

Sustainable Inland Saline Aquaculture: Opportunities, Challenges and Future Prospects

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Abstract

Inland saline aquaculture (ISA) is an emerging approach for the productive utilisation of saline groundwater and salt-affected land, particularly in arid and semi-arid regions where freshwater availability and agricultural productivity are limited. The accumulation of salts in agricultural soils, increasing groundwater salinisation and inadequate drainage have created challenges for conventional farming systems. However, these underutilised resources may provide opportunities for aquatic food production through the culture of suitable fish, shrimp, crustaceans and other euryhaline organisms. This review discusses the opportunities, challenges and future prospects of inland saline aquaculture, with emphasis on species selection, salinity tolerance, ionic composition, osmoregulation, mineral requirements and acclimation. The potential of selected freshwater, brackishwater and marine species for production in inland saline environments is also examined. Particular attention is given to the utilisation of saline groundwater, integration with agriculture and halophytic crops, water and nutrient recycling, and environmentally responsible production systems. Although inland saline aquaculture offers opportunities for food production, livelihood development and productive use of degraded land, its success depends on water chemistry, species adaptability, infrastructure, economic feasibility and environmental management. Potential risks include saline-water discharge, groundwater contamination, nutrient accumulation, disease transmission and excessive groundwater extraction. Future research should focus on developing salinity-tolerant species, improving ionic and nutritional management, strengthening biosecurity, integrating aquaculture with agriculture and assessing long-term environmental impacts. With suitable site-specific planning and sustainable management practices, inland saline aquaculture can contribute to resource utilisation, livelihood diversification and the development of resilient aquatic food-production systems.

Keywords

Inland saline aquaculture; Saline groundwater; Salt-affected soils; Salinity tolerance; Euryhaline species; Osmoregulation; Ionic balance; Mineral supplementation; Sustainable aquaculture; Aquaculture–agriculture integration; Resource utilisation; Environmental sustainability.

Introduction

Salinity is an increasingly important environmental and agricultural challenge in many parts of the world. Soil and water salinisation reduces agricultural productivity, affects freshwater resources and can alter aquatic ecosystems such as rivers, streams and wetlands. Globally, salt-affected soils occur over a very large area, with historical estimates approaching 953 million hectares when saline and sodic soils are considered together (FAO/UNESCO, 1980). More recent assessments also indicate extensive areas affected by salinity and sodicity, particularly in drylands and irrigated regions (FAO, 2024).

Salinity is particularly problematic in arid and semi-arid regions, where low rainfall, high evapotranspiration, rising groundwater tables and inadequate drainage promote salt accumulation in the soil profile. Irrigation without appropriate drainage can accelerate secondary salinisation and progressively reduce the productivity of agricultural land. Consequently, the availability of both freshwater and productive agricultural land is becoming an important constraint to food production.

In India, approximately **6.74 million hectares of land are reported to be salt-affected**, distributed mainly across arid, semi-arid and irrigated regions. Inland saline water is particularly important in states such as Haryana, Punjab, Rajasthan, Uttar Pradesh, Gujarat, Madhya Pradesh, Maharashtra, Tamil Nadu and Andhra Pradesh (Jahan et al., 2025).

Although saline soils and groundwater are generally considered constraints to agriculture, they can also represent an underutilised resource for aquaculture. **Inland saline aquaculture (ISA)** involves the culture of aquatic organisms using saline or brackish groundwater or surface water in areas located away from the coast. It offers an opportunity to

convert otherwise underutilised saline land and water resources into productive food-production systems (Allan et al., 2009; Jahan et al., 2025).

Characteristics of Inland Saline Water and Salt-Affected Soils

Salt-affected soils are broadly classified into **saline, sodic and saline-sodic soils**. Saline soils contain excessive concentrations of soluble salts, whereas sodic soils are characterised by excessive exchangeable sodium and usually high soil pH. Saline-sodic soils exhibit characteristics of both conditions.

Sodic soils may have high concentrations of sodium in the soil solution and on the soil exchange complex. Excess sodium can adversely affect soil structure, permeability, nutrient availability and plant growth. In severe cases, soil pH may exceed 10, creating unfavourable conditions for crop production.

Saline soils, on the other hand, contain soluble salts such as chlorides and sulphates of sodium, calcium and magnesium. Sodium chloride is frequently a major component. Salinity is commonly associated with shallow groundwater tables, particularly where saline groundwater occurs within approximately 2 m of the soil surface.

The development of saline soils is strongly associated with **rising groundwater levels, excessive irrigation and inadequate drainage**. In canal-irrigated areas, continuous irrigation may raise the water table, allowing dissolved salts to move upward through capillary action and accumulate in the root zone. Such processes are particularly important in dry and semi-arid environments (FAO, 2024).

From an aquaculture perspective, the chemical composition of inland saline water is more important than salinity alone. Unlike seawater, saline groundwater can have substantially different concentrations and ratios of major ions such as K^+ , Ca^{2+} and Mg^{2+} . Consequently, two water sources having similar salinity may produce very different results in aquaculture (Allan et al., 2009; Jahan et al., 2025).

Scope of Inland Saline Aquaculture

Inland saline aquaculture has considerable potential for increasing aquatic food production while reducing competition for conventional freshwater resources. Saline groundwater can be used for the culture of selected **euryhaline fish, shrimp, crustaceans and molluscs**.

The concept is particularly relevant where saline land has limited agricultural value. Instead of abandoning such land, appropriately designed ponds or tank-based systems can be developed after evaluating the water chemistry, soil characteristics, drainage and environmental risks.

Countries including Australia, the United States, Israel and India have investigated or developed inland saline aquaculture systems. Species evaluated in these systems include tilapia, Asian seabass, trout, shrimp and oysters (Allan et al., 2009).

In India, research has also investigated both **brackishwater/marine species and selected freshwater species** for culture in inland saline environments. Species such as *Penaeus monodon*, *Litopenaeus vannamei*, *Chanos chanos*, *Mugil cephalus*, *Etroplus suratensis*, *Labeo rohita*, *Catla catla*, *Cirrhinus mrigala*, *Cyprinus carpio* and *Macrobrachium rosenbergii* have been investigated under different saline-water conditions (Garg, 2005; Varghese et al., 2023; Jahan et al., 2025).

Recent reviews indicate that freshwater carps can also tolerate certain inland saline conditions. In experimental systems, rohu (*Labeo rohita*) has shown relatively high survival compared with some other freshwater species, although performance depends strongly on water chemistry and salinity (Jahan et al., 2025).

Utilisation of Poor-Quality Groundwater for Aquaculture

Freshwater availability is becoming increasingly constrained by population growth, agricultural demand, groundwater depletion and climate variability. Agriculture is the major consumer of freshwater in India, making efficient utilisation of alternative water resources increasingly important.

In several arid and semi-arid regions, groundwater may contain elevated concentrations of salts and therefore have limited suitability for conventional irrigation. Long-term use of poor-quality groundwater can contribute to soil salinisation and sodicity. However, the same water may have potential for aquaculture when appropriate species and production systems are selected.

Inland saline aquaculture therefore represents a **resource-reuse strategy** in which saline water and degraded land can be brought into productive use without directly competing with high-quality freshwater resources. However, saline

groundwater should not automatically be regarded as suitable for aquaculture. Water must be analysed for salinity, pH, alkalinity, hardness, major ions, toxic substances and other relevant parameters before culture begins.

Selection of Species for Inland Saline Aquaculture

Species selection is one of the most important factors determining the success of inland saline aquaculture. A suitable species should possess:

- Good tolerance to the available salinity range.
- Strong growth performance.
- Established hatchery and seed-production technology.
- High survival under local water conditions.
- Resistance or tolerance to common diseases.
- Good feed utilisation.
- Strong consumer demand and market value.
- Ability to adapt to the specific ionic composition of the water.

Euryhaline species are particularly suitable because they can tolerate a relatively broad range of salinities. However, **salinity tolerance varies according to species, life stage, acclimation period and water chemistry**. A recent review of fish salinity tolerance emphasises that tolerance should be evaluated in relation to survival, growth, reproduction, disease and production performance rather than by considering a single salinity value (Seale et al., 2024).

Physiological Effects of Salinity on Fish

Salinity is a major environmental factor affecting fish growth, metabolism, reproduction and survival. Fish must maintain an appropriate balance of water and dissolved ions between their bodies and the surrounding environment. This process is known as **osmoregulation**.

The major organs involved in osmoregulation include the **gills, kidneys and intestine**. The gills are particularly important for ion exchange. The enzyme **Na⁺/K⁺-ATPase (NKA)** provides energy for active ion transport and plays a central role in maintaining ionic and osmotic balance.

When fish are exposed to changes in salinity, they must modify ion transport, water regulation and energy allocation. Euryhaline fish can adjust their physiological mechanisms during transitions between freshwater and seawater environments. These adjustments involve changes in gill ionocytes, Na⁺/K⁺-ATPase activity, intestinal ion transport and other physiological processes (Marshall & Grosell, 2006).

Salinity stress can also influence **oxidative stress, immune function, metabolism and blood biochemical parameters**. When environmental stress increases, fish may produce greater quantities of reactive oxygen species (ROS), potentially affecting cellular functions and disease resistance.

Therefore, successful inland saline aquaculture requires gradual acclimation, appropriate stocking density, good nutrition and continuous monitoring of water quality.

Importance of Ionic Balance

One of the major challenges in inland saline aquaculture is that saline groundwater does not necessarily have the same ionic composition as seawater. In particular, deficiencies or imbalances of **potassium, magnesium and other essential ions** can affect the performance of aquatic animals.

Potassium is physiologically important for maintaining cellular function, nerve activity, muscle function and osmoregulation. Research on inland saline aquaculture has therefore given considerable attention to potassium supplementation.

Studies have demonstrated that correcting ionic deficiencies can improve the performance of some cultured species. For example, potassium supplementation has been investigated for species cultured in inland saline groundwater, while magnesium and other mineral supplements have also been evaluated in low-salinity shrimp culture (Jahan et al., 2025). Recent research on low-salinity *Litopenaeus vannamei* production also highlights the importance of ionic balance, particularly **Na⁺:K⁺ and Mg²⁺:Ca²⁺ relationships**, for osmoregulation, growth and immune competence (2026 review).

Thus, **salinity alone should not be used as the sole criterion for evaluating inland saline water**. Detailed ionic analysis is essential before selecting species and designing a production system.

Role of Potassium, Calcium and Magnesium Supplementation

Mineral supplementation may be necessary when the ionic composition of saline groundwater differs substantially from the physiological requirements of the cultured organism.

Potassium

Potassium deficiency can impair osmoregulatory processes and reduce growth and survival in some species. Potassium salts or mineral mixtures may therefore be added to culture water where laboratory analysis confirms deficiency.

Calcium

Calcium is involved in osmoregulation, skeletal development, muscle function and other physiological processes. Where calcium levels are inadequate, calcium supplementation may improve survival and growth.

Magnesium

Magnesium plays an important role in enzyme activity, ionic regulation and cellular metabolism. Low-salinity shrimp culture studies have demonstrated the importance of magnesium supplementation under certain water conditions.

However, mineral supplementation should be **based on water analysis rather than routine addition**. Excessive supplementation can increase production costs and may create new water-quality problems.

Acclimation of Fish to Saline Water

Acclimation is an important management practice when freshwater or low-salinity species are transferred to saline environments. Sudden changes in salinity can impose severe osmotic stress, whereas gradual acclimation allows fish to adjust their osmoregulatory mechanisms.

The appropriate acclimation protocol depends on species, size, life stage, initial and final salinity, temperature and water chemistry. Therefore, gradual salinity adjustment under controlled conditions is generally preferable to abrupt exposure.

The ability of euryhaline species to modify gill and intestinal ion transport enables them to tolerate changing salinity conditions. Nevertheless, physiological adaptation requires energy, and excessive or prolonged salinity stress may reduce the energy available for growth and reproduction (Marshall & Grosell, 2006; Seale et al., 2024).

Inland Saline Aquaculture and Freshwater Fish

An important research direction in India is the development of **freshwater fish culture in low-salinity inland saline water**.

Traditional freshwater aquaculture depends heavily on suitable freshwater resources. In regions where freshwater is limited but saline groundwater is available, salt-tolerant freshwater species may provide an alternative production opportunity.

Research has examined Indian major carps and other freshwater species for their ability to survive and grow in saline environments. Recent research suggests that selected freshwater species can be cultured under appropriate saline conditions, although species-specific tolerance and water chemistry remain critical considerations (Jahan et al., 2025).

This approach could be particularly valuable in inland areas where saline groundwater and degraded agricultural land occur together.

Integration with Agriculture

Inland saline aquaculture does not necessarily need to operate as an isolated activity. It can be integrated with **agriculture, halophytic crops, algae production and other farming systems**.

Integrated systems can improve resource-use efficiency by recycling water and nutrients. For example, aquaculture effluent may potentially be used for selected salt-tolerant crops after appropriate treatment and assessment. Periphyton-based systems have also been investigated as a means of improving nutrient utilisation and reducing dependence on external inputs (Garg, 2005).

The integration of aquaculture with agriculture may therefore support a circular production system in which water, nutrients and biomass are reused rather than discarded.

Biochar and Water-Quality Management

Water-quality management is critical in inland saline aquaculture. Besides salinity and ionic composition, parameters such as pH, alkalinity, dissolved oxygen, ammonia and other water-quality variables influence fish and shrimp performance.

Biochar has been investigated as a potential material for improving water and sediment characteristics. Agricultural residues can be converted into biochar, creating an opportunity to utilise crop waste while potentially supporting water-quality management.

However, the effectiveness of biochar depends on its raw material, production conditions, application rate, water chemistry and culture system. Therefore, site-specific research is required before large-scale application.

Environmental Considerations

Although inland saline aquaculture offers opportunities for productive use of saline resources, it should not be considered environmentally risk-free.

Potential environmental concerns include:

1. Leakage of saline water into surrounding agricultural soils.
2. Discharge of untreated aquaculture effluent.
3. Accumulation of nutrients and organic matter.
4. Changes in groundwater chemistry.
5. Introduction of non-native species.
6. Disease transmission.
7. Excessive groundwater extraction.
8. Disposal of saline sludge and concentrated brine.

Consequently, inland saline aquaculture should be developed using **lined ponds or appropriately contained systems, water recycling, effluent treatment and regular monitoring of groundwater and surrounding soils.**

Advantages of Inland Saline Aquaculture

The major potential advantages include:

- Utilisation of saline and otherwise underutilised groundwater resources.
- Productive use of salt-affected and degraded land.
- Reduction of direct competition with freshwater aquaculture.
- Diversification of aquaculture production in inland regions.
- Opportunities for culture of euryhaline fish, shrimp and other aquatic organisms.
- Potential integration with agriculture and halophytic crops.
- Recycling of water and nutrients.
- Employment and income generation in saline-affected regions.
- Potential contribution to food and nutritional security.

Recent research indicates that inland saline aquaculture has particular potential in India's salt-affected regions, although its expansion depends on appropriate species selection, water chemistry management, infrastructure and economic feasibility (Jahan et al., 2025).

Challenges and Future Research Priorities

Despite its potential, inland saline aquaculture faces several technical and economic challenges.

Important areas requiring further research include:

- Development of species with improved salinity tolerance.
- Selective breeding and genetic improvement.
- Identification of suitable indigenous freshwater species.
- Determination of species-specific salinity limits.
- Development of cost-effective mineral supplementation.
- Understanding long-term effects of ionic imbalance.
- Improvement of low-salinity shrimp and fish feeds.
- Development of biosecurity protocols.
- Efficient water-recycling systems.
- Integration with agriculture and halophyte production.
- Assessment of groundwater and soil impacts.
- Development of economically viable commercial production models.

Recent research also emphasises the need for integrated studies involving **physiology, nutrition, microbiology, water management, biosecurity and environmental sustainability** rather than considering salinity as an isolated production variable.

Conclusion

Inland salinisation is a major challenge to agricultural productivity and freshwater availability, particularly in arid and semi-arid regions. At the same time, saline groundwater and salt-affected land represent potentially valuable resources for alternative food production.

Inland saline aquaculture provides an opportunity to convert degraded land and poor-quality saline water into productive aquaculture systems. Successful development, however, depends on appropriate species selection, detailed water-quality assessment, ionic balancing, gradual acclimation, efficient feeding and careful environmental management.

India has considerable potential for inland saline aquaculture because of its extensive salt-affected areas and saline groundwater resources. Research has demonstrated the potential of several marine, brackishwater and selected freshwater species in these environments (Varghese et al., 2023; Jahan et al., 2025).

Future development should focus on **low-salinity-tolerant freshwater species, improved mineral management, water recycling, integrated aquaculture-agriculture systems and environmentally safe production technologies.** With appropriate site-specific management, inland saline aquaculture can contribute to the productive utilisation of marginal resources while supporting sustainable aquatic food production.

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