Inland saline aquaculture: Prospects and challenges

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Salinity is a major problem in many regions and is expected to worsen over the next 30 to 50 years. Most research has focused on its impact on land, particularly the loss of agriculturally productive areas. However, increased salinity can also cause significant changes in aquatic ecosystems, including rivers, streams, and wetlands.

Globally, about 953 million hectares of fertile land have reduced productivity due to high salt concentrations in the root zone. Australia has the largest area affected by salinity and sodicity, followed by Asia. Salt-affected soils and brackish groundwater are mainly found in arid and semi-arid regions, where they contribute to freshwater depletion. In India, over 273 million hectares of land have been affected by salinity and sodicity. Secondary salinisation caused by irrigation in dry areas has also increased salt levels in groundwater, further degrading freshwater resources.

In coastal Andhra Pradesh and other areas, large-scale shrimp farming with seawater has rendered approximately 0.85 million hectares of land unsuitable for agriculture. Similarly, in north-western India, 30 to 84% of groundwater is saline or brackish, making it unfit for irrigation. The use of poor-quality irrigation water has left thousands of hectares of productive land barren.

Salinity-induced land degradation is a major challenge to food and nutritional security in developing nations. A growing population is increasing the demand for water, making efficient resource use essential. Pressure is mounting to utilise all available resources responsibly to produce protein-rich food and combat malnutrition. One underutilised resource is inland saline areas, which have not been fully exploited for food production.

According to the FAO/UNESCO soil map, sodicity affects 953 million hectares, about 8% of the world's land surface. Salt-affected soils cover 42.3% of Australia's land, 21.0% of Asia's, 7.6% of South America's, 4.6% of Europe's, 3.5% of Africa's, 0.9% of North America's, and 0.7% of Central America's. Australia has the largest saline-affected area, covering nearly one-third of the continent. In India, 2.73 million hectares of land are affected by soil salinity and alkalinity. Additionally, around 25% of India's groundwater is becoming sodic. Long-term use of these water sources for irrigation has led to large-scale salinisation, further degrading freshwater supplies.

Increased irrigation in dry and semi-arid areas without proper drainage has worsened salinity problems. Many canal-irrigated regions are already waterlogged and salinised. In several irrigation districts across India, the water table is rising at a rate of 30 to 100 cm per year. The severity of this issue varies by region, depending on topography, hydrology, climate, drainage, land use, and agricultural practices.

Given the scarcity of arable land and the presence of saline groundwater, inland saline aquaculture offers a promising solution. Water management experts suggest that increasing the efficiency of existing water resources is the best long-term strategy for addressing water scarcity. Using salinised water for aquaculture in low-salinity areas could be a viable approach for sustainable food production. Low-salinity aquaculture for freshwater fish can help reduce pressure on freshwater supplies while enabling fish farming in dry and semi-arid regions.

This article examines land degradation in inland saline areas, characteristics of these environments, species' salt tolerance and its physiological effects, global salinity challenges and opportunities, and mitigation strategies.

Characteristics of inland saline water

Salt-affected soils in India are classified into two main types: alkali (sodic) soils and saline soils. In some cases, saline-sodic soils also occur. These are generally grouped with sodic soils since their treatment is similar, except that they require additional water to leach soluble salts before amendments can be applied.

Sodic soils contain high concentrations of sodium in the soil solution and on the exchange complex. High pH levels, often exceeding 10.0 in severe cases, and an exchangeable sodium percentage of up to 90% negatively affect crop growth. These conditions disrupt nutrient availability, damage soil structure, and suppress biological activity. Sodium carbonates and bicarbonates undergo alkaline hydrolysis, further increasing sodium levels in the soil. Alkali soils are deficient in nitrogen, calcium, zinc, and organic matter, while some micronutrients cause toxicity or deficiency issues.

Alkali soils mainly form due to irrigation with groundwater high in carbonate and bicarbonate ions, rising groundwater levels from canal irrigation, and salt-laden runoff from undrained basins. Inland saline plains are common in arid and semi-arid canal-irrigated regions. These soils contain neutral soluble salts such as sodium, calcium, and magnesium chlorides and sulphates, with sodium chloride being dominant.

High soil salinity is often linked to shallow groundwater, typically within 2 metres of the surface. Since subsoil water is usually saline, irrigation worsens soil degradation and reduces crop yields. While saline soils often have good physical properties, poor drainage is a major problem. The formation of saline soils is mainly due to rising water tables caused by irrigation and inadequate drainage.

These degraded lands, which are unsuitable for agriculture, could be used for inland saline aquaculture. This approach could help increase fish production while ensuring environmental sustainability.

Scope of inland saline aquaculture

Inland saline aquaculture includes various species, production systems, and water conditions. These systems offer significant potential for increasing aquaculture output. Using or reusing inland saline water can help produce high-quality seafood while making use of underutilised resources in salt-affected areas. This is particularly important as demand for freshwater and coastal marine areas continues to rise.

The integration of aquaculture with traditional farming systems, halophytic crops, or seaweed farming could further enhance efficiency and sustainability. Ongoing research is providing the knowledge needed to develop these systems into viable commercial operations. Key research areas include the use of aquaculture effluents for crop production and the physiological challenges of rearing high-value species in inland saline conditions.

With increasing global competition for limited resources, future challenges will include water scarcity, climate change impacts on conventional crops, and fertiliser shortages. Inland saline aquaculture offers a sustainable way to increase seafood production and address these growing concerns.

Use of poor-quality water for aquaculture

India holds 42% of the world's freshwater resources and supports 17% of the global population. Agriculture consumes about 85% of India's freshwater, while domestic and industrial sectors use the remaining 15%. Groundwater quantity and quality are critical for high productivity. However, regions with water scarcity often rely on low-quality groundwater.

The dry and semi-arid states of Rajasthan, Haryana, Delhi, Punjab, and Uttar Pradesh have the highest concentrations of saline and brackish groundwater. Due to freshwater shortages and rising pumping costs, brackish groundwater is increasingly used for irrigation. Over-extraction of groundwater has led to contamination of once high-quality aquifers, making them unsuitable for agriculture.

The indiscriminate use of poor-quality water, without effective soil, water, crop, and livestock management, poses serious risks to soil health, livestock, human health, and the environment. Prolonged use leads to sodicity and toxicity buildup in soils, reducing crop yields and often rendering land unsuitable for farming. However, the aquaculture sector can utilise these salt-affected water resources to boost fish production in degraded areas.

Species tolerance to inland saline water

The key criteria for selecting fish species for large-scale inland saline aquaculture are similar to those in other aquaculture sectors. Suitable species must have established hatchery protocols, strong market demand, disease resistance, robustness, salt tolerance, fast growth, and consumer popularity. Additionally, the water quality requirements of a species must align with the available water conditions to ensure optimal performance. This is particularly important for fish farming in inland saline environments.

Various species have been studied for their suitability in inland saline conditions, including marine, estuarine, diadromous, and freshwater euryhaline species. The following species are currently being tested for commercial production in inland saline water (refer Table 1).

Salinity is a key environmental factor influencing the growth, development, and reproduction of marine fish. Teleosts regulate plasma ion balance through their osmoregulatory organs, including gills, kidneys, and intestines. The Na^+, K^+-ATPase (NKA) pump plays a critical role in ion transport by creating the electrochemical gradient needed for ion and water exchange across cell membranes.

Research on salinity stress has focused on physiological and biochemical responses. Blood biochemical parameters are commonly used to assess fish health and diagnose diseases. Studies show that salinity levels influence blood ion composition, which is monitored to evaluate fish osmoregulatory capacity. In euryhaline teleosts, salinity stress affects protein synthesis, enzyme activity (such as Na^+, K^+-ATPase), and the development of specialised cells like pavement cells, ionocytes, and mitochondria-rich cells, which adapt to either seawater or freshwater conditions.

Table 1. Species being tested for commercial production in inland saline water.

Species	Tolerable salinity ‰	Species	Tolerable salinity (‰)
Labeo rohita	12	*Macrobrachium rosenbergii*	12-15
Ctenopharyngodon idella	25	*Penaeus monodon*	23-25
Hypophthalmichthys molitrix	10	*Penaeus japonicus*	35
Cyprinus carpio	12	*Scylla serrata*	28-34
Oreochromis niloticus	20	*Artemia*	>200
Channa punctata	13	*Dunaliella salina*	>200
Heteropneustes fossilis	9	*Isochrysis*, *Tetraselmis*, *Chaetoceras*	30
Clarias magur	8	*Spirulina platensis*	30
Pangasius hypophthalmus	15	*Gracilaria* spp.	30
Carassius auratus	10	*Ulva* spp.	30
Crayfish	6-8	*Caulerpa* spp.	30

Salinity fluctuations are also linked to immune responses and oxidative stress. Increased reactive oxygen species (ROS) production can weaken immune function, making fish more vulnerable to diseases. In addition to digestion, the intestines play a role in osmotic and ionic regulation by absorbing water. Salinity changes may also impact intestinal microbiota, which is essential for metabolism, growth, and overall health.

Intestinal microbial communities are gaining attention in both human and animal research due to their role in various biological processes. In aquaculture, gut microbiota activity has been linked to the growth of euryhaline species such as Oreochromis niloticus and Litopenaeus vannamei. However, there is limited understanding of how fish intestinal microbiota respond to salinity changes in aquaculture conditions. Further research is needed to explore these interactions and their implications for fish health and growth.

Despite differences in local soil chemistry, certain patterns in sodicity management are observed globally. In the Wakool region of Australia, saline groundwater contained the lowest potassium levels, with only 5% of the concentration found in seawater of equivalent salinity. Calcium levels in saline groundwater varied widely, ranging from 1.4 to 130 times higher than in seawater. Sulphate levels were generally in excess, except in Alabama and Haryana, India. Magnesium deficiencies were noted in some areas, particularly in Australia.

Extensive research has focused on correcting water chemistry imbalances. Various mineral sources have been identified as potential supplements for major cations, addressing deficiencies in different water sources used for shrimp farming worldwide. Among these ions, potassium has received significant attention due to its physiological importance.

Red sea bream (*Pagrus auratus*) lost balance and became dormant within three days of exposure to saline groundwater. However, when potassium was supplemented, survival and growth matched those observed in coastal seawater. Other species farmed in saline groundwater, such as *Argyrosomus japonicus*, *Sciaenops ocellatus*, and *Litopenaeus vannamei*, have also benefited from potassium supplementation.

Inland saline water often has irregular calcium levels. Research has shown that adding calcium chloride to low-salinity groundwater improves survival, growth, and feed efficiency in red drum (*Sciaenops ocellatus*). While lowering pH can also help, it is often too costly and impractical. Most inland saline groundwater sources contain excessive calcium compared to seawater.

In Haryana, groundwater has higher calcium and magnesium concentrations than seawater, which affects *Macrobrachium rosenbergii* larval production. A filtration system containing 0.5 m^3 of ion exchange resin can treat 2,500 litres per day of saline groundwater, supporting a *Macrobrachium* hatchery producing 1.5 million post-larvae (PLs) annually.

Ions are lost from aquaculture ponds due to rainfall overflow, soil adsorption, and water exchange. Remediating these losses can be expensive. Potassium, in particular, is strongly adsorbed by pond sediments due to clay minerals that fix it between tetrahedral layers.

Attempts to correct potassium deficiencies in saline groundwater through dietary modifications have not been effective for finfish. However, *Litopenaeus vannamei* raised in low-salinity groundwater showed improved osmoregulatory function when their diet was supplemented with magnesium, potassium, phospholipids, and cholesterol.

Saline groundwater often contains various ionic imbalances and potential pollutants, requiring site-specific investigations. Most research has focused on major variations in individual ions, but as aquaculture using saline groundwater expands, chronic effects may become more evident. Studying the physiological responses of aquaculture species in low-salinity water and developing artificial mixed-salt environments can help address these challenges.

In addition to ionic composition, suboptimal pH negatively impacts aquaculture potential. Acidic conditions can arise from acid-forming fertilisers, acid sulphate soils, ferrolysis, and high levels of dissolved carbon dioxide. To improve water quality and boost primary productivity, biochar can be applied to both sediment and water. Research suggests that applying biochar in lower doses to water is more effective than using larger amounts in sediment.

Biochar use in inland saline pond water (ISPW) can also help replenish potassium, which is essential for fish and crustacean osmoregulation. This approach could enhance productivity in degraded soil and water systems. Producing biochar from agricultural crop waste could support aquaculture development in degraded land areas, making better use of saline groundwater resources.

Advantages of inland saline aquaculture

- Inland saline aquaculture enhances the conjunctive use of freshwater in salt-affected areas worldwide.
- There are abundant water resources, promising early results with temperate fish, and successful commercial operations using saline groundwater.
- Research is ongoing into using saline water for fish culture in evaporation ponds, indoor systems, and intensive fish-farming facilities.
- Inland saline aquaculture requires water to be treated, contained, and possibly recycled on-site.
- It supports the development of national environmental management policies for sustainable aquaculture.
- It helps reduce the release of untreated nutrients into aquatic ecosystems.
- When cultivating algae for food and feed, saline groundwater may offer advantages over seawater.
- Several molluscan species, including Pacific oysters, Sydney rock oysters, tropical oysters, flat oysters, pearl oysters, silver-lipped oysters, black-lipped oysters, and winged oysters, may be suitable for culture in inland saline waters.

- It enables the creation of a database documenting inland saline water source characteristics.

Conclusion

Freshwater supplies are declining globally, while land and groundwater salinisation are increasing. In the coming decades, saline water will become a primary resource for both agriculture and aquaculture. In India, inland saline water lacks potassium ions, requiring fortification with K^+ in the culture medium or mineral supplementation through feed before use in aquaculture.

Rising salinity levels threaten aquatic species by causing oxidative stress, disrupting metabolism, and weakening immune function. Shrimp farming is widely practised in India's inland saline regions. However, given the high population density and environmental concerns, cultivating low-salinity-tolerant species may be a more sustainable approach than shrimp farming in low-saline conditions. This would allow better utilisation of underused water resources in inland saline areas.

Inland saline water can also be used for freshwater fish culture if appropriate production methods are applied to prevent environmental damage. Research indicates that aquatic organisms adapt better to salinity stress when given a longer acclimatisation period, improving survival rates in aquaculture systems.