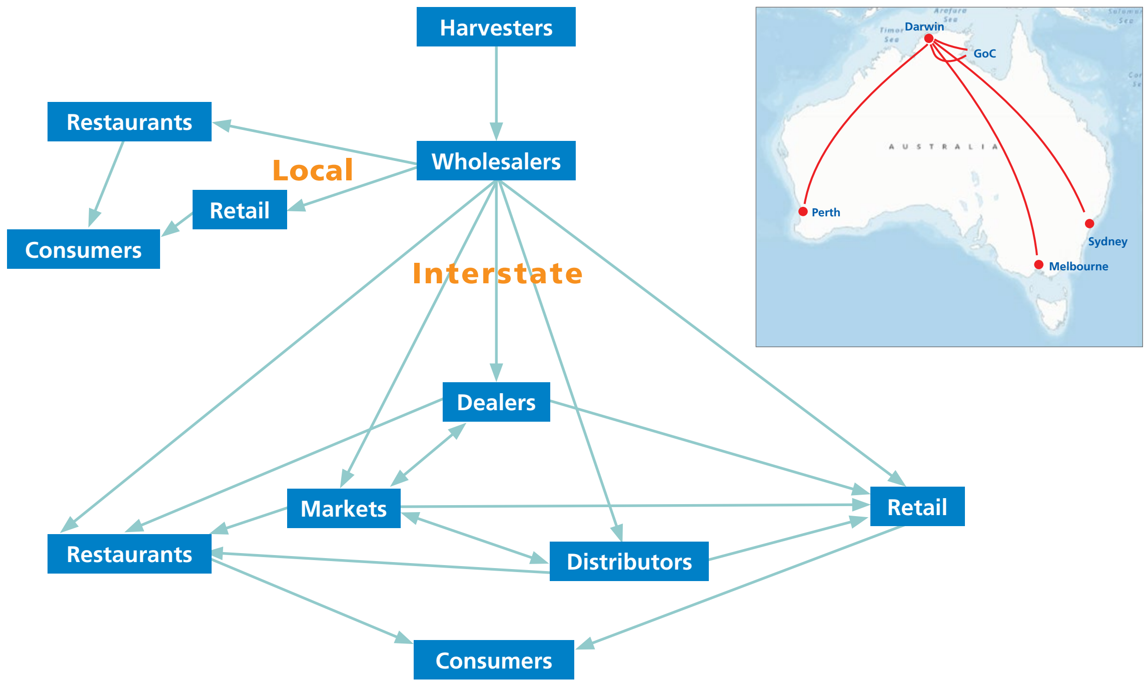
The market is for live product only and the financial return gained is dependant on meat content and liveliness of the crabs, as determined by the buyer at the purchase point. The main markets in Australia are in the high population states of New South Wales (NSW), mainly Sydney; and Victoria, mainly Melbourne, with Queensland also being a major market. Reaching these markets from remote areas can result in a very long supply chain from harvest to market.

An example of that supply chain, which is probably the longest and most extreme, is shown in Figure 1 outlining the Northern Territory (NT) routes from the Gulf of Carpentaria (GoC) crabbing area. The supply chain for mud crabs from the NT fishery can be up to 15 days, with expectation of further survival of crabs at retail level and to consumption point. The physical demand on the crabs can be extreme, as they are transported and distributed packed dry in air.

There are multiple handling steps within these supply chains, with the extremes highlighted in the NT route, as shown in Figure 1 and further detailed in Table 1.

FIGURE 1

Major supply chains paths in Australia from the Northern Territory



Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Calogeras, C., Mayze, J. & Poole, S. 2012. Using industry expertise to build a national scheme for grading of live mud crabs. FRDC 2011-225, Final Report. Fisheries Research and Development Corporation, Canberra.

Harvest location dictates the length of time the crabs are out of water (emersed) as well as transport pathways. Capture is by baited pot from estuarine mangrove habitat, rivers and adjacent mud flats in isolated locations. Crab pots are cleared as tides permit, typically once per day as there can be a 2–10 m tide change twice per day depending on location. Once taken from the pot, the crabs' claws are usually tied against their body and retained in the dinghy until all pots have been cleared – commonly this takes around 2 hours.

There are different methods of tying the claws, but most crab fishers tie as shown in Figure 2. This method is chosen as the mouthparts of the animal are still free and, should the crab accidentally be lost overboard, the animal may still be able to feed adequately to survive. Prior to packing, the crabs are allowed to purge for up to 24 hours so as to reduce excretory discharge when packed within a container.

In the dinghy, the crabs are held in a fish crate or lug box covered with a thick dampened hessian sack. After clearing all pots, harvesters return to camp and crabs are inspected for quality and limb loss. They are returned to plastic fish crates (Figure 2) and covered with damp heavy hessian sacking. If using lug boxes (Figure 3), the sacking is carefully folded in an interlocking manner to retain maximum moisture for the crabs and to exclude flies, which cause a major quality problem when crabs have fly larvae contamination.

Crab crates are stored in open air in a damp cool shaded area; in the simplest form this is under a tree or some form of shade cover. More sophisticated operations have screen storage sheds with sprinkler systems to maintain dampness (Figure 4). Crabs are held at a camp location for up to 7 days and the sacking cover is checked regularly for dampness and evidence of fly larvae.

FIGURE 2
Mud crab showing tied claws in a fish crate following collection

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FIGURE 3
Mud crab stored at a harvest camp in lug baskets

©C. Calogeras

FIGURE 4
Screened shed with sprinkler and water system

©C. Calogeras

Once a week the crates are loaded onto an open four-wheel drive vehicle and transported out to Borroloola, a small town located in the Northern Territory (NT) about 2 hours away from the main mud crab landing site. This transport stage includes demanding four-wheel driving and rough road surfaces, imposing severe disturbance on the crabs. At Borroloola the crab crates are transferred to a cool room (~16 °C). Time of storage at this temperature varies according to truck pickup time co-ordination (and weather). From Borroloola to Darwin, the crab crates are transported in a slightly chilled truck for a period of around 15 hours on tar-sealed roads.

On arrival in Darwin, crabs remain in the truck with refrigeration switched off for 2–5 hours. Crabs are then transferred inside an air-conditioned facility (~22 °C) for grading and pack-out prior to air transport to market. Crabs are lightly cleaned with town supply water to remove mud and debris. The condition of the crabs is then assessed by experienced graders and categorized generally into the following grades (Table 1).

TABLE 1
Commercial grades used for mud crabs in Australia

Grade	Crab general appearance description
Grade A	Lively, robust Shell hardness, no flex
Grade B	Lively, robust Males – shell hardness, slight flex on both middle segments, more flex on outer segments Female – shell hardness, slight flex on both sides and no flex in middle section
Grade C	Lively, robust Males – shell hardness, easily flexed on all segments Female – shell hardness, easily flexed on both sides and some flex on middle section
One claw	Lively but missing a claw
Slow	Judged by eye and antennae movement, resistance exhibited from claws, legs to applied gentle pressure
CUC	Commercially unsuitable crab (soft shell, little meat present)
Discard	Dead or diseased

Graded crabs are packed into waxed cardboard cartons which have small ventilation holes at the sides of the carton. Crabs are packed bottom-end down with eyes and gills upwards (Figure 5). Depending on crab size, there may be two layers within a carton and these are separated by clean paper or cardboard. Once packed, cartons are held briefly within the chilled facility ready for transport to the airport by truck or van, a < 30-minute trip on tar-sealed roads.

FIGURE 5
Mud crabs packed out in a carton box for air transport to market

©C. Calogeras

The mud crabs are flown out to interstate or international markets and this may involve transfer to further flights according to the final market destination. Due to these long supply chains and the multiple handling steps and temperature changes involved in mud crab distribution in Australia, crab mortality at times reached 30 percent of shipments. This equates to significant revenue loss for the industry as dead crabs are rejected for sale at market.

In the following example (Table 2), the Wearyan River in the GoC to southern markets is used to highlight one of the most demanding and lengthiest distribution channels in Australia. It should be noted that when the supply chain distances and timeframes are shortened (e.g. NSW northern coast to Sydney) the same variables are in play, but the severity of each will most likely be lessened.

Although industry sectors throughout the supply chain implemented various handling modifications to reduce high mortality rates, a coordinated and consistent approach was ultimately needed.

TABLE 2
Mud crab supply chain handling stages using Northen Territory example

Supply chain stage	Duration	Activity
Harvest and removal from trap	2–6 hours	Physical disturbance from handling and tying of claws, boat noise and transport over water.
Landed at camp for short-term holding	< 7 days	Crabs wrapped in damp hessian in crate. Dehydration, disturbance with daily checking condition of crabs.
Transport from camp to truck pickup point	2–4 hours	Crabs wrapped in damp hessian in crate covered with tarpaulin on back of utility vehicle or airconditioned vehicle. Transported over "rough" rutted track. Dehydration, movement, noise.
Holding storage at pickup point	2–12 hours	Crabs wrapped in damp hessian in crate. Storage overnight in 16 °C cool room or outside. Dehydration, movement, noise.
Wholesaler processor delivery	15–20 hours	Arrival at distributor via refrigerated truck transport (1 100 km). Dehydration, movement, noise.
Grading and pack-out in cartons	2–8 hours	Physical disturbance of crabs, dehydration.
Air transport	5–20 hours	Physical handling disturbance, noise, temperature. Low temperature imposed on flight transport, or on arrival at destination (e.g. NT temperature 30 °C and Sydney as low as 3 °C during winter or > 40 °C in summer).
On-transport to markets	2 hours to 4 days	Physical handling disturbance, noise, dehydration, temperature. Low or high temperature imposed on delivery vehicle or end user.

KEY STRESS POINTS IN HANDLING CHAINS IDENTIFIED

How an individual crab responds to or deals with the stresses imposed during the supply chain is directly dependent on the physiological condition of the crab. The physical robustness of mud crabs is influenced by the animal's health, moult cycle, season and nutritional state. These parameters also strongly influence the individual animal's tolerance to stress imposed.

A crab in a weakened state will have less ability to tolerate any level of stress imposed and will surrender to mortality more rapidly. Undernourishment during extended handling and transport chains may also contribute to lowered stress tolerance and during these periods, crab use its bodily energy stores, a process known as catabolism. In crabs, blood protein reserves are used first, followed by the hepatopancreas and eventually muscle. Starvation is unlikely to be a primary cause of mortality on its own; however, over the long-term, it may contribute by reducing the animal's ability to tolerate stress. Key metabolic parameters used by researchers to measure stress level experienced by the crab are pH, glucose, lactate and ammonia excretion.

Harvest

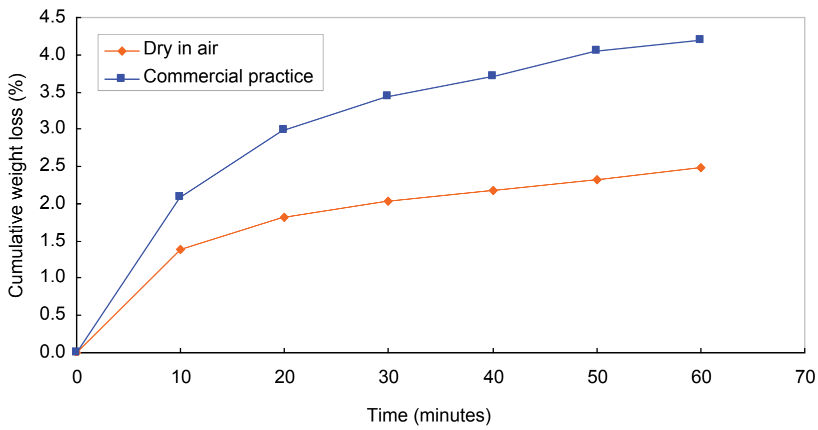
At capture, removal of crabs from the mesh traps and subsequent on-board handling can cause physical shell damage and limb loss. At this point, there is a requirement to restrict aggressive behaviour inherent in mud crabs, thereby limiting physical damage when crabs are in a confined space. Crabbers seek to minimize aggressive behaviour and generally will tie the crab's claws (see Figure 2) to minimize negative interactions with other crabs and the harvesters.

Dehydration

For dry live transportation of mud crabs, the animals are taken out of the water. The first effect is rapid dehydration with water loss equating to reduction in live animal weight and hence less revenue return. Initial water loss results in animal weight loss of around 4 percent within the first 60 minutes (Figure 6). During the first 24 hours, further dehydration causing weight loss occurs (Figure 7). In order to minimize dehydration, the crabs are kept moist by wrapping them in hessian and are kept in cool shady place.

FIGURE 6

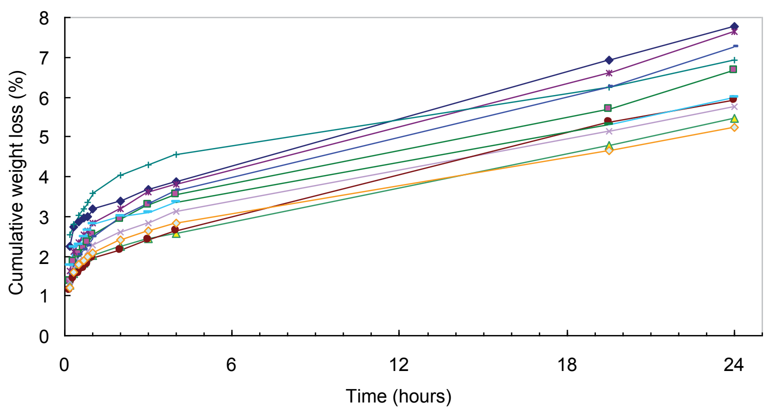
Cumulative weight loss from crabs during the first hour of emersion



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

FIGURE 7

Cumulative weight loss in mud crabs emersed for 24 hours



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

Metabolic processes

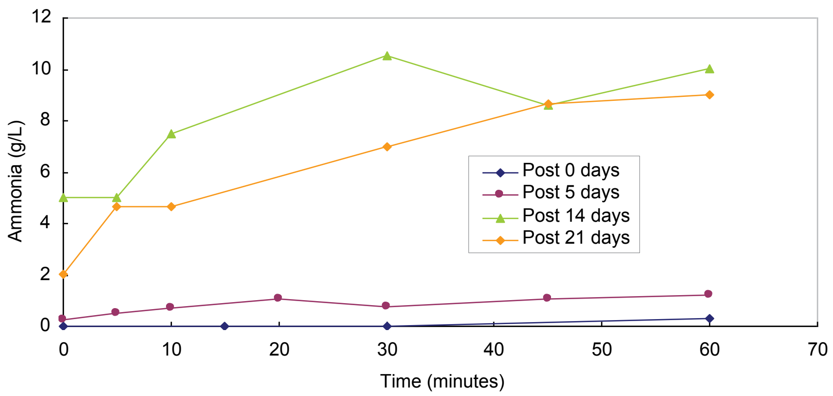
Crabs are aquatic animals and removing them from the aquatic environment for extended periods is uncharacteristic, causing respiratory and metabolic stresses. However, mud crabs are able to tolerate such treatment far more readily than many other crab species.

Crabs are poikilothermic and therefore the metabolic rate is largely determined by external environmental temperatures. Hence, the higher the temperature the greater the metabolic rate and the more rapidly the crab will deplete its oxygen supply.

Mud crabs, similar to other crustaceans, exchange respiratory gases with the environment through the gills. Oxygen is taken up from the water and the metabolic end product, carbon dioxide, is excreted back to the water. When in water with low oxygen saturation levels or when fully emersed (in air), mud crabs have to find a way to "breathe" without an external supply of oxygen. They do this through anaerobic respiration by switching metabolic systems to use alternative compounds to create energy.

Such anaerobic glycolysis is utilized to meet the shortfall in oxygen uptake and results in accumulation of lactic acid in the haemolymph and tissues. The combination of aerobic and anaerobic metabolism can be sufficient to maintain energy levels within the crab for essential existence and even allow some degree of vigour in mud crabs. However, liveliness is reduced and the crab becomes semi-comatose. Additionally, the end by-product of anaerobsis is ammonia which can accumulate in the blood to levels rapidly toxic to the crabs (Figure 8).

FIGURE 8
Ammonia excretion rates by crabs after different periods of emersion



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

Handling and disturbance during distribution chain

Anecdotal advice from experienced mud crab harvesters and wholesalers are to leave them alone; keep them damp, keep them quiet and they'll be fine! Handling and transport chain studies undertaken indicate that the comment has substance and that any form of disturbance, be it noise or movement, causes an instant and sometimes extreme response within the crab.

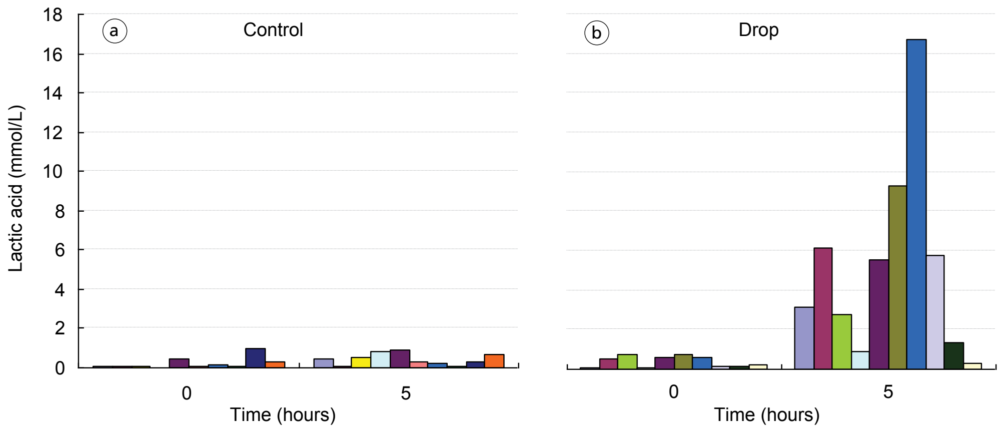
Movement

While held at camp, mud crabs are usually checked daily for liveliness, mortalities and to ensure claws remained tied by a gentle unwrap and sort, but without removing animals fully from the crates. The check for dead crabs is particularly important as upon death mud crabs release ammonia rapidly and this immediately affects other crabs in the crate, stressing them to a level that can lead to mortality. In addition, mortalities attract flies, and increases the chance of fly eggs being laid and subsequently larvae developing.

Crabs receive a final sorting and grading just prior to being trucked out of camp for further transport. In later steps of the supply chain, crated or boxed crabs are handled and transferred several times through transport distribution steps. Further disturbance arises from physical vehicle movement during transport.

Crab physiological response to strong or sudden movement is far more pronounced than stress caused by being held emersed, as shown in Figure 9, with high blood lactate levels in the mud crabs after they experience a sudden jolt movement.

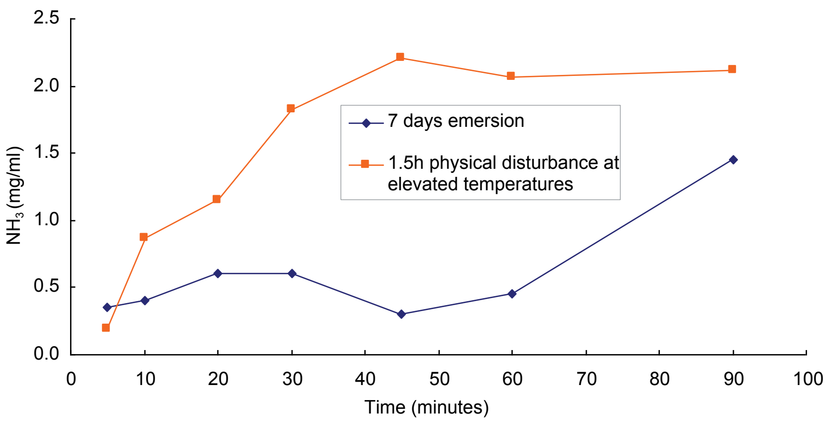
FIGURE 9
Blood lactate levels in undisturbed (a) and disturbed crabs (b)



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

The effect of disturbance can also be seen when crabs experience constant movement during transport in elevated temperatures, similar to that occurring when crabs are transported on the back of an open-backed vehicle (Figure 10).

FIGURE 10
Excretion rates of ammonia by crabs subjected to different stresses



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

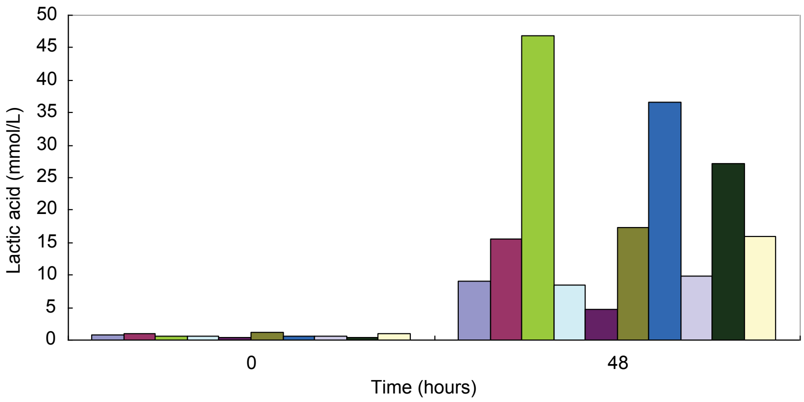
Breeze/wind

The detrimental effect of breeze on exposed crabs has common recognition among experienced harvesters. Hence the industry practice of covering crabs with damp hessian and storing them in a draught-free condition is important.

Unfortunately, this practice is not always adopted further along the supply chain. Within wholesale and retail sectors, crabs can commonly be exposed to strong air disturbances such as fan-forced air conditioning, regular opening and closing of doors, and storage positions affected by natural breezes.

Such air movement disturbances not only rapidly increase dehydration rate and weight loss, there is also a strong metabolic response evidenced indicating higher stress level in the crabs. The variability in individual crab reaction is illustrated in (Figure 11).

FIGURE 11
Blood lactate levels in crabs subject to breeze and wind



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

Noise

The effect of exposure to noisy environments is often mentioned by industry as a contributing factor in crab mortalities. Generator units in close proximity to stored crab at basecamp or in retail situations and even loud music or rowdy people are reported to have detrimental effects on crabs. Indication that such noise disturbance causes a metabolic response in mud crabs is illustrated by elevated glucose levels (Table 3) suggesting increased metabolism and energy reserve use. From other research undertaken it is shown that glucose levels between 1–3 mmol/L indicate a stress in mud crabs. Glucose level response in crabs subjected to noise are at the lower end of this range implying crabs were not unduly stressed. However, stress imposed by noise adds to other stresses imposed and have a cumulative effect contributing to mortalities and so should be minimized.

TABLE 3
Metabolic response in crabs subjected to noise disturbance

Crab treatment	Blood glucose level (mmol/L)	
	0 hours	48 hours
Control – crabs held quietly	0.16 ± 0.06	1.27 ± 0.77
Crabs subjected to noise	0.15 ± 0.07	1.75 ± 0.64

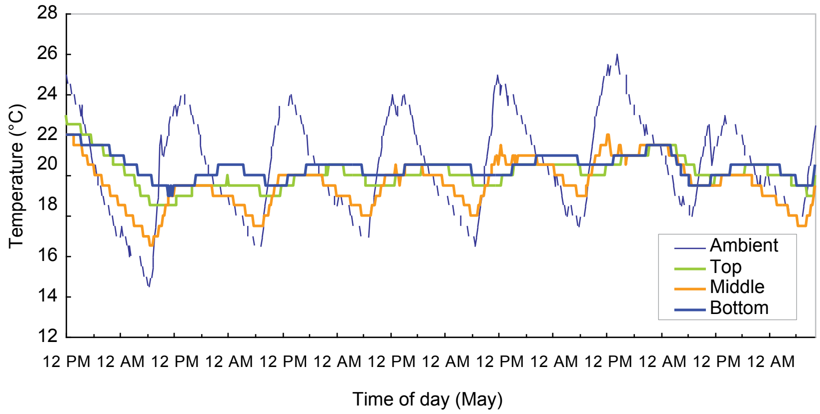
Temperature

Mud crabs are able to tolerate daily temperature fluctuations with little stress imposition. It was observed that the temperature of crabs held in crates in shade with a damp hessian cover does not directly reflect the external temperature change (Figure 12). This is likely due to temperature change occurring gradually and an insulation effect from crab body heat within confined storage.

However, mud crabs are subjected to wide temperatures changes throughout the supply chain (Figure 13) and transport steps including refrigerated transport or flight transport imposes severe stress on crabs due to the sudden and extreme temperature changes involved (Figure 14).

FIGURE 12

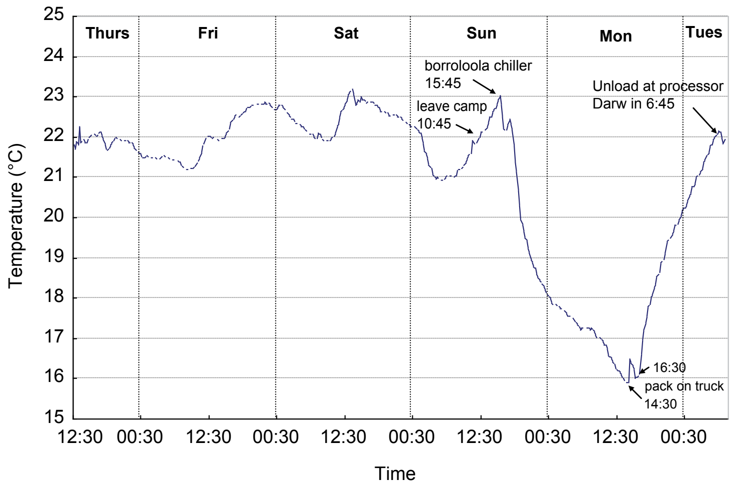
Temperature of mud crabs held in hessian wrapped crates at camp



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

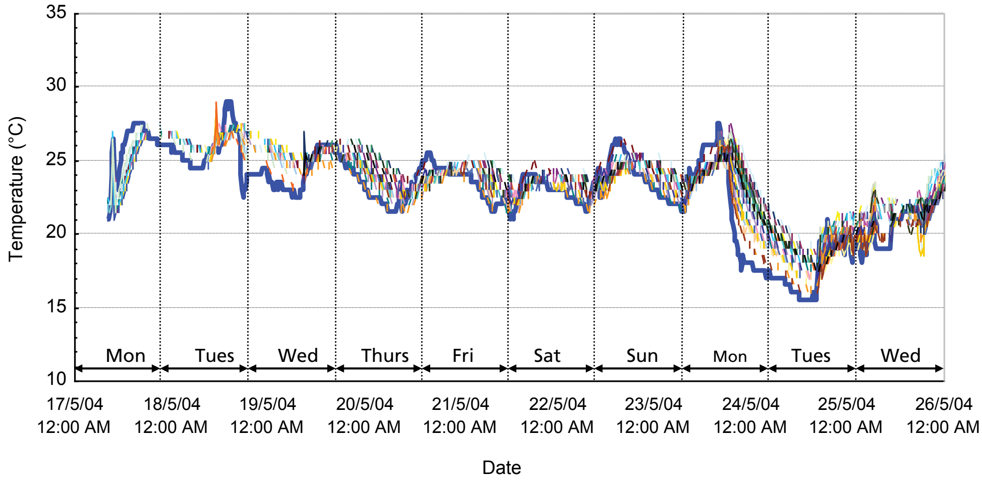
FIGURE 13

Temperature fluctuations in the mud crab supply chain: from Wearyan River (GoC) to Darwin



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

FIGURE 14
Temperature fluctuations in the mud crab supply chain: from capture to Brisbane via air transport

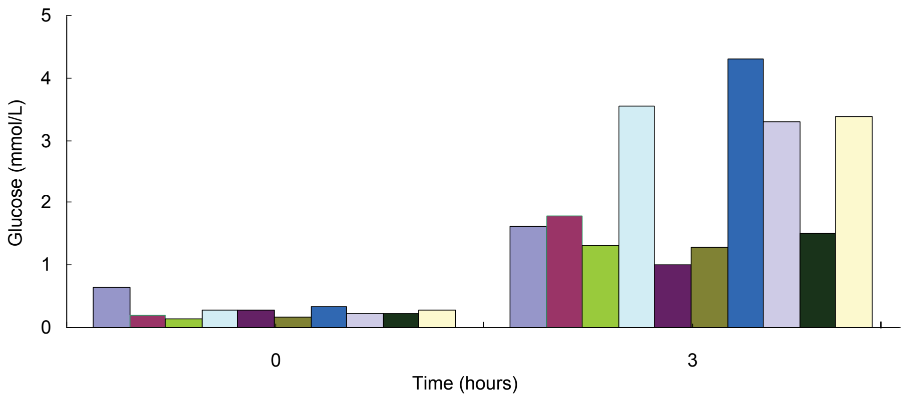


Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

Aggressive behaviour

Mud crabs are naturally territorial and inherently aggressive in behaviour. These traits are exacerbated when crabs are in close confines and such inherent behaviour results in higher stress levels occurring (Figure 15) and often physical animal damage leading to limb or haemolymph loss (Figure 16). Research undertaken in 2020 showed that stress and aggression levels were lower in tied versus untied crabs.

FIGURE 15
Blood glucose levels in crabs with untied limbs in close confines



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

FIGURE 16
Haemolymph loss from mud crab following aggressive interaction

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Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

Modified handling for stress reduction

The natural environment for mud crabs is seawater and when removed from this environment and held dry in air, stress occurs. As previously mentioned pH, glucose, lactate and ammonia excretion are the key metabolic parameters used to measure stress levels. By developing an understanding of the main steps in the supply chain, where high stress is imposed upon the live crab, modified or alternative handling practices have been developed. Table 4 provides a comparison of the impacts of some key disturbances and stressors on blood lactate levels in mud crabs.

TABLE 4
Circulating lactic acid in mud crabs in response to stressors

Treatment	Lactic acid (mmol/L)
At rest in holding tank	0.17
Emersed in damp hessian, 3 hours	7.83
"Annoyed" for 15 minutes	11.08
Breeze for 48 hours	35.88

Based on research and practical application the following practices have been shown to reduce stress levels.

Limit aggression

The current commercial industry practice of holding crabs with claws tied tight to the body in a crate with dampened hessian wrap is highly effective for minimizing stress imposition on the animals. It is important that the crabs are checked regularly (every 1–2 days) and the hessian wrap remains constantly damp.

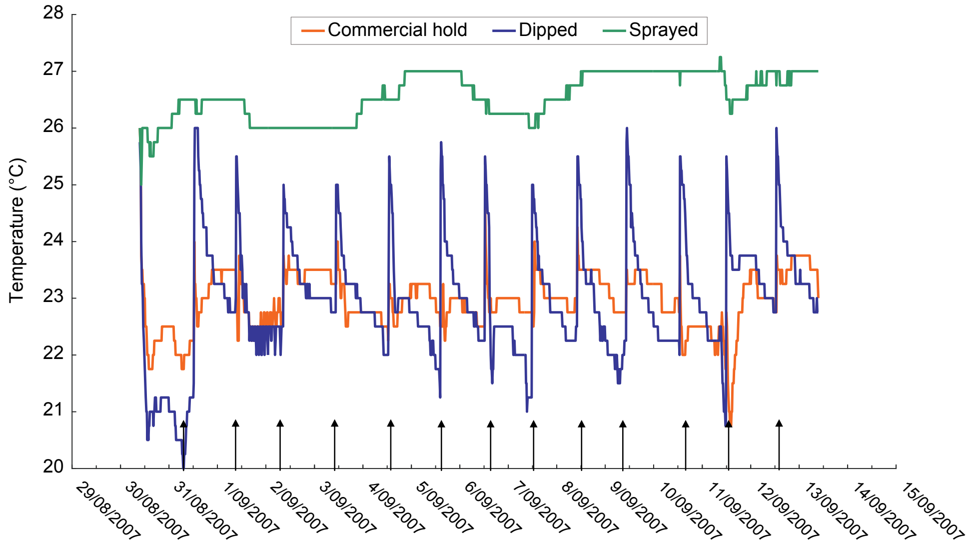
Limit disturbance

Disturbing crabs results in an immediate metabolic reaction with level of disturbance dictating degree of reaction. Disturbance arises from all physical movements subjected to the crabs including checking for dead and during grading, moving crates and packed boxes of crabs during loading and unloading, transport movement, direct air flow, loud noise, and crab behavioural aggression.

Limit rapid temperature changes

Based on multiple studies, it was concluded that slight lowering of the temperature of crabs slows metabolism and induces a semi-comatose state which reduces imposed stress reactions. However, temperature change must be gradual to be tolerated and not sudden nor severe or go to too low a level. It was found that temperature reduction should not be > 8 °C lower than the water temperature the crabs were harvested from. No specific thresholds were able to be set, as harvest water temperature will vary with geographic location, season and weather. Studies illustrated that holding crabs in constant high humidity results in a steady temperature of the crabs (Figure 17).

FIGURE 17
Temperature of mud crabs held under different conditions
(times of water additions indicated by arrows)



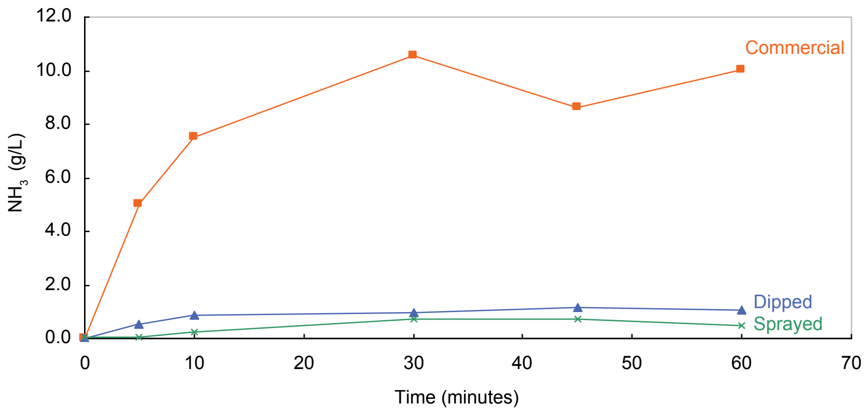
Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

INCLUSION OF RECOVERY STEP IN THE SUPPLY CHAINS

Given that mud crab supply chains in Australia can involve crabs harvested from isolated locations with little infrastructure and very long transport distances, it is inevitable that the animals will endure accumulated stress. A possible way to reduce high stress levels in crabs could be to include a "recovery step" along the chain. Several methods were explored for full or partial recovery of the animals. These included regular short dips, longer soaks, continual spray systems and full reimmersion for longer periods. For longer term tanking, water salinity of between 15–35 ppm is preferred whereas fresh clean seawater, bore water, town water or rainwater could be used along with prescribed measures around timing and temperature.

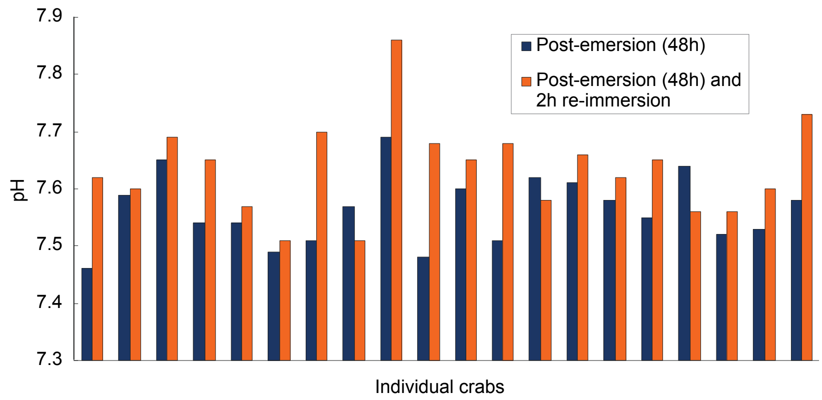
Both spray and dip methods appeared to produce crabs with lower stress levels as assessed by ammonia excretion (Figure 18) than those held immersed as per

FIGURE 18
Excretion of ammonia by crabs immediately after re-immersion following 14 days held under different conditions



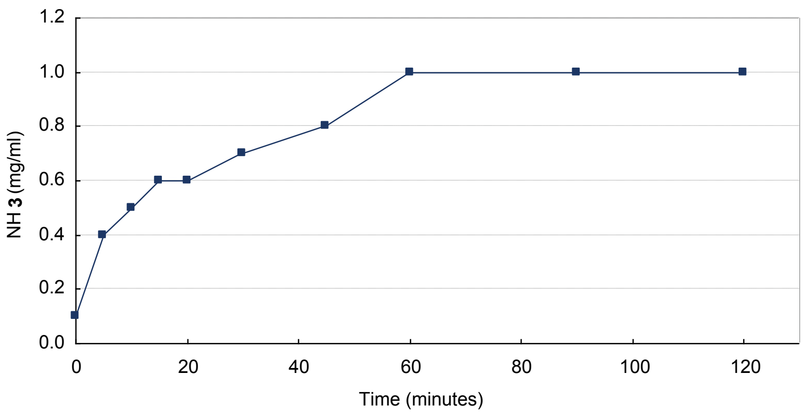
Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

FIGURE 19
pH after emersion and recovery of individual crabs



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

FIGURE 20
Ammonia excretion by crabs upon re-immersion after 3 days of air exposure



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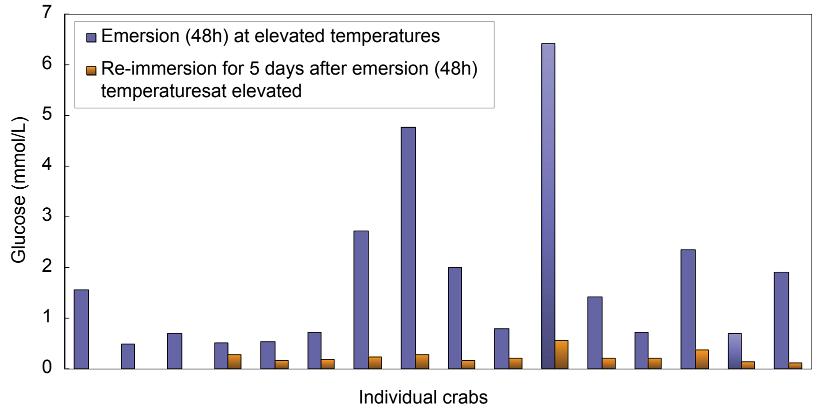
commercial practice. However, when assessing robustness and liveliness of the crabs during the following 7 days, it was noted that many of the animals dipped for short "dips" (1–5 minutes), were weak and "slow" compared to crabs not dipped at all. Such results suggested a short dip is detrimental to the crabs rather than de-stressing them. It is possible that the dip triggers hormonal response to initiate detoxification processes and this is not readily reversible after the crabs are taken out of the dip. Dipping also results in temperature fluctuations in the crabs while a constant spray system holds their temperature steady.

A similar situation could occur for sprayed crabs when they are packed dry for the next transport stage of the chain. When crabs are soaked for 2 hours with full reimmersion in water, the blood pH increases towards that of rested crabs (Figure 19) and this time length is sufficient to allow excretion of ammonia (Figure 20). Seawater was used for all dips, sprays and soaks but studies showed that the soak method was also effective when using freshwater. However, longer freshwater immersion was detrimental.

FIGURE 21
Blood glucose levels in individual stressed crabs and after recovery in holding tank



Source: Poole, S., Mayze, J., Exley, P. & Paulo, C. 2008. *Maximising revenue within the NT mud crab fishery by enhancing post-harvest survival of mud crabs.* FRDC 2003-240, Final Report. Fisheries Research and Development Corporation, Canberra.

Longer emersion durations of several days were demonstrated to be the most effective method, resulting in practically full recovery of the crabs as seen in Figure 21 where blood glucose levels have returned close to those of rested crabs.

QUALITY GRADING METHODS

Carapace pressure test

Within the supply chain the quality of a mud crab is commonly assessed by gentle thumb pressure applied to the crab shell at specific points. This pressure test is a proxy for meat content. The thumb pressure test is carried out as shown in Figure 22. The top of the shell is used for female crabs and the underside for males. A fully hard shell,

FIGURE 22
Pressure applied to carapace for female (a, b) and male (c, d) mud crabs

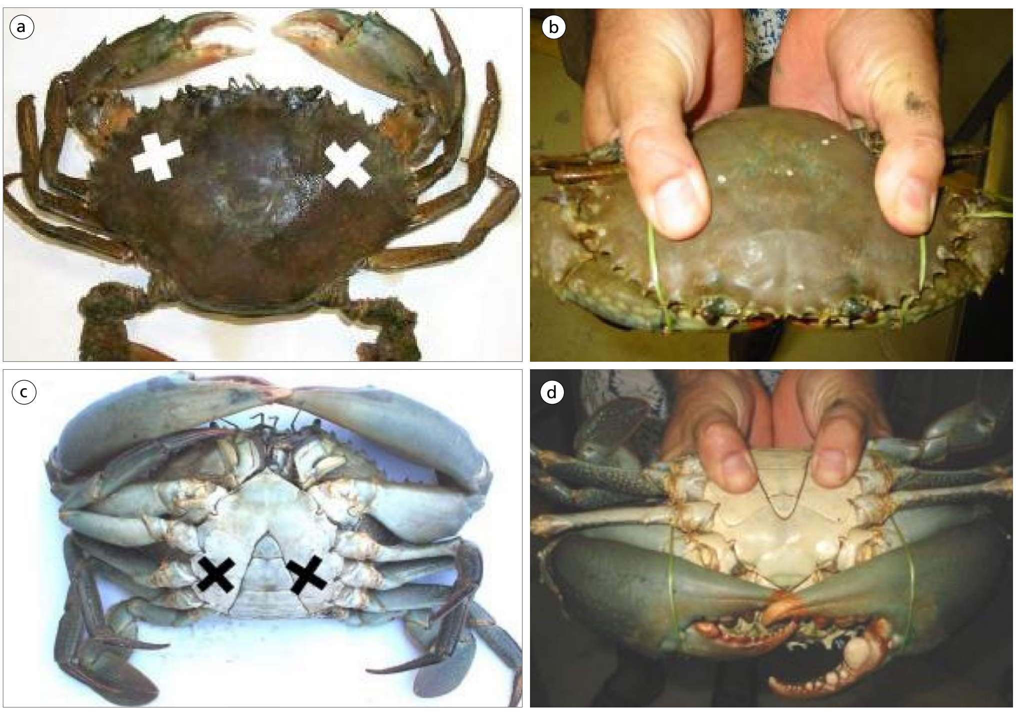
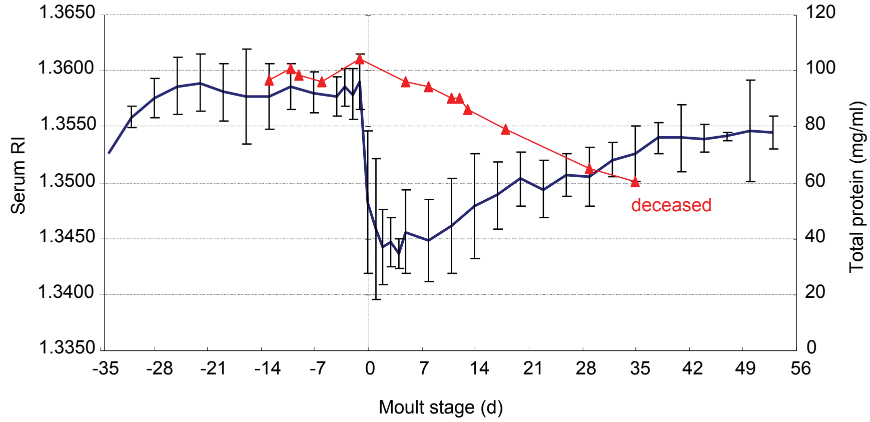


FIGURE 23
Total blood protein levels in mud crabs through moulting cycle



Source: Mayze, J., Poole, S., Exley, P. & Calogeras, C. 2016. *Building precision into the Australian Industry Live Mud Crab Grading Scheme (AILMCGS) through addressing grading and regional anomalies*. FRDC Project 2014-218, Final Report. Fisheries Research and Development Corporation, Canberra.

that allows no indentation when pressure is applied, is generally considered as high-grade crab (with some exceptions to this rule). Crabs that demonstrate shell flexing with applied pressure are noted as lesser-grade animals. The method can be refined by applying pressure to the underside of the crab at other segments, but this is only applicable to male crabs and is not suitable for female crabs.

The pressure test is, however, inherently subjective in nature as degree of flex, if any, is dependent on force applied and also how many times the test is repeated along the supply chain, as the shell could potentially weaken or crack from repeated pressure. Also, the degree of shell flex is closely related to moult cycle phase of an individual mud crab – the more recent the moult the softer the shell. It was also found that the level of total protein circulating in the animal's blood is related to moult cycle (Figure 23) due to the muscle replacement following shell shedding and re-hardening.

Measuring total protein in the crab blood provided an objective assessment method and was found to align mud crabs within grades well. It proved a useful research tool and can also present opportunity for use within the industry sectors to confirm grades assigned.

However, correlating total blood protein to shell hardness assessment is not definitive of top-quality crabs. This arises from crabs in the late-moult phase exhibiting a fully hardened shell but still requiring up to a further 2 weeks for body muscle to be fully replaced, i.e. the claws filling with meat. Hence a crab can be determined as top quality by total protein (and shell hardness) methods, yet not be full of meat, similar to claw meat fullness levels illustrated in Figure 24.

At the consumer end of the supply chain, such occurrences engender a strong negative buyer reaction due to the disappointment of purchasing an expensive mud crab that is found to have little meat upon consumption.

In an attempt to quantify "quality", minimize disputes and improve customer experiences, the industry with the support of researchers sought to codify a national grading scheme via a national workshop held in 2012. As a result of the workshop a general flow chart for grading mud crabs was developed to provide a clear grading process that could be utilized nationally as the Australian Industry Live Mud Crab Grading Scheme (AILMCGS) (Figure 25).

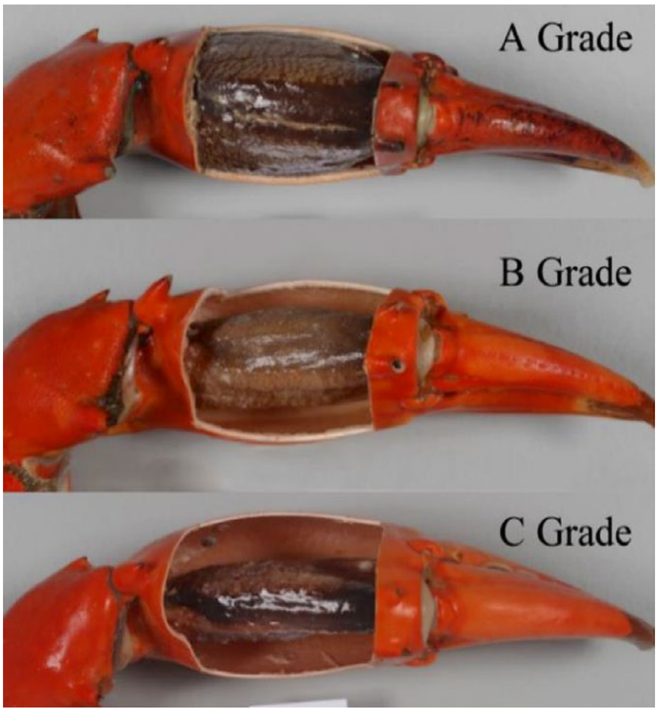
This approach aligned well with the system in place in the NT but not so with some of the operators in other jurisdictions, which lead to some level of revision to the scheme via future projects. It must also be noted that each jurisdiction has its own set of rules on the taking, possessing or selling of mud crabs and each supply chain participant may also apply their own grading requirements depending on the market segment they are targeting.

FURTHER ACTIVITIES

As consumer satisfaction and certainty is critical for industry revenue return and viability, further and ongoing research has focused on the feasibility of developing methods that would predict the meat yield of cooked mud crabs. Many technologies were explored including haemolymph protein–RI (refractive index), candling, X-ray, ultrasound and near-infrared technology in the form of near-infrared spectroscopy (NIRS) (Table 5).

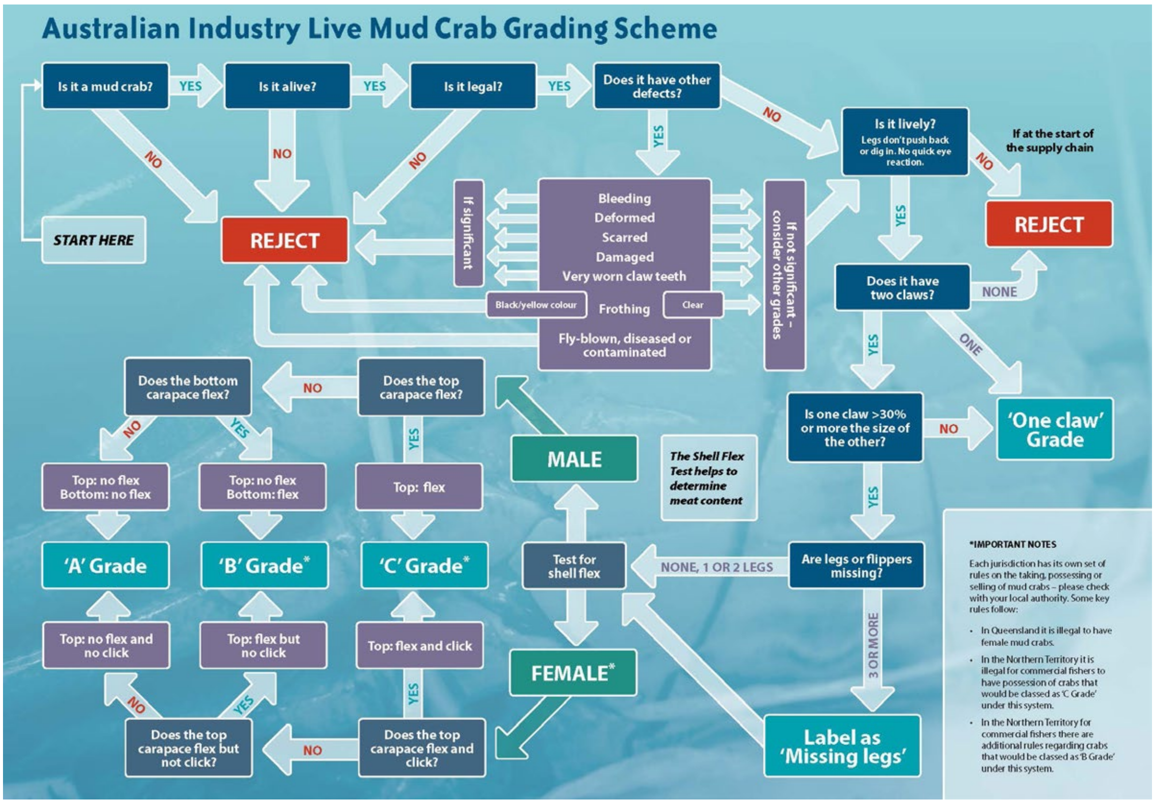
All of the methodologies showed some level of applicability, but NIRS demonstrated the most promise (Table 6). The existing body of work provided the basis for further research by Queensland Department of Agriculture and Fisheries (DAF) in developing NIRS assessment for applicability across different Australian mud crab

FIGURE 24
Cooked meat fullness of mud crab claws



Source: Calogeras, C., Mayze, J. & Poole, S. 2012. Using industry expertise to build a national scheme for grading of live mud crabs. FRDC 2011-225, Final Report. Fisheries Research and Development Corporation, Canberra.

FIGURE 25
Live mud crab grading scheme flowchart in Australia



Source: Calogeras, C., Mayze, J. & Poole, S. 2012. Using industry expertise to build a national scheme for grading of live mud crabs. FRDC 2011-225, Final Report. Fisheries Research and Development Corporation, Canberra.

supply chain sectors. As such, NIRS is being further investigated through a current Fisheries Research Development Corporation (FRDC) project that is developing non-invasive methods to assess mud crab meat fullness using portable NIRS.

TABLE 5

Technologies explored to determine meat yield from live crabs

Methodology	Considerations	Outcome
Ultrasonics	Assesses rates at which sound waves travels through a medium. Can be used to assess physiochemical changes in the muscle of a mud crab at the beginning and end of a moult cycle.	Acoustic information can provide a useful predictive tool if a clear measurable signal could be obtained. Ultrasound transducers are small and inexpensive, so are a technology potentially suited to practical deployment. If signal clarity issues can be resolved evidence shows acoustic measurements can predict meat yield in terms of broad grade categories.
Candling	Least technologically advanced method. Involves putting a light source underneath the crab and then looking at the image that comes out the top, similar to that used in egg fullness tests.	Investigations indicated no obvious correlation between percentage meat yield of cooked claws versus the illumination of the carapace and dominant claw. Could be further investigated using other imaging capturing techniques to see if enhancing the image improves correlations.
X-Ray	Electromagnetic radiation.	Only suitable for a very large throughput of product at major market facilities. Not at all suitable for wider and geographically dispersed locations.
Haemolymph protein–RI	Haemolymph collected from crabs via a syringe. Placed on hand held refractometer and RI assessed.	RI values correlated to yield percentage traits, but not to physical characteristics.
Near-infrared spectroscopy (NIRS)	Muscle meat differs between hard- and soft-shell mud crabs. Three components vary greatest; moisture, NaCl and protein. Irradiation causes some molecules to change vibrations from one energy level to another. Energy is absorbed at a certain frequency and this absorption is detected by NIRS instruments.	Preliminary results using hand held devices showed positive results in separating mud crabs into three classes: A, B, and C based on meat yield (see Table 6 and Figure 24). Requires further research to refine method and spectra collection platform, plus assessment of sufficient number of mud crabs to enable construction of robust calibration models for predictive purposes.

TABLE 6

Percentage correct classification assessed by shell hardness method and NIRS for predicting mud crab grade based on percentage of cooked meat yield

Grade (% meat yield from weight whole crab)	Mud crab fullness assessment method (% correct)	
	Pressure test	NIR instruments
A (> 45%)	44	Up to 91
B (35–45%)	40	60–84
C (< 35%)	52	75–86
All grades combined (A, B, C)	48	86

CONCLUSION

Due to the close industry involvement in the work, adoption of improved handling practices occurred readily with methods adapted to fit individual harvester operation and respective supply chains. The research also engendered creation of a national AILMCGS with the purpose of establishing consistency across states, territories and markets. This scheme has been revised a number of times and is not a formal national standard.

Current practices still utilize thumb test technologies to provide guidance on quality and the steps involved in determining liveliness are based on the stepwise process identified in the AILMCGS. The existing body of research provided the basis for further research by DAF developing NIRS assessment for applicability across different Australian mud crab supply chain sectors. Current research is also focused on developing traceability systems within the mud crab supply chain from harvest to consumer.

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Overview of management and monitoring of mud crab fisheries in Australia

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ABSTRACT

Australia has highly regulated fisheries for mud crab which are managed by four different states and territories. Each jurisdiction has its own regulatory framework, although all have similar basic high-level regulations in place. Both recreational (for own use) and commercial (to derive an income) fishers must comply with a raft of regulations. These involve minimum size limits, gear restrictions, protection for females or berried crabs and – for the commercial sector – limited entry plus extensive data and monitoring systems. First Nation fishers are generally entitled to use the resources of an area of land or water in a traditional manner. All Australian mud crab fisheries are currently regarded as sustainable.

To maintain commercial catches within an overall harvest level, some jurisdictions have ventured down the catch quota path, whilst others rely solely on input controls. Data and compliance requirements continue to increase to meet the needs of various stock assessment models being developed and to comply with management arrangements, including driving data needs for harvest strategies. These arrangements recognize economic and social values as well ecological sustainability.

These regulatory frameworks are relatively expensive to oversee, with the cost being borne more and more by the commercial fishers as governments across Australia move to cost recovery models. These heavy cost burdens and regulatory requirements may be hard to support in countries that lack economic resources, or the social drivers to approach their regulations in this manner. A cost benefit analysis of outcomes from existing management arrangements in place in Australia would be a critical first point before any jurisdiction should consider modelling their regime on an existing Australian approach.

To contextualize the impacts of the various frameworks, this paper provides an overview of the Australian crab fisheries industry, the regulatory frameworks, and the monitoring and research programmes in place. The benefits, and drawbacks, of each are briefly covered in the conclusion. Details in the paper are heavily drawn from report outputs derived from a national workshop held in Australia in 2022. The workshop was led by the authors and sought to identify key national management and research need and directions via a Fisheries and Research Development Corporation (FRDC) Project 2018/177 titled: "If you don't know where you are going, you'll end up someplace else – Future proofing the Australian mud crab industry through improved strategic direction" (Calogeras and Buckworth, 2023). A key finding from this project related to the need to better understand the impacts of habitat disturbance, chemical and ecological processes, and the roles each play in resource sustainability now and into the future.

Despite many commonalities, the Australian mud crab fisheries have no formal cross-jurisdictional connectivity amongst industry, management or research and monitoring. Overcoming this barrier could unlock many opportunities for improvement for Australian mud crab fisheries.

THE AUSTRALIAN MUD CRAB WILD CAPTURE INDUSTRY

FIGURE 1
Map of Australia indicating approximate distribution boundaries for mud crabs

Note: Refer to the disclaimer on the copyright page for the names and boundaries used in this map.

Source: Geospatial Information Section of the United Nations. https://www.un.org/geospatial/mapsgeo

Species

Globally, mud crabs can be found from South Africa, east around the Indian Ocean, through Southeast Asia to Japan, and across the Pacific Ocean to Hawaii, Fiji and Samoa. This includes Australia.

In Australia mud crabs are caught in estuaries, tidal flats and mangrove areas and are widely distributed across northern Australia, extending from well south of Broome in Western Australia (WA) to Eden in southern New South Wales (NSW) (Figure 1).

Of the four species of mud crab, two are found in Australian waters: *Scylla serrata* (giant or green mud crab) and *Scylla olivacea* (orange, brown or red mud crab) (Gopurenko, Hughes and Keenan, 1999; Keenan, Davie and Mann, 1998). The former constitutes more than 99 percent of the commercial catch of mud crab in the Northern Territory (NT), and the entire commercial catch in NSW and Queensland (Qld). *S. olivacea* is a very minor component of the NT catch in discrete areas, occurring extremely rarely in the Gulf of Carpentaria (GoC) and the Australian east coast. In WA it appears to be a large proportion of the catch.

Genetic evidence suggests that there are at least two biological stocks of *S. serrata* in Australian waters. One identified stock is to the west of Torres Strait, while the other is to the southeast. These stocks are commonly referred to as the northern Australian and the east-coast biological stocks, respectively. For management purposes, the mud crab fisheries in the Gulf of Carpentaria (GoC) are also managed respectively by the NT and Qld as a separate stock.

Female mud crabs in Australia are reported to migrate offshore during October to December to release their eggs. The planktonic larval stage can last for several weeks, which might facilitate gene flow between areas, depending on local oceanography. The extent of connectivity between areas is not well known.

Mud crabs are fast growing and short lived, with longevity believed to be up to 4 years. A green mud crab matures at about 110 mm carapace width (CW) and a brown at about 90 mm. Mud crab can grow to a size of up to 150 mm CW within 1 year, depending on environmental conditions.

The levels of recruitment of mud crab fisheries fluctuate considerably – most likely due to environmental influences such as rainfall, run off levels and water temperature – which impact spawning success and larval survival through to recruitment (Hay *et al.*, 2005; Meynecke *et al.*, 2010; Halliday and Robins, 2007). Annual mud crab harvests vary between and within years, dependent on recruitment, seasonal catchability and levels of fishing effort.

There are significant differences in the relative performance of the six Australian fisheries operating across the two currently identified biological stocks of green mud crab. This suggests that despite apparent larval connectivity within those stocks, there are different exploitation rates on components of the adult stock in different areas and/or there are environmental and ecological variances that may impact stock size.

Importantly in Australia, there is no fishery for the collection of crablets or juvenile mud crabs – this is strictly prohibited in all jurisdictions and is a pillar of every management regime in the country. There is currently no mud crab aquaculture taking place in Australia, so any future development in this sector will rely on hatchery-produced seed stock.

OVERVIEW OF AUSTRALIAN FISHERY OPERATIONS

Each fishery in Australia is operated in a different regulatory and operational environment. To provide context, a brief outline of each of the jurisdictional fisheries follows. Greater detail on each jurisdiction's fisheries' status, operations and management arrangements can be found at the relevant government or industry websites or via the Status of Australian Fish Stocks 2020 Report (Piddocke *et al.*, 2021).

Northern Territories (NT)

The Northern Territory coastline, including its islands, spans approximately 11 000 km (Geoscience Australia, 2024), and mud crabs can be found and caught along its entire length. This coastline remains relatively undisturbed. There are 49 licences issued, each with entitlement to two 30-pot units. There are only about 30–35 crabbers. Crabbers use 60–120 pots per operation, which they check and bait at least daily. Most operations are single-fisher based and occasionally a crew member may be taken on to assist if crab numbers are very high, or as part of a succession process.

NT fishers operate from dinghies between 5.0–7.2 m in length, powered by petrol outboard motors ranging from a single 40 hp to twin 250 hp, depending on fishing range.

- When trapped, legal crabs are retained, tied, and stored on board the vessel in hessian lined fish lug boxes. The NT requires crabbers to sort their crabs as soon as possible and release unwanted or illegal crabs, including undersized, berried females and what are termed Commercially Unsuitable Crab (CUC) back to the water and tie any retained crab before they return to land. CUC are those crabs deemed to be soft in the shell (intermoult) and illegal to retain. Shell hardness and softness is used as proxy for meat content and is based on shell pressure tests.
- Some crabbers operate as day trippers back to a base camp and others live on their dinghies or mother craft for 5–6 days at a time, crabbing up to 200 km from a base camp. Remote crabbers may stay away from Darwin for 6 or more months depending on access, weather conditions and crab numbers.

On return to base camp, crabs are stored short-term and transported back to Darwin weekly for consolidation. This distance ranges from a 2-hour drive for the closest crabbers, a 1 000 km trip from the GoC, or a 1- or 2-day barge trip from Arnhem Land (see Figure 1). Crabbers aim to catch a minimum of one basket of crabs/day (around 30 kg) for a 60-pot operation to maintain their fishing ventures.

Queensland (Qld)

The coastline is around 13 300 km and mud crab are found, and can be caught, along the whole length. The coastline in the GoC and northern Qld remain relatively undisturbed, except around areas where there is developed residential, commercial, farming and resource utilization.

Catch quota was introduced in September 2021 for Qld GoC and East Coast entitlements, with a minimum quota requirement of 1.2 t required to be able to harvest mud crab. This led to a need to access additional quota from other quota holders for those who wished to continue to crab but did not receive the necessary minimum quota holding.

There are around 380 crab entitlements allowed to use 50 pots each. However, for a range of market, operational and stock reasons, there is a large amount of potential latent effort (i.e. unused entitlements). Qld crabbers generally fish from dinghies between 4.0–6.0 m in length, powered by petrol outboard motors ranging from 60–70 hp. Most operations are single-fisher based and occasionally a crew member may be taken on to assist.

Crabbers use 50–100 pots per operation, which they check and bait at least daily. Retained crabs are generally tied and stored on board the vessel in crates or lug boxes. Most crabbers operate as day trippers back to a base camp, or home, where crabs are stored short-term, and then transported to markets. Professional crabbers aim to catch at least 3 t of crab/year/50 pot operation.

North South West (NSW)

The coastline is around 2 100 km and mud crabs are mainly found and caught in the northern parts of the state, accounting for around 50 percent of the whole length. This coastline is the most disturbed of all jurisdictions due to residential development and associated infrastructures to service resource sector needs and agricultural operations.

NSW is a catch quota-based fishery with an Interim Total Commercial Access Level (ITCAL) set at 206.3 t prior to the transition to full total allowable catch (TAC) management. The ITCAL was implemented in 2017–2018 and the declared TAC will remain the same for each financial year up to 30 June 2024. Total catch reported to date has not exceeded 70 percent of the allocated TAC.

There are around 280 fishing businesses (FB) that hold mud crab quota. Approximately 75 percent of quota is held by 50 fishing businesses with between 40–60 percent reported utilizing quota over the last 3 years. The 2020–2021 season was impacted by COVID-19 and saw a reduction in participation. NSW fishers may undertake multiple fishing methods under their various entitlements.

Fishers who wish to take mud crabs must have a minimum holding of 125 shares which equates to an allowance of 10 pots. For each additional 10 shares, fishers can utilize an additional one pot, e.g. 125 shares = 10 pots, 135 shares = 11 pots, 300 shares = 27 pots and so on. The fishery has seen a significant restructure arising from the move to quota. Most fishers have 10 pots, there are a few that have about 20, a "handful" with approximately 50 pots, and a "couple" with around 70 pots. There are also investors in the fishery who have people working their entitlements using 20–50 pots each.

NSW crabbers generally fish from dinghies between 5.0–6.0 m in length, powered by petrol outboard motors ranging from 30–80 hp. Most operations are single fisher-based and occasionally a crew member may be taken on to assist. Most crabbers operate as day trippers back to a base camp, or home, where crabs are either stored short-term, or transported to markets or co-ops. Some use holding tanks.

Western Australia (WA)

The coastline is around 20 800 km and mud crabs are found, and caught, in the northern parts of the state, accounting for almost half of the WA coastline length. The coastline in this region remains relatively undisturbed except in areas linked with the resources sector and residential development. WA practices limited access fishery with three 200-pot commercial licences and a 600-pot allocation for aboriginal use. The three 200-pot licences can be split (sold) into six 100-pot licences. Pot allocation to aboriginal communities has yet to be confirmed and is waiting for research to provide biological, spatial and relative abundance data.

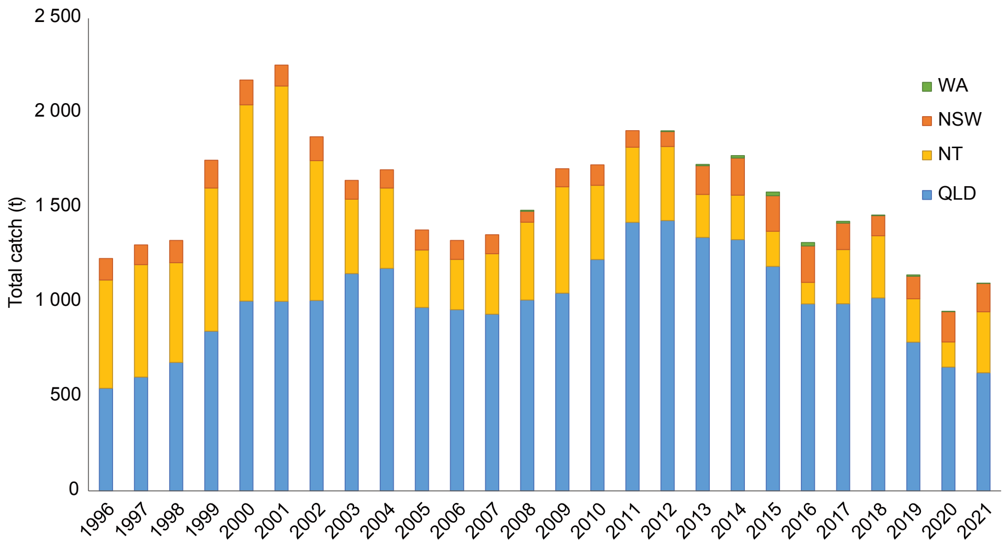
WA crabbing is at such a low level it is not possible to determine what best suits the fishery and fishers over time. Currently, most of the commercial licence holders are those that lease their pots to operators and use a mothership with smaller tenders servicing the pots. Catch has remained below 20 t with a high latent effort due to limited and sporadic fishing.

REPORTED CATCHES

The Australian market generally demands live mud crabs, and there are no oversea competitors in the domestic market space due to federal biosecurity legislation which prohibits the import of live mud crab into Australia (DAFF, 2016; DCCEEW, 2024). Australian markets are therefore not impacted directly by international volumes as the domestic live market is only accessible to Australian fisheries. Export markets though are impacted by international supply and demand.

Over the last couple of decades, annual reported total national commercial production has ranged from 1 100–2 000 t, with Qld producing around 70 percent, NT 20 percent, NSW 10 percent and WA less than 0.5 percent (Figure 2).

FIGURE 2
Australian mud crab reported production (t) by jurisdiction – 1996 to 2021
2021 WA and NSW production are estimates



In Australia, mud crabs are mainly sold in the NSW, Melbourne, Victoria and Qld markets, targeting Asian-based cuisine and demographics, and for the whole steamed/boiled crab market, often for non-Asian consumers. Historically the majority of product is destined for the food service restaurant sector rather than for home consumption, although COVID responses and lock downs shifted this focus slightly.

Within Australia there is competition in the various markets from producers in NT, Qld and NSW, based on availability, quality, price and sex of the mud crab. Qld is the major supplier (but only of male crabs) whilst all other jurisdictions allow the sale of female crabs. WA is a minor player at this stage.

Demand for mud crab is strong within Australia, but as the market relies on a live product it is relatively easy to oversupply, and this can lead to decreased prices when all jurisdictions are supplying at the same time. Small volumes are exported, mainly to

China, China, Hong Kong SAR, and Singapore. In the past, there were also significant sales to Malaysia and the United States of America.

COMMERCIAL REGULATORY FRAMEWORKS

All states and the NT operate under some form of limited entry access with associated gear and catch controls for the commercial sector. Table 1 provides a high-level summary.

TABLE 1
Summary of Australian commercial mud crab management arrangements

Regulation	WA	NT	Qld	NSW
Total allowable commercial catch in place	No	No	770 t East 108 t GoC	ITCAL (2017–2024) 206.3 t
Limited entry	Yes	Yes	Yes	Yes
Licence numbers or access holders	Three commercial licences. Aboriginal commercial licences (not yet allocated).	49	Approximately 380	280 fishing businesses
Effort limits – pot numbers	Yes 200 per commercial. 600 total for First Nation fishers.	Yes Effort units, minimum two 30-pot units.	Yes 50 pots per licence	Yes* Linked to fishing shares. Minimum 125 shares.
Gear restrictions	Yes	Yes	Yes	Yes
Male-only harvest	No	No	Yes	No
Protection of berried females	Yes	Yes	Yes	Yes
Protection for soft-shell crabs	No	Yes	No	No
Minimum carapace size limits	Width Green 150 mm Brown 120 mm	Width Male 140 mm Female 150 mm	Width Male 150 mm	Length 85 mm
Management zones	No	Yes Western and GoC**	Yes Eastern and GoC	Yes No transfer of traps between regions.
Spatial closures	Yes	Yes	Yes	Yes
Temporal closures	No	No	No	No
Management plan	Draft	Yes	No (regs)	No (regs)
Harvest strategy	Draft	Yes	Yes	No
Data collection systems	Monthly catch effort paper logbooks.***	Monthly catch effort paper logbooks.	Daily catch effort logbooks.	Daily catch, effort. Real-time quota reconciliation.
e-logs available****	No e-logs	e-logs	e-Fisher app	e-logs
E-monitoring	No	Trialling	No	No
Vessel monitoring systems (VMS)	Yes	Yes	Yes	No

Notes:

* Can use other methods to take crab in the Estuary General Fishery such as mesh netting, etc.

** GoC = Western Gulf of Carpentaria Mud Crab Fishery (WGCMCF); Western = Arafura West Mud Crab Fishery (AWMCF).

*** In an exemption-based fishery, fishers were required to submit research logbooks with finer scale daily info and transect spatial data, etc. Since the fishery converted to managed status, these are no longer compulsory.

**** Can provide catch and effort logbooks, market returns and nil returns electronically through CatchLogs software.

SUSTAINABILITY AND ENVIRONMENTAL STATUS REPORTING

There are six identified management units across Australian mud crab fisheries, these are:

- NT – Arnhem West Mud Crab Fishery (AWMCF) and the Western Gulf of Carpentaria Mud Crab Fishery (WGoCMCF);
- Qld – Gulf of Carpentaria (GoC) and East Coast;
- NSW – Estuary General Fishery (EGF) which allows the take of mud crab; and
- WA – Kimberley Crab Managed Fishery (KCMF).

Each of these six mud crab units in Australia, as identified by Status of Australian Fish Stocks (SAFS) 2020, can be assessed in a number of ways to determine their sustainability and environmental performance.

Four key indicators are:

1. If it has a Wildlife Trade Operation (WTO) approval. If you want to export Australian native wildlife, including seafood, for commercial purposes, it must come from an approved WTO. This indicates that it is harvested within an approved management arrangement approved by the Commonwealth Department of Climate Change, Energy, the Environment and Water (DCCEEW).
2. The fishery sustainability status as provided in the SAFS 2020 report. This report brings together available biological, catch and effort information to report on the status of Australia's key wild catch fish stocks (see current status in Table 3).
3. Whether a formal Harvest Strategy is in place (A Harvest Strategy is a framework that specifies pre-determined management actions in a fishery for defined species [at the stock or management unit level] necessary to achieve the agreed ecological, economic and/or social management objectives).
4. If it has third party accreditation such as Marine Stewardship Council (MSC) or Friends of the Sea.

Table 2 shows the status of these indicators by jurisdiction and fishery unit.

TABLE 2
Sustainability indicators for each jurisdiction's fisheries

Indicator	WA	NT	Qld	NSW
SAFS	KCMF sustainable	AWMCF and WGoCMCF sustainable	GoC and East Coast sustainable	EGF sustainable*
WTO status	No	WTO until 21 August 2026	WTO until 27 May 2022. Revoked as conditions unmet	WTO until 31 March 2022
Harvest strategy	No**	Yes	Yes	No
Third party certification	No – MSC Pre-assessment 2014	No	No	No

Notes:

* Pre 2020 there was uncertainty around the use of excess gear, lack of biomass estimate, or fishing mortality rates.

** A draft Harvest Strategy has been developed.

TABLE 3
Mud crab stock status in Australia in 2020

Jurisdiction	Fishery	2016	2018	2020	Indicators
WA	KCMF	Sustainable	Sustainable	Sustainable	Catch, effort, catch rate
NT	AWMCF	Sustainable	Sustainable	Sustainable	Catch, effort, catch rate
NT	WGoCMCF	Transitional – depleting	Sustainable	Sustainable	Catch, effort, catch rate, biomass, fishing mortality
QLD	GoC	Sustainable	Sustainable	Sustainable	Catch, effort, catch rate, biomass, fishing mortality
QLD	East Coast	Sustainable	Sustainable	Sustainable	Catch, effort, catch rate, fishing mortality
NSW	EGF	Undefined	Undefined	Sustainable	Catch, catch rate, biomass, fishing mortality

KCMF = Kimberley Crab Managed Fishery; AWMCF = Arnhem West Mud Crab Fishery; WGoCMCF = Western Gulf of Carpentaria Mud Crab Fishery; GoC = Gulf of Carpentaria; EGF = Estuary General Fishery.

Source: Piddocke, T., Ashby, C., Hartmann, K., Hesp, A., Hone, P., Klemke, J., Mayfield, S., Roelofs, A., Saunders, T., Stewart, J., Wise, B. & Woodhams, J. 2021. Status of Australian fish stocks report 2020. University of Tasmania. Report. https://hdl.handle.net/102.100.100/495213

RESEARCH AND MONITORING

Over the last 20 or so years, over 30 research projects have been funded by the FRDC alone to investigate impacts of environmental and oceanographic drivers on recruitment, increasing profitability, improving gear, bycatch reduction, product handling and management evaluations. In addition, individual agencies have been, and continue to, collect a large amount of biological and fisher-related information, generally based on commercial fishers catches and movement. Much of this data are collected to better inform management decision making and aid in compliance.

Catch, effort and operational data collection

The fineness of scale and regularity of data collection varies for a range of jurisdictional and operational reasons. Logbooks can be paper sheets where the information is written by hand and then entered onto a data base or via an electronic application called an eLog or an App where the data are recorded digitally and then straight to a database if the system is properly set up. Completion of logbooks is mandatory. Common data collected are:

- who fished?
- under what authority (licence, quota holding etc)?
- when fished?
- fishing vessel details.
- location(s) fished?
- days fished and pot pulls, where applicable?
- type and amount of fishing gear used.
- volumes and possibly numbers caught.
- bycatch details?
- where offloaded?
- where sold?

This information is collected, entered into databases, and analysed routinely. The collected data is used for two main purposes:

- to provide biological and operational information, and statistical data to assist fisheries scientists, managers and other interested parties; and
- to assist enforcement to meet management and regulatory requirements.

Data systems can be relatively expensive to run and often are partially cost-recovered from industry.

Vessel Monitoring System

Vessel Monitoring System (VMS) is used in NT, Qld and WA. This satellite surveillance system allows the real time monitoring of where each fishing vessel is at a given time based on pre-set (but adaptable) polling schedules (i.e. polling is how often the VMS unit is "pinged"). VMS allows compliance and management agencies to monitor vessel identification, geographical position, date and time of position, course and speed.

Each vessel must have its own VMS unit, linked to a satellite system and there must also be a "back room" to monitor data, instigate compliance action and adjust protocols as required by the authorities. Vessels must be able to maintain power continually to operate the unit. VMS systems can be relatively expensive to run and are often cost-recovered from industry.

Electronic monitoring

E-monitoring is used or is being considered for adoption in some jurisdictions. These systems use video cameras, and potentially sensors, capable of monitoring and recording fishing activities which can be reviewed later to verify fishers' logbooks relating to catch and possible interactions with Threatened, Endangered and Protected Species (TEPS).

The practicality of these systems on small fishing vessels is a matter of conjecture at this time, but as technology improves small-scale systems will become more available.

E-monitoring systems can be relatively expensive to run and are often cost-recovered from industry. The cost of agency staff physically viewing many hours of data is a significant expense, although a benefit is that it is considered an alternative to having a physical observer on board to watch and record fishing operations. The possible development of AI solutions in the future may reduce costs.

Compliance and enforcement

Each fishery jurisdiction has either its own compliance unit or uses a branch of a broader police, or other compliance force, to undertake fishery compliance within its jurisdiction. Under formal arrangements, compliance can also be undertaken by another jurisdictions force, indigenous ranger groups and/or compliance officers from other agencies such as national or marine park rangers.

Generally, compliance strategies utilize intelligence, or targeted activities, to ensure that fishers and others along the supply chain (transporters, buyers, processors and marketers) are complying with the various regulations pertinent to their specific fishery.

General task relates to inspecting fishing vessels, gear, licences and catches and patrolling waters and ports. In addition, compliance is also undertaken on those transporting seafood, processing and selling it to ensure the integrity of the supply chain and limit illegal sales. A trusted sound compliance programme is an integral component of a comprehensive fisheries management program. Aspects of compliance may be cost-recovered from industry.

Physical monitoring

Along with compliance officers, most jurisdiction have some form of physical onboard observer that can watch and record details of fishing operations. They can be government employees or third party contracted staff, but importantly they should be independent specialists trained in sampling techniques including the collection of biological samples, sex and size of animals, bycatch, environmental observations and interactions with TEPS.

This data is often the only independent data collected in many fisheries and provides a valuable source of information to complement other material such as logbooks and research data that are used in fisheries management. Observer programmes can be very expensive, depending on the amount of at-sea time required, and are often cost-recovered from industry.

Stock assessments

The above data, along with environmental, ecological and economic data can be computer-modelled to provide estimates of a range of fishery performance measures. Stock assessments are quantitative models that estimate fish population size and how it is affected by fishing and other factors and can inform the management process about fishery performance, regulations and future research needs. Assessment outputs can be factored into fishery management decision-making processes.

These models, or stock assessments, should form the basis for the management decision-making process and development of TAC or Total Allowable Effort (TAE) for use in quota systems or as part of monitoring and adjusting the performance of the fishery against key performance indicators.

These indicators may be a part of a formal harvest strategy, an Ecological Risk Assessment (ERA) or some other third-party requirement such as complying with WTO or certification conditions and requirements.

It should be noted that fisheries are part of dynamic systems and subject to change with, or without, fishing activity due to environmental and other drivers. Good models can incorporate these variations. These matters are still being worked on in the Australian context for mud crab fisheries. Aspects of undertaking stock assessments may be cost-recovered from industry.

MANAGEMENT PLANS AND REGULATIONS

All commercial fisheries in Australia are regulated under specific fishery legislation, fishery acts, management plan, regulations or some form of executive order.

WA, Qld and NSW currently manage their fisheries via regulations and orders. The NT has a formal Management Plan (DOF, 2006) for its mud crab fishery which basically aligns with what are regulations for the fishery. Section 5 of the plan directs the Director of Fisheries to undertake certain actions, in the form of a formal review, if certain triggers around catch levels, effort changes, median size, by-product levels or ecosystem impacts are detected. WA developed a draft Management Plan in 2018 but is yet to be implemented (DPIRD, 2018).

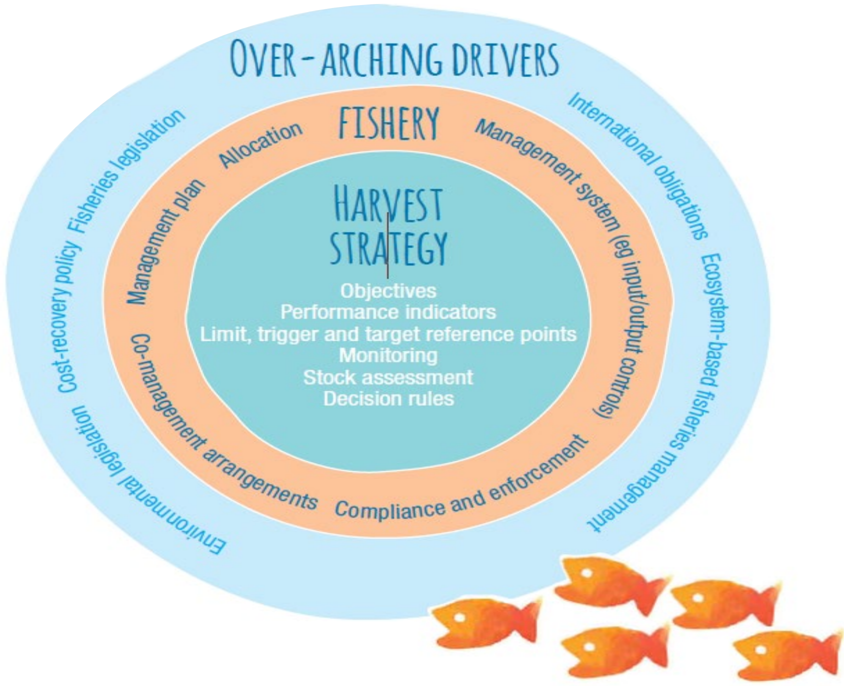
HARVEST STRATEGIES

Harvest strategies have become an integral part of the Australian fishery management landscape over the last decade or so. NT and Qld have formal harvest strategy processes for management of mud crab and are in development in NSW and WA. Conceptually, a harvest strategy is a plan for stating how the catch taken from a stock will be adjusted year-to-year, depending on the size of the stock, the economic or social conditions of the fishery, conditions of other stocks, and perhaps the state of uncertainty regarding biological knowledge of the stock (Hilborn and Walters, 1992).

The following section provides a brief overview of harvest strategies and draws from key areas developed under FRDC Project 2010/061 National Guidelines to Develop Fishery Harvest Strategies (Sloan *et al.*, 2014) (see Figure 3).

Harvest strategies essentially involve an iterative process that leads to the development of a framework that government, fishers and key stakeholders will respond to various conditions before they occur. This is achieved by bringing together key research, monitoring, assessment, management and operational considerations and information that impact or guide the activities and impacts on a fishery.

FIGURE 3
Harvest strategy overview



Source: Sloan, S., Smith, A., Gardner, C., Crosthwaite, K., Triantafillos, L., Jeffries, B. & Kimber, N. 2014. National guidelines to develop fishery harvest strategies. FRDC Report – Project 2010/061. Fisheries Research and Development Corporation, Canberra.

The aim of the strategies is to identify predetermined actions to achieve agreed ecological, economic and social management objectives. Rather than being ad hoc, knee-jerk actions in a context of urgency, tactical management responses to various conditions can be carefully evaluated and pre-agreed among stakeholders.

Harvest strategy development should follow a number of steps that seek optimal outcomes including implementation and adoption. These include defining the fishery, stakeholder engagement mechanisms, developing clear, measurable and robust performance indicators and undertaking periodic reviews and updates of the strategy. Performance indicators built into the harvest strategy are used to track a fishery's performance against key defined objectives. The indicators are established to show how the fishery is performing in respect to reference points.

Reference points set benchmarks to which the fishery's performance can be assessed to let managers, researchers, fishers and other stakeholders see if the fishery is performing below, above or at the level required for sustainable operation. Depending on the performance, reference points are linked to trigger points which should have clear decision rules in place that guide the management actions in response to the status. These actions might, for example, provide adjustment to catch rates, exploitation levels or some other performance measure.

There are three common types of reference points:

- *Target Trigger Limit* – where the fishery is, should be, or should be when operating well.
- *Trigger Reference Point* – this point is when the fishery is operating below the target and is an early warning that action may be required to stop the fishery moving to an area where you don't want it to be and move it back towards the target.
- *Limit Reference Point* – is when the fishery is not achieving its objectives and significant action is required to return the performance of the fishery to an acceptable level, toward the trigger and eventually target reference point.

Each of the NT and Qld governments have a general fishery harvest strategy policy and operate their mud crab fisheries under a corresponding harvest strategy.

NT harvest strategy overview

Since 2017 the NT has operated under a Management Framework for the NT Mud Crab Fishery with a review set after 5 years of operation (DPIR, 2017). The harvest strategy is an important component of the framework.

The primary biological performance indicator for the NT Mud Crab Harvest Strategy is commercial retained Catch Per Unit Effort (CPUE), under the assumption that CPUE is indicative of stock biomass. CPUE levels, based on those of recent years, indicate the reference points. The upper trigger point indicates that the stock is above the target level and a high level of exploitation will not impact sustainability of the stock. The lower trigger point indicates that the fishery spawning biomass has declined with a potential risk to sustainability, and a reduction harvest is required.

A secondary indicator is derived from a fishery assessment model (a delay-difference model) (Grubert *et al*., 2019), which informs the target level as well as providing additional guidance for decision rules. The Target Reference Point is the desired annual level of performance from the fishery whilst the limit reference point indicates that the spawning stock biomass has declined to a point where recruitment levels are significantly reduced and a substantial reduction in harvest is necessary.

Qld harvest strategy overview

Since 2016, Qld has had a mud crab harvest strategy (DAF, 2021). The aim of this harvest strategy is to manage the fishing mortality of mud crabs by setting a TAC at a level that allows the stock to achieve specified biomass targets. The primary performance indicator in this harvest strategy is exploitable biomass of legal-size male mud crabs – the portion of a stock's biomass that is available to be harvested.

The Target Reference Point specifies the exploitable biomass level at 60 percent relative to the unfished state. The Limit Reference Point (20 percent of the exploitable biomass) is the point where the risk to the stock is unacceptably high, and at which the stock is defined as overfished. Initial TACs for the fishery were based on population modelling (Northrop *et al.*, 2019) and future harvest strategy decisions will be based on biomass estimates.

WA and NSW harvest strategy status

WA has developed a draft harvest strategy and associated control rules have been developed that set limits, threshold and performance indicators based on commercial catch rate. The strategy is yet to be adopted.

NSW is partnering with commercial, recreational and aboriginal cultural fisheries across the state to develop tailored harvest strategies. It should be noted that the Australian National Harvest Strategy Guidelines are currently under review to assess impacts of new developments in fisheries management and science, including in relation to stock assessments, quantitative decision rules and ecosystem-based fishery management. This review seeks to resolve complex issues and balance shared access and competing interests. Amongst other matters the review will seek to address broader issues including the relationship and function of harvest strategies in addressing cultural interests, ecological issues (e.g. habitat degradation, pollution and climate change), and marine conservation areas.

FORMAL CONSULTATIVE MECHANISMS

Jurisdictions utilize a range of formalized groups or committees to provide expert advice or as a consultative mechanism. Each jurisdiction has its own arrangements which may include one or more of the following:

- Management Advisory Committees (MACs), provide advice to agencies on a number of matters relating to specific fisheries. These can include input on scientific and economic status of fish stocks, impacts of fishing on the marine environment and operational matters, where relevant. Members are from commercial industry, policy, conservation, government agencies, research, recreational, charter, or indigenous sectors. Appointments can be via a statutory approach and may or may not be provided sitting or other fees.
- Resource Assessment Groups (RAGs) are research and scientific committees. Their main function is to review scientific data and information and provide advice to agencies on the status of fish stocks, fishery economic and fishery impacts on the marine environment. Experts in the field of fisheries science and economics are key members along with experience from industry members and other interest groups.

Along with these groups, other options include, working groups, advisory groups, expert panels, stakeholder forums, research committees and seeking formal public comment.

OTHER MEASURES

Conserving mud crab primary habitat, including mangrove forests, seagrass beds and mud flats, is critical to supporting their populations. This is becoming more apparent as research shows strong and varied relationships with environmental drivers that indicate the potential for impact of environment/habitat-driven variation in fishery performance (Robins *et al*., 2020).

Developing a better understanding of the impacts of habitat disturbance, chemical and ecological processes, and the roles each play in resource sustainability now and into the future will become a greater focus moving forward.

CONCLUSION

Australia produces mud crabs across four jurisdictions, but each is managed differently. Nevertheless, all these fisheries focus on adult crabs (no crablets or juveniles are fished) and each of the fisheries have further strong input control frameworks.

The input control systems have the advantage that sustainability is largely protected, irrespective of the information that might be required for more explicit control of the fishery, and these fisheries are all regarded as sustainable. This is an important underlying value of the Australian mud crab fisheries. The implementation or development of harvest strategies in WA, NT, Qld and NSW means that agencies are elaborating management and monitoring systems that move beyond sustainability, to take account of economic and social values as well.

Two jurisdictions, QLD and NSW, respectively, have or are moving to TAC and individual transferable quota (ITQ) management. The NT industry has resisted such approach.

Given that mud crab fisheries are typified by strong, environmentally driven variation, a complexity that will no doubt be exacerbated by climate change, this will require greater emphasis on understanding the dynamics of these fisheries and greater reliance on monitoring information, as well as the development of formal stock assessments. These management developments should be aimed at improving the value of the fisheries in biological, economic and social terms. It is important, however, to understand that such system improvement necessitates trade-offs between those improved values, and the increased costs of monitoring and assessment, and controlling the fishery.

Mud crab fisheries across Australia depend on the same species and cater to similar markets, creating significant shared challenges and opportunities. Common issues include the need for better information gathering, improved data analysis, and comprehensive stock assessments. Additionally, there is potential for enhancing catch value through advancements in handling practices, marketing strategies, and reducing compliance and management costs.

Despite these shared interests, the absence of formal cross-jurisdictional collaboration between industry stakeholders, management agencies, and research bodies presents a major barrier. Establishing stronger connectivity across jurisdictions could foster the exchange of knowledge, streamline processes, and unlock substantial opportunities for improvement in the sustainability and profitability of Australian mud crab fisheries.

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ANNEXES

Annex 1 – Workshop prospectus

FAO EXPERT WORKSHOP ON THE STATUS, TECHNOLOGICAL INNOVATIONS, AND INDUSTRY DEVELOPMENT NEEDS OF MUD CRAB (*SCYLLA* SPP.) AQUACULTURE

27–30 NOVEMBER 2023 – SINGAPORE

Food and Agriculture Organization of the United Nations

BACKGROUND

The four widely distributed species of mud crab, *Scylla* spp., are under increasing pressure from overfishing throughout their distribution, with the notable exception of Australia. Crabs of all sizes are being harvested for farming, fattening and direct consumption. Anecdotal market information reflects decreasing average sizes of mud crabs from most countries and increasing raw material costs, reflecting unsustainable fishing and capture-based aquaculture practices.

Whilst mud crab hatchery techniques have been developed, this sector is in its infancy in most countries, other than the Philippines and Viet Nam, where they are well established. With relatively few hatcheries in most other mud crab producing countries, they are yet to scale sufficiently to support large-scale development of mud crab aquaculture. Different approaches to hatchery and nursery development are being used.

Market demand for live, hard-shell mud crabs, is greater than supply. China, together with countries with a sizeable Chinese diaspora and other Asian countries favour this aquatic food and consume mud crabs of a large range of sizes from 100 g to over 1 kg.

Soft-shell crabs (SSC) are mainly processed, individually wrapped in a variety of sizes from 9–14 cm in carapace width and 40–>200 g in weight and frozen for international shipping via containers. The market for SSC is quite different, with key markets in the United States of America, Japan, and the European Union, where their most common use is in Asian cuisine, although they are adaptable to most cuisines. As the size of SSC is generally rather small, a greater number of crabs is required by the market.

Hatchery-based production will be essential for the sector moving forward if production is to grow to meet current market demand and support future opportunities for the development of more value-added products.

This workshop brings together recognized international experts in their fields to share their research, industry practices and innovations, as well as mud crab faming challenges and needs from different countries. Through the workshop, possible strategic directions, practices, and recommendations discussed would help those interested in building and supporting a sustainable mud crab aquaculture sector. Whilst there have been many small mud crab workshops and meetings over the last couple of decades, including a workshop held at the Rajiv Gandhi Centre for Aquaculture in India in 2013, the last major international seminar on mud crab culture and trade was held in Thailand in 1991. The upcoming event in November 2023 will provide a much-needed update on the current mud crab farming and production status other than potential mud crab-centric development options for the sector.

The workshop is organized and funded by the Food and Agriculture Organization of the United Nations (FAO) under its Blue Transformation (BT) initiative (www.fao.org/3/cc0459en/cc0459en.pdf) which aligns to the 2021 Declaration for Sustainable Fisheries and Aquaculture of the FAO Committee on Fisheries (COFI) and FAO's Strategic Framework 2022–2031. The BT vision recognizes that resilience in aquatic foods supply and sustainable production form an integral part of the solution to mitigate hunger and malnutrition. The three key objectives of the BT initiative are to support sustainable development of aquaculture; ensure effective capture fishery and aquaculture farm management and finally to develop all aquatic food value chains with the aim of reducing production losses and wastes. In addition, facilitating market accessibility for the products/produce and raising awareness of the consumer on the value of aquatic foods are also important aspects for fulfilling the objectives of the BT initiative.

OBJECTIVES

The objectives of the workshop are to:

- Provide an update on the status of the mud crab aquaculture sector in key production countries.
- Present and discuss biological and technological innovations.
- Discuss and provide guidance on best mud crab aquaculture practices and operations including hatchery, nursery, grow-out, processing and distribution of live hard-shell and soft-shell mud crabs.
- Highlight and recommend future opportunities and potential solutions to meet the needs of the mud crab aquaculture sector.

PRESENTATIONS, DISCUSSIONS AND OUTPUTS

The presentation arrangements of the workshop will be as follows:

- Submission of country status papers on mud crab production will be made prior to the event. Concise summaries of key points will be presented and discussed at the workshop.
- Presentation and discussion of key technical topics on mud crab aquaculture.
- Country and technical papers along with key technical and policy recommendations will be collated into a workshop proceeding and published online by FAO.

ORGANIZERS AND STEERING COMMITTEE

The workshop is organized by the Food and Agriculture organization of the United Nations (FAO) (https://www.fao.org/fishery/en) in collaboration with the Aquaculture Innovation Centre (AIC) in Singapore (https://www.tp.edu.sg/aic). Support is provided by the Mud Crab Workshop Steering Committee comprising representatives from Scylla Mud Crab Consultancy, Integrated Services for the Development of Aquaculture and Fisheries Inc., and the Universiti Malaysia Terengganu.

PARTICIPANTS

Mud crab experts and researchers from Australia, Bangladesh, China, India, Japan, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam.

Annex 2 – Workshop agenda

FAO EXPERT WORKSHOP ON THE STATUS, TECHNOLOGICAL INNOVATIONS, AND INDUSTRY DEVELOPMENT NEEDS OF MUD CRAB (*SCYLLA* SPP.) AQUACULTURE

27–30 NOVEMBER 2023 – SINGAPORE

DAY 1	**27 NOVEMBER 2023**	
08.00-08.30	Lee Chee Wee, AIC Alessandro Lovatelli, FAO	Welcome remarks
Time	**Speaker**	**Topic: International mud crab industry status reports**
08.30-08.50	Colin Shelley	Global overview of the mud crab production sector
08.50-09.10	Vu Ngoc Ut	Status Report – *Viet Nam*
09.10-09.30	Yushinta Fujaya	Status Report – *Indonesia*
09.30-09.50	Kandan Shanmuganathan	Status Report – *India*
15 mins	**Coffee break**	
10.05-10.25	Md. Mojibar Rahman	Status Report – *Bangladesh*
10.25-10.45	Haihui Ye	Status Report – *China*
10.45-11.05	Emilia Quinitio	Status Report – *Philippines*
11.05-11.25	Andrew Ng	Status Report – *Myanmar*
11.25-11.45	Sukree Hajisamae	Status Report – *Thailand*
11.45-12.05	D. Chan, M.F.M. Hanafiah, T. Sanda	Status Report – *Singapore*, *Malaysia* and *Japan*
12.05-12.30	**Moderator:** Colin Shelley	Discussion of country status reports
90 mins	**Lunch break**	
14.00-14.20	Rowena Eguia	Domestication and selective breeding
14.20-14.40	Hongyu Ma	Domestication and the future of genetically improved mud crabs
14.40-15.00	Sukree Hajisamae	Broodstock management
15 mins	**Coffee break**	

		Working Group: Broodstock
15.05-16.00	**Moderator:** Muhammad Ikhwanuddin Abdullah	**WG-1:** Broodstock selection, quarantine, quality, health management and biosecurity measures
16.00-17.00	**Moderator:** Muhammad Ikhwanuddin Abdullah	**WG-2:** Broodstock maintenance/management, feeds, treatments of crabs/egg mass
17.00-18.00	**Moderator:** A. Lovatelli	Day-1 Working Groups discussions and recommendations
19.30	**Official Dinner**	

DAY 2	28 NOVEMBER 2023	
Time	**Speaker**	**Topic: Mud crab hatchery, larviculture and nursery production**
08.30-09.05	Tran Nguyen Duy Khoa	Hatchery and nursery systems: *Viet Nam*
09.05-09.40	Emilia Quinitio	Hatchery and nursery systems: *India*, *Bangladesh* and *Philippines*
09.40-10.20	Waiho Khor	Review of larval rearing and seed production
15 mins	Coffee break	
		Working Group: Hatchery production
10.35-11.35	**Moderator:** Colin Shelley	**WG-3:** Larval rearing
11.35-12.35	**Moderator:** Colin Shelley	**WG-4:** Larval culture system design
85 mins	Lunch break	
14.00-14.20	Nguyen Thi Bich Ngoc	Juvenile nutrition for soft-shell crabs and functional foods
14.20-14.40	Noratat Prachom	Mud crab nutrition, feeds and management
14.40-15.00	Diana Chan	Crab health and nutrition management
15 mins	Coffee break	
		Working Group: Megalopa to crablet nursery management
15.15-16.15	**Moderator:** Waiho Khor	**WG-5:** Megalopa to crablet management
16.15-17.15	**Moderator:** Rowena Eguia	**WG-6:** Nursery and juvenile production
17.15-18.00	**Moderator:** Fanny Yasumara & Arefin Rahman	Day-2 Working Groups discussions and recommendations

DAY 3	29 NOVEMBER 2023	
08.00-11.00 12.00-12.45	**FIELD VISIT** – Oceania LLP and Aquaculture Innovation Centre (AIC) R&D farm. – AIC research facility tour at Temasek University.	
	Lunch break	
Time	**Speaker**	**Topic: Value chains, marketing and farming systems**
		Value chain and marketing
14.00-14.20	Alvin Seah	Value chain, marketing and the international trade in hard-shell mud crab
14.20-14.40	Andrew Ng	Value chain, processing and the international trade in soft-shell mud crab
14.40-15.00	Emilia Quinitio	Quality standards of mud crabs
15 mins	Coffee break	

15.15-15.35	Emilia Quinitio	Hard-shell crab farming systems
15.35-15.55	Soh Chee Weng	Sustainability in soft-shell crab production
15.55-16.15	Colin Shelley	Precision aquaculture and the future technology requirements of the mud crab aquaculture sector
16.15-16.35	Rowena Eguia	Mud crab aquaculture, including innovations in use of apps and nutrigenomics
16.35-18.00	**Moderator:** Padmanabhan Saravanan & Diana Chan	Day-3 discussions and recommendations
19.30	**Official Dinner**	

DAY 4	**30 NOVEMBER 2023**	
Time	**Moderator/Speaker**	**Topic: Farming systems, value chains, conservation, and future needs**
		Working Group-7: HARD-shell crab farming
08.00-09.30	**Moderator:** Emilia Quinitio	Hard-shell crab farming systems
15 mins	**Coffee break**	
		Working Group-8: SOFT-shell crab farming
09.45-11.15	**Moderator:** Colin Shelley	Soft-shell crab farming systems
11.30-11.50	Chris Calogeras	Hard-shell crabs: Harvest and post-harvest technology, transportation, packaging, quality control and maintenance and mortality reduction in mud crab value chains
90 mins	**Lunch break**	
13.30-14.00	Chris Calogeras	Effective management and monitoring of mud crab fisheries
14.00-14.30	**Moderator:** Diana Chan	**Working Group-9: Management, conservation and transportation**
15 mins	**Coffee break**	
		Working Group-10: Future industry needs
14.45-17.00	**Moderator:** Waiho Khor	Training, R&D and future technology requirements
17.00-17.30	**Moderator:** Colin Shelley	Day-4 Working Groups discussions and recommendations
End of Workshop		
17.30-18.00	Lee Chee Wee, AIC Alessandro Lovatelli, FAO	Closing remarks and handling of attendance certificates Photo-taking

Annex 3 – List of participants

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Annex 4 – Expert profiles

Chris CALOGERAS has over 30 years of fishing and seafood industry experience including senior government management positions, operations manager at an export-focused seafood company and the last 20 years as Director of C-AID Consultants. His qualifications include resource, fisheries and business management as well as seafood processing. For the Australian Government Dr Calogeras has managed aquatic resource programs covering fishery management, marine parks, data management and collection, education, legislation, recreational research, and numerous external projects. He specializes in inshore tropical species and has been involved in over 50 national and international projects. He is recognized both nationally and internationally for his mud crab work, particularly supply chain management to maximize survivability and quality. Dr Calogeras chaired the Northern Territory Mud Crab Licensee Committee and provided leadership and capacity across the Australian industry. Key projects involved upskilling several aquaculture operators to optimize mud crab quality and survivability in Fiji, the Federated States of Micronesia, Madagascar, Malaysia and trial farms in Australia. He led projects to build knowledge and equip industry with best practice handling skills to improve economic returns along the supply chain. He also led projects to build an Australian system for grading live mud crabs to bring consistency and quality. In 2022, his contribution to industry saw him inducted into Seafood Industry Australia's Hall of Fame.

Colin SHELLEY has been working on mud crab aquaculture since 1992, initially leading R&D at the Darwin Aquaculture Centre and collaborating with other Australian and overseas research groups. He has established mud crab hatcheries in Fiji, Indonesia, Malaysia, the Federated States of Micronesia, and the United Republic of Tanzania, and has been the CEO of two mud crab farming companies producing hard- and soft-shell mud crabs. In 2011, he co-authored the first FAO manual on mud crab aquaculture. His international mud crab aquaculture consultancy Scylla™ supports all aspects and components of the value chain of hard- and soft-shell aquaculture and has worked on mud crab farm development in Africa, Central and Southeast Asia, and the Pacific. His current interests include improving soft-shell mud crab production systems, developing mud crab feeds, and incorporating RAS technology into mud crab aquaculture systems.

Mhd Mojibar RAHMAN obtained his PhD from Bangladesh Agricultural University in 2022 and has 14 years of experience in R&D. He is currently engaged with the Local Government Initiatives on Climate Change (LoGIC) project, a multidonor collaborative initiative in Bangladesh coordinated by the United Nations Development Program (UNDP) that focuses on strengthening community-based climate change adaptation solutions. Dr Rahman supports and manages the livelihood diversification portfolio considering local climate drivers and the disaster risks of vulnerable coastal communities. As a livelihood officer he has provided technical support and training in mud crab aquaculture including the preparation of training material and sustainable farming guidelines. Prior to joining UNDP, he provided consultancy services to various development agencies mostly on mud crab fattening, nursery and grow-out, as well as preparing the Seafood Risk Assessment Review for *Scylla serrata* in Bangladesh commissioned by the Hong Kong Sustainable Seafood Coalition (HKSSC). For 8 years he worked with WorldFish in Dhaka as the coordinator of a large mud crab culture initiative, which resulted in the production of technical and operational manuals on different crab nursery technologies whilst building awareness among crab harvesters and traders on the importance of conservation measures.

Hongyu MA is a professor at Shantou University, China. He also serves as the director of Guangdong Provincial International Joint Research Center for the Development and Utilization of Marine Varieties at the South China Sea Region. He is a co-founder of the Shantou University–Universiti Malaysia Terengganu (STU–UMT) Joint Shellfish Research Laboratory, the vice-chair of the Technological Innovation Platform of Chinese Mud Crab Industry, and the director of the Agricultural Science and Technology Professional Committee of Guangdong Young Scientists Association, China. With his expertise in the field of crustacean biology and breeding, Professor Ma is a recipient of the Thousand Talents Program for Support of Top-notch Young Professionals, and the Leading Talent Project of Special Support Plan of Guangdong Province. Professor Ma primarily focuses on marine biotechnology and breeding and aquaculture of mud crabs. He has obtained 25 scientific research grants, with 5 at the national level and 14 at the provincial and ministerial level. He has published more than 100 scientific papers and holds 13 national patents, along with 12 utility models and one software copyright. His contributions in the field of crab aquaculture have earned him over ten scientific and technological awards, including the second prizes of the Shanghai Scientific and Technological Progress Award, the China Industry University Research Cooperation Innovation Achievement Award, and the Invention and Innovation Award of the China Association of Inventions.

Haihui YE has been a faculty member at the College of Fisheries, Jimei University (JMU), China, since 2020. Before joining the university, he served as lecturer, associate professor and professor at Xiamen University, China, where he obtained his PhD in marine biology. His research interests include the development of culture techniques for commercially important crustaceans and marine ornamentals, ecophysiology and behaviour of crustacean larvae and juveniles, and the physiology, reproductive biology and molecular endocrinology in crustaceans. He has been engaged in the fundamental research and aquaculture technology of the mud crab (*Scylla paramamosain*) for 27 years. He currently leads a research team focusing on the mud crab aquaculture and breeding at JMU. Dr Ye has published 160 publications in peer-reviewed scientific journals and holds 17 national patents on mud crab aquaculture.

Kandan SHANMUGANATHAN is currently the director of the Rajiv Gandhi Centre for Aquaculture (RGCA), the research and development arm of the Marine Products Export Development Authority (MPEDA), Government of India. The RGCA currently operates 13 projects nationwide focusing on aquaculture diversification (including mud crab) as well as providing auxiliary services to the shrimp sector with the establishment of the first Aquatic Quarantine Facility (AQF) for *Litopenaeus vannamei* and *Penaeus monodon*, the Broodstock Multiplication Centre (BMC) for *Litopenaeus vannamei*, and the Nucleus Breeding Centre (NBC) for *P. monodon*. Dr Shanmuganathan is a mariculturist who has worked for MPEDA since 1995. He was instrumental in the development of shrimp aquaculture in Gujarat State from 1995 to 1998. He has been involved in several coastal community-based mud crab projects throughout the country as well as in the RGCA's mud crab hatchery project since 2004. To date the Centre has established the only commercial crab hatchery producing *Scylla serrata* seeds in India, which has been patented by the Government of India. He was the coordinator of the country's first International Seminar on Mud Crab Aquaculture and Fisheries Management (ISMAF) held in 2013. He has published more than 36 research papers in peer-reviewed journals and is the author of several books on aquaculture. He is a member of the policymaking body on aquaculture and related subject matter in India.

Yushinta FUJAYA is a professor at Hasanuddin University in Makassar, Indonesia. She obtained her BSc in Fisheries from the same university in 1988, followed by a MSc and PhD in Reproductive Biology from Bogor Agricultural Institute, Indonesia, in 1996 and 2004, respectively. Her doctoral research project revolved around the reproduction process of mud crabs. Since becoming a lecturer, Professor Fujaya has been actively engaged in numerous aquaculture research and community development activities. In 2008, she patented a technology innovation for soft-shell crab production, achieved using herbal extracts. Her research work and findings have been presented and published widely at national and international fora. Professor Fujaya served as speaker at the International Symposium on Fisheries Sustainability in Rome (2019), the National Seminar on Sustainable Crab Cultivation Management hosted by the Maritime Coordinating Ministry of Indonesia (2018), and the International Workshop on Portunid Crab Cultivation and Sustainable Fisheries in Malaysia (2016). Notably, in 2022, she received a Fulbright award as a visiting researcher in the United States of America to study management and conservation of blue crabs in the Chesapeake Bay region. In the same year she played a key role in the development of the Indonesian Fisheries Management Plan for Mud Crab (*Scylla* spp.). Professor Fujaya actively contributes to community development as an instructor and trainer to increase the technical skills of mangrove crab fishers. In addition to her academic role, Professor Fujaya also serves as the administrator of the Indonesian Aquaculture Society, holds the director position of the Indonesian Aquaculture Professional Certification Institute and is the executive editor of Akuakultura Indonesiana, the official journal of the Indonesia Aquaculture Society.

Tetsuya SANDA is a scientist at the Production Engineering Division, Aquaculture Research Department of the Fisheries Technology Institute, National Research and Development Agency, Fisheries Research and Education Agency in Japan. At the Yaeyama Field Station (Ishigaki Island) his research revolves around production engineering of mud crabs and sea cucumbers. He engages in the development of production techniques for mud crabs, focusing on challenges including cannibalism and thermal adaptation. He specializes in aquaculture and crustacean ecology. In 2023, he was appointed as a member of the Japan International Cooperation Agency (JICA) funded project focusing on mud crab aquaculture in Bangladesh. Dr Sanda obtained his PhD in 2023 at the Graduate School of Tokyo University of Marine Science and Technology (TUMSAT).

Mhd Ikhwanuddin bin ABDULLAH serves as the director of the Institute of Tropical Aquaculture and Fisheries at Universiti Malaysia Terengganu. With over 3 decades of work in the fields of crustacean biology, reproduction, fisheries and aquaculture, he has emerged as a prominent figure in his field. His expertise centres around fisheries and aquaculture of economically significant crustacean species, including mud crab, tiger prawn, giant freshwater shrimp and the blue swimmer crab. He also served as a member of the National Technical Committee for the Malaysian Department of Fisheries on the portunid crab aquaculture and capture fishery programme, marine shrimp population enhancement and conservation programme, and the South China Sea Fisheries Refugia Initiative. He has authored over 280 research publications, numerous books and book chapters, and seven policy papers. Under his guidance, 18 PhD and 25 MSc students have successfully graduated, contributing to the continued growth and development of the sector. Through a series of structured knowledge transfer programs and consultancy projects, Professor Mhd. Ikhwanuddin maintains a close partnership with local aquaculture communities so to improve their understanding of sustainable fishery and the adoption of sustainable mud crab culture techniques and farming practices.

Mohd Fazhan bin MOHD HANAFIAH, a senior lecturer at the Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu, has dedicated over 10 years to the study of mud crabs. He completed his PhD in Aquaculture, focusing on the characterization of wild mud crab population dynamics and the hybridization of mud crabs in captivity. During his 4-year postdoctoral tenure at Shantou University in China, he utilized mitogenome analysis, orthologous gene study, and partial nuclear gene sequences to clarify the ambiguity surrounding Portunidae subfamilies. Currently, Dr Hanafiah is working on the adaptability of crustaceans, including mud crab broodstock and larvae, to different environmental external factors such as salinity and temperature resulting from global climate change. He employs a multi-omics approach in this research. He is also involved in the genetic and selective breeding of crustaceans and has contributed to the development of a Broodstock Multiplication Centre in Malaysia for mud crabs, tiger shrimp and other crustacean species. Dr Hanafiah has contributed significantly to the planning of Malaysia's first mud crab seed production centre, collaborating closely with industrial partners and other experts in mud crab cultivation. In addition, his research also delves into the genetic diversity of other portunid crabs and penaeid shrimps, and the development of hybrid mud crabs and new penaeid shrimp culture species.

KHOR Waiho is a senior lecturer at the Institute of Tropical Aquaculture and Fisheries, Universiti Malaysia Terengganu, Malaysia. After obtaining his PhD in Aquaculture at same university, he spent 2 years as a postdoctoral researcher at Shantou University, China. He works on the biology and physiology of crustaceans, particularly on the mud crab genus *Scylla*. His work aims to fully incorporate mud crabs into aquaculture settings, providing a new commodity to Malaysia's aquaculture sector and alleviating stress on natural crab resources due to the increasing scale of capture fisheries. Dr Khor's focus is on core processes such as reproduction, moulting and growth to accelerate the integration of mud crabs into the aquaculture sector. He is also currently investigating the impact of climate change on the overall growth and reproduction of crustaceans. Dr Khor has strong international linkages with globally renowned researchers, and this is reflected in his publications and collaborations. Throughout his academic career, he has published over 80 Web of Science (WoS) papers and serves in the editorial board of several journals, including Biodiversity and Conservation, PeerJ and PLoS One. In his commitment to ensuring the sustainable management of mud crab resources, Dr Khor has spearheaded knowledge transfer initiatives aimed at enlightening local communities about the significance of size-specific fishing practices and replenishment programs. This endeavour not only improves the wellbeing of these communities but also plays a role in advancing food security.

Soh CHEE WENG has a multidisciplinary techno-commercial background in research, applications support, nature conservation, marketing and export sales while attached with companies including Beckman-Coulter, the World Wide Fund for Nature, Fonterra, Ancom and Texchem. He has an honours BSc in Microbiology from the National University of Singapore and a MSc in Fisheries Biology from Buckingham University, the United Kingdom of Great Britain and Northern Ireland. While with Texchem for 15 years, he also embarked on the development of hatchery technologies for the mangrove crab (*Scylla* spp.) to ensure the sustainability of the soft-shell crab production of the company. He had study attachments with the Southeast Asian Fisheries Department Center (SEAFDEC) at Iloilo City, the Philippines, and the Fisheries Research Agency of Japan (FRA) at the Tamano and Noto Stations. Subsequently he conducted joint collaborations with Universiti Sains Malaysia (USM) in Penang, Can Tho University (CTU) in Viet Nam and with the Myanmar Sustainable Aquaculture Programme (MYSAP) at Labutta, Myanmar. In 2018, he established and operated a mangrove crab hatchery and engaged in community education and development of extensive crab farming at Labutta, Myanmar.

In 2021, he co-founded and set up a vertically integrated mangrove crab aquaculture operation, Crab Universe, in Perak, Malaysia. His area of interest is in the application of nature-based solutions to hatchery, grow-out and soft-shell shedding of the mangrove crab (*Scylla paramamosain*).

Andrew NG is the director of business development at SG Crabs World which, together with its affiliated companies in Myanmar, represents the world's largest and longest-standing producers of soft-shell crabs (*Scylla serrata*). The companies collectively produce 300 tonnes of soft-shell crabs annually that are exported to the international market. In his role at SG Crabs World, Dr Ng leads the sales and marketing activities to expand the company's global buyer network. Additionally, he is responsible for developing and executing the corporate strategy to expand the business, while adhering to the company's values in product excellence, sustainability and social responsibility. In his previous industry roles, Dr Ng was a managing consultant and practice lead at Lumanity, a biopharma strategy consultancy firm based in the United States of America and the United Kingdom of Great Britain and Northern Ireland, where he advised clients on the scientific, commercial and regulatory opportunities and challenges for innovative, next-generation medicines in various therapeutic areas. Dr Ng earned his BSc and PhD at the State University of New York at Buffalo, the United States of America, where he led collaborations with the University of Pennsylvania in deploying a leading proteomics platform to characterize genes that regulate bone development and skeletal aging. During this time, he also worked within the university's Business Entrepreneur Partnerships team to help in the spin-out of academic technologies. In this role he performed an assessment for cell and gene manufacturing in the Buffalo Niagara Region to support a New York State economic initiative.

Rowena ROMANA-EGUIA is an Associate Professorial Lecturer at the De La Salle University, Manila, after retiring as a geneticist from the Aquaculture Department of the Southeast Asian Fisheries Development Center (SEAFDEC/AQD) where she worked for 40 years. She has a BSc in Zoology from the University of the Philippines, an MSc in Genetics from Swansea University, the United Kingdom of Great Britain and Northern Ireland, and a PhD in Agricultural Science (Fish Population Genetics) from Tohoku University, Japan. Her field of interest is primarily on the applications of DNA-markers in the genetic characterization of commercially important aquaculture species such as tilapia, milkfish, abalone, mangrove crabs and tropical Anguillid eels for biodiversity conservation, aquatic genetic resources management as well as marker-aided selective breeding. While at SEAFDEC/AQD, she participated in projects on the domestication of the mangrove crabs as well as the evaluation of the genetic diversity of both wild and hatchery stocks of *Scylla serrata* for use in selective breeding schemes. She has also worked in collaboration with the Practical Genomics Laboratory of the De La Salle University on the comparative transcriptome analysis of heat stress responses in mangrove crabs obtained from sites with varying climate profiles. Recently, the same team completed nutrigenomic studies on local natural sources of immunostimulants for use in improving the survival of farmed crabs during the nursery phase.

Emilia TOBIAS-QUINITIO obtained her BSc and MSc in Fisheries from the University of the Philippines and her PhD in Fisheries Science from Hokkaido University in Japan. She worked at the Aquaculture Department of the Southeast Asian Fisheries Development Center (SEAFDEC/AQD) for 41 years until her retirement as senior scientist in 2017. Her professional career focused on shrimp and crab biology, breeding and domestication; seed production and hatchery operation; the reproductive physiology of shrimps and crabs; crab nursery and grow-out operation; crab fattening; soft-shell crab production; and crab hatchery layout and construction, including mud crab training activities. She has been involved in the drafting of fisheries ordinances and regulations on mud crab exploitation, and in the development of the Philippine National Standard for crustaceans and other fishery products. She became the country's programme coordinator of the National Mud Crab Science and Technology programme funded by the Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development (PCAARRD). She has provided consultancy services to different national and international development agencies on mud crab aquaculture. Dr Quinitio has published 75 papers in local and international refereed journals, proceedings and manuals on shrimp and crab culture. She is a recipient of local and international awards and became the R&D leader for Mindanao State University-Maguindanao under the R&D Leadership Program of the National Research Council of the Philippines.

Diana CHAN has a PhD in Microbiology from the National University of Singapore. Since 2007, she has led the way in enhancing aquaculture expertise by establishing the first aquaculture training diploma and industry-focused research and services at Temasek Polytechnic. Her mud crab research started as a marine conservation project under the Marine Life Fund from Resorts World Sentosa in 2011. As deputy director of the Aquaculture Innovation Centre (AIC), Dr Chan strengthened mud crab culture by setting up the AIC R&D farm for mud crab research in 2019. Given the local limitations on land, resources and workforce, her research centres around the idea of "achieving more with less." This involves leveraging innovation and advanced technologies to minimize the use of land, water, energy and labour, while reducing both feed and farm production costs. Her research revolves around the development of feeds using alternative protein and lipid sources, with a particular focus on repurposing processed food waste and other biomass into valuable ingredients for pellet feed production, catering to the dietary needs of crablets during moulting and adult crabs during spawning. Beyond this, her research interests encompass topics ranging from prophylactic treatments for adult crabs to crab genetics and broodstock development, along with the development and implementation of protocols for disease diagnosis and prevention. Diana has been working with standards development organizations to develop aquaculture standards since 2018. She is currently collaborating with a local university and a commercial entity in developing an innovative integrated system for advancing soft-shell crab production as well as collaborating with the Asian Institute of Technology in aquaculture welfare research.

LEE Chee Wee holds the position of centre director at the Aquaculture Innovation Centre, serves as the technology advisor at Temasek Polytechnic, and acts as the co-director for the Centre for Aquaculture Research, Innovation and Education at Nanyang Technological University. He earned his BSc and MSc degrees from McGill University, Canada, and later obtained his PhD from the University of Alberta, Canada. Dr Lee was distinguished as a recipient of the Alberta Heritage Foundation Scholarship for Medical Research. Following his academic pursuits, Dr Lee completed his postdoctoral fellowship at Yale University School of Medicine, the United States of America, and subsequently embarked on his academic career at the YLL School of Medicine, National University of Singapore, where he currently holds the position of adjunct associate professor. Notably, he has been recognized as an honouree of the Singapore Spirit of Enterprise and is a graduate of the General Management Program at Harvard Business School. Dr Lee has served as a board member of the Intellectual Property Office of Singapore (IPOS) and contributed to the development of the intellectual property competency framework for IPOS. His expertise extends to various life science companies and organizations, including the Asian Development Bank and Japan Shangri-La Medical Group. Additionally, Dr Lee is a founding member of the International Anti-aging and Regenerative Medicine Organisation based in Japan.

Mhd Arefin RAHMAN is a senior research executive at Aquaculture Innovation Centre (AIC), Temasek Polytechnic, Singapore. He has been involved with aquatic animal nutrition research for 7 years. He has a BSc in Fisheries and an MSc in Aquaculture from Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur, Bangladesh, and a PhD from Prince of Songkhla University (PSU), Hat Yai, Thailand. His primary research interest is in developing sustainable aquafeed using alternative feed ingredients for economically important aquatic animals such as the Asian seabass, tilapia, shrimps, mud crab and crayfish. His PhD studies focused on fish oil replacement in the Asian seabass diet. As a research assistant at PSU, Dr Rahman worked on the production of insect meals and researched on their use in fish diets. As a member of the R&D team at AIC, he is focusing on developing formulated diet for mud crab to produce high-quality broodstock and enhance moulting during the grow-out stage in recirculating aquaculture systems.

Fanny Ayumi YASUMARU holds a PhD in Biological Oceanography from the University of Sao Paulo and an MSc in Aquaculture from the Federal University of Santa Catarina, Brazil. Since 2019, she has served as the research and services manager at the Aquaculture Innovation Centre. Dr Yasumaru's extensive research experience primarily focuses on fish and shrimp nutrition, encompassing feed formulation and production, feed and feeding performance studies, as well as feed analysis and digestibility assessments. Currently, she is actively involved in investigating alternative proteins derived from both plant- and animal-based biomass for fish meal replacement. Furthermore, Dr Yasumaru has conducted research on mud crab feed development, emphasizing feed texture and customized forms tailored for moulting and growth performance. Beyond her research commitments, she co-teaches courses on Singapore Standards in Good Aquaculture Practices.

Saravanan PADMANABHAN earned his PhD in Medical Microbiology and conducted postdoctoral research at the Center for Biologics Evaluation and Research (CBER) in Bethesda, the United States of America, as well as at the Department of Anatomy, National University of Singapore. With over 25 years of experience in medical and applied microbiology, he is a member of ISO technical committees ISO/TC281/WG3, ISO/TC206/WG9 and ISO/TC8/SC2 of the Standards Development Organization, as well as the Singapore Chemical Industry Council Limited (SCIC). Presently, he serves as a lead scientist at the Aquaculture Innovation Centre (AIC), focusing on aquatic animal health. He leads research and service projects on preventive and diagnostic solutions as well as disease investigation of aquatic animals, including finfish and crustaceans. His current research interests include oral vaccines, on-site molecular diagnostics and biodegradable therapeutic alternatives to antibiotics. Dr Saravanan has collaborated with AIC teammates on induced spawning in mud crab *Scylla serrata*, conducted egg quality checks through physical and microbiological methods, and trained the AIC team in disease investigation techniques. He was involved in treating sick crabs using chemotherapeutics, antibiotics and organic plant extracts for shell disease and gill fouling or parasites. Currently, he is focused on mud crab prophylactic treatment approaches, including the rapid oxidative degradability of compounds.

Sukree HAJISAMAE was born in a traditional fishing village in the Pattani Province in southern Thailand. Although now trained as an aquaculture technologist and fisheries ecologist, his initial fascination with mud crabs started back during his childhood when he used to catch mud crabs and fattened them in plastic containers. Currently his research is focused on aquatic ecology and fish biology while at the same time he is actively involved in fish farming. In 2016, he explored opportunities in mud crab culture and found several technical and academic gaps, especially in the knowledge encompassing the whole supply chain. With a colleague, after consulting with several experts and engaging in extensive discussions with crab scientists and farmers, he started the first research project focused on the development of a mud crab aquaculture system in the province of Pattani, Thailand. Upon completion of the project, they continued to develop a business model for the whole supply chain of mud crab production. Apart from the development of several crab farms in the region, the main success within these projects has been the consistent production of high-quality berried female mud crabs through this newly developed system. These accomplishments positioned them as the main mud crab broodstock supplier in Thailand, receiving ongoing support from the Thai Government to expand their work to other provinces across the country. Moreover, alongside his colleague, he is actively engaged in research on the ecology and biology of mud crabs, contributing fundamental knowledge to support mud crab fisheries and aquaculture in Thailand.

Noratat PRACHOM earned his PhD from Tokyo University of Marine Science and Technology, specializing in Fish Nutrition, and holds a MSc in the same field from the Asian Institute of Technology, Thailand. Currently serving as the director of the Fish Feed Technology Development Centre at Kasetsart University, Thailand, Dr Prachom is at the forefront of advancing innovative solutions in fish nutrition. His research is centred on exploring nutrient availability and digestibility, particularly in the context of replacing traditional fish meal with biomass derived from diverse sources. This encompasses the valorization of food waste, utilization of insect meal, chicken by-products and various other biomass options to enhance fish and crustacean growth performance. Dr Noratat extends his research interest to the field of mud crab nutrition, contributing valuable insights to optimize growth performance in these crustaceans.

NGUYEN Dieu is a researcher working at the Research Institute for Aquaculture 3 (RIA 3) in Viet Nam. He obtained his Aquacultural Engineering degree from Nha Trang Fisheries University in 1997 and then joined the mud crab hatchery production (*Scylla* sp.) research group. In 2002 he successfully implemented a project on the artificial seed production of the mud crab, *Scylla paramamosain*, in Khanh Hoa and other northern provinces in Viet Nam. The project received the World Intellectual Property Organization (WIPO) Global Award as well as the Viet Nam Science and Technology Innovation Award (VIFOTEC). Since 2003, he has overseen several national projects on the transfer of mud crab seed production technology to coastal provinces where mud crab aquaculture is commercially practised. In 2011, he worked as a mud crab specialist in New Caledonia. Beside his work with mud crabs, Nguyen Dieu is also engaged in research and technology transfer projects on blood cockle, Pacific oyster, abalone and sweet snail seed production and farming.

NGUYEN Thi Bich Ngoc is a senior researcher at the Research Institute for Aquaculture 3 (RIA 3) in Viet Nam where she has been working for 29 years. Her field of research is on live food and nutrition of commercially important aquaculture species such as crabs, shrimps, abalone and Babylon snails. From 2011 to 2014 she undertook her PhD work on "Commercial mud crab *Scylla serrata*: study on growth, energy and protein requirement of juveniles in the view to develop pelleted feed for crab farming in New Caledonia." In RIA 3 she led several research projects including one on "Formulating effective pellet feed for producing soft-shell crabs" supported by the Vietnamese Ministry of Agriculture and Rural Development, and the recently completed project on the "Application and development of soft-shell crab (*Scylla* sp.) farming fed on formulated feed in Can Gio District, Viet Nam" funded by a technology development programme of Ho Chi Minh City, Viet Nam. Since 2020, she has worked as a technical consultant for hard- and soft-shell crab farming and soft-shell crab feed formulation. Her current applied research team oversees the technology transfer of soft-shell crab production, based on hatchery-produced seed.

TRAN NGUYEN Duy Khoa is an MSc graduate in Aquaculture from the College of Aquaculture and Fisheries, Can Tho University, Viet Nam. He subsequently obtained his PhD in the same field from Kagoshima University in Japan. He is currently a senior lecturer at Can Tho University. He is an aquaculturist with 14 years of practical experience in the development of sustainable aquaculture systems, operation and management of crustacean hatcheries and farms. He currently works on diet optimization, the development of larviculture techniques, and seed production of mud crab, giant freshwater prawn and several commercially important marine fish species. He has been involved in several mud crab and shrimp development projects in Viet Nam and Malaysia.

VU Ngoc Ut is currently the rector of the College of Aquaculture and Fisheries, Can Tho University. He obtained his PhD in 2002 at the University of Bangor, the United Kingdom of Great Britain and Northern Ireland, with the dissertation entitled "Assessment of feasibility of stock enhancement of mud crab *Scylla paramamosain* in the Mekong Delta, Viet Nam". He has been involved in many mud crab aquaculture activities including two large EU-funded projects on "Mud crab larviculture" and "Culture of mud crab *Scylla* sp." from 1998 to 2005. The findings from these projects have been successfully applied and introduced throughout the Mekong Delta, where mud crab culture dependency on wild seed has been dramatically reduced. Recently, Professor Vu supervised a PhD student who has completed his dissertation on "Study on the application of ozone in mud crab (*Scylla paramamosain*) seed production", an important alternative to the antibiotics commonly used in mud crab hatcheries. He has supervised over 50 MSc and 8 PhD students and has been teaching and conducting research on water quality management, live food production, aquatic ecology, biodiversity and biomonitoring. Professor Vu has led more than 20 research projects both in scientific research and education at national and international levels. He has published over 140 papers as the main author and co-author in national and international peer-reviewed journals.

Alessandro LOVATELLI, an aquaculturist, obtained his BSc and MSc from the universities of Southampton and Plymouth (the United Kingdom of Great Britain and Northern Ireland), respectively. He joined the Food and Agriculture Organization of the United Nations (FAO) in 1987 working initially in Southeast Asia and then in Latin America and the Caribbean. In 1993 he headed the aquaculture and fisheries component of a large European Union project in Viet Nam. He then joined the European Commission Rehabilitation Programme for Somalia to provide technical advice in fishery and aquaculture. In 1997 he rejoined FAO working in Central and Eastern Europe and then moving to FAO's headquarters. In 2016 he was posted in the Regional Office for Latin America and the Caribbean before returning to Rome in 2020. His work over the years has included the gathering, compiling and sharing of best farming practices and innovations focused on important and emerging aquatic farmed species. He has achieved this through the organization of technical expert workshops, publication of training material, field consultations and training activities. He further promotes the exchange of farming experiences through technical meetings and in collaboration with regional fisheries and aquaculture management organizations. He actively engages with countries in developing policies and incentives to ensure the sustainable expansion of aquaculture. In 2011 he commissioned and contributed to the preparation of the first FAO technical manual on mud crab aquaculture, and in 2023 he commissioned the preparation of the second edition of this manual that will include the farming advances presented at the FAO and Aquaculture Innovation Centre (AIC) mud crab expert workshop held on 27–30 November 2023 in Singapore.

Annex 5 – **Workshop opening and closing remarks**

OPENING AND CLOSING REMARKS DELIVERED BY DR LEE CHEE WEE, DIRECTOR, AQUACULTURE INNOVATION CENTRE, DURING THE FAO TECHNICAL WORKSHOP ON MUD CRAB AQUACULTURE HELD IN SINGAPORE FROM 27–30 NOVEMBER 2023.

OPENING REMARKS

The domain of mud crab farming stands at the edge of an extensive knowledge landscape that is marked by discernible gaps that currently hinder the achievement of sustainable cultivation practices. Recognising the magnitude of these knowledge deficiencies is crucial, and we understand that a singular workshop cannot comprehensively address the myriad challenges inherent in the industry.

Nevertheless, one of the primary objectives of this workshop is to initiate collaboration and bring together experts from across the globe to share their insights, experiences, know-hows, technological advancements, as well as business acumen, trade practices and much more. While the workshop serves as a pivotal platform for knowledge exchange, it is imperative to delineate its inherent limitations. The intricate and diverse challenges confronting mud crab farming and the supply chain demand a sustained and collective endeavour extending beyond the temporal confines of this week-long workshop.

We envisage this workshop will act as a catalyst sparking a global network of expertise sharing, technology transfer and collaboration. The aim is to gradually bridge the knowledge gaps and to establish the groundwork for developing sustainable supply of mud crabs through responsible cultivation practices, harvest and post-harvest technologies, innovations, and eco-friendly approaches. I would like to extend our profound gratitude to each participant for dedicating time and expertise to this workshop. The intensity of our collective efforts here reflects your dedication to enhancing the transformation of the mud crab industry by addressing its production and entire value chain.

Furthermore, our heartfelt appreciation extends to the Food and Agriculture Organization of the United Nations (FAO) and organizing committee for their invaluable support and guidance. The FAO's commitment to assembling world experts in Singapore underscores the global significance of addressing technical challenges within the mud crab industry. We are sincerely grateful for the Organization's dedication to fostering knowledge exchange and international cooperation.

In conclusion, the privilege of hosting this meaningful workshop at the Aquaculture Innovation Centre at Temasek Polytechnic fills me with delight. We take pride in contributing to this collective endeavour aimed at addressing the technical challenges, supply chain issues, as well as farming practices and processing issues faced by the mud crab industry. As we engage in fruitful discussion over the next four days of the workshop, let us remain mindful of the potential impact that our collective efforts can have on transforming the mud crab industry into a sustainable and prosperous one.

CLOSING REMARKS

As we come to the close of this international mud crab workshop, I want to take a moment to reflect on the incredible journey that we have shared over the past few days. The openness in sharing your knowledge and techniques was truly amazing and inspiring during the workshop. It has been a privilege to gather with experts, practitioners, and enthusiasts from around the world, all united by the same passion for advancing mud crab aquaculture.

Throughout our sessions, we have explored innovative practices, shared valuable research findings, and tackled the challenges facing our industry value chain from production to markets. From hatchery techniques to sustainable farming strategies and post-harvest techniques and processes, each discussion has contributed to a deeper understanding of how and what we can do to enhance our practices and ensure a prosperous future for mud crab farming and commercialization.

I want to extend my heartfelt thanks to our speakers for their enlightening presentations and to all participants for your active engagement. Your insights and experiences have enriched our discussions and will undoubtedly shape the path forward.

Let us carry the knowledge gained here back to our communities and continue to foster collaboration among our networks. Together, we can build a sustainable aquaculture sector that not only meets market demands but also preserves our precious marine ecosystems.

As we conclude, I encourage all of us to stay connected. Share your successes, challenges and innovations with one another. Our collective efforts can lead to meaningful change in mud crab aquaculture.

Thank you once again for your participation and commitment. Safe travels home and I look forward to seeing the impact of our shared knowledge in the field.

Thank you.

Dr Lee Chee Wee
Director, Aquaculture Innovation Centre
Singapore

Annex 6 – **Group photograph**

GROUP PHOTOGRAPH OF ALL THE EXPERTS ATTENDING THE FAO MUD CRAB WORKSHOP HELD IN SINGAPORE FROM 27–30 NOVEMBER 2023.

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Seated: Susila Krishnasamy, Khor Waiho, Colin Shelley, Emilia Tobias-Quinitio, Alessandro Lovatelli, Chee Wee Lee and Diana Chan.

Middle row: Fanny Ayumi Yasumaru, Yun Tzu Huang, Nguyen Thi Bich Ngoc, Md Arefin Rahman, Rowena Romana-Eguia, Nguyen Dieu, Sukree Hajisamae, Yushinta Fujaya, Kandan Shanmuganathan and Vu Ngoc Ut.

Back row: Ng Rongxin, Haihui Ye, Mhd Mojibar Rahman, Andrew Ng, Hongyu Ma, Chris Calogeras, Mohd Fazhan bin Mohd Hanafiah, Soh Chee Weng, Saravanan Padmanabhan, Noratat Prachom, Mhd Ikhwanuddin bin Abdullah, Tran Nguyen Duy Khoa and Tetsuya Sanda.

Annex 7 – **Certificate of participation**

CERTIFICATE OF PARTICIPATION AWARDED TO ALL EXPERTS WHO ATTENDED THE FAO MUD CRAB WORKSHOP HELD IN SINGAPORE FROM 27–30 NOVEMBER 2023.

Food and Agriculture Organization of the United Nations

aquaculture innovation centre

Temasek POLYTECHNIC

Certificate of Participation

to

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For active and invaluable participation during the

FAO Mud Crab Expert Workshop

27–30 November 2023

Organised by:
Food and Agriculture Organization of the United Nations
&
Aquaculture Innovation Centre, Singapore

Alessandro Lovatelli
Aquaculture Officer
Food and Agriculture Organization of the United Nations (FAO)

Lee Chee Wee, PhD
Centre Director
Aquaculture Innovation Centre (AIC)

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Status, technological innovations, and industry development needs of mud crab (*Scylla* spp.) aquaculture

FAO Expert Workshop
27–30 November 2023
Singapore

The FAO Expert Workshop on Mud Crab Aquaculture convened international experts to address critical challenges and opportunities in the cultivation of *Scylla* spp. mud crabs. Topics focused on assessing current industry status, advancements in hatchery and nursery technologies, and sustainable farming practices. The workshop emphasized the need for hatchery-based production to meet global demand and reduce reliance on wild seedstock.

Key recommendations focused on broodstock genetic improvement, formulated feed development, and enhanced water quality and biosecurity measures. Innovations in larval rearing techniques, advanced disease management strategies, and optimized farming systems were thoroughly covered. Discussions also highlighted the importance of improving value chains through better handling, packaging and post-harvest standards.

The workshop stressed sustainable fisheries management and mangrove habitat conservation as priorities for supporting mud crab populations. Collaborative efforts in training, research, and international knowledge exchange were identified as essential for future growth of the aquaculture sector.

The workshop proceedings, aligned with FAO's Blue Transformation initiative, offers actionable insights to foster a sustainable and resilient mud crab aquaculture sector, thereby enhancing global food security and supporting the livelihoods of producing communities.

ISBN 978-92-5-139558-5 ISSN 2070-6103
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CD3976EN/1/01.25