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REVIEW

Current perspective of aquaculture in India: future challenges and opportunities

Nayan Chouhan . Bhavesh Choudhary

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Abstract The development of innovative aquaculture methods has led to a significant increase in the contribution of aquatic goods to job opportunities. India has been a significant participant in the aquaculture sector. This study develops an index to measure the amount of upgrading in the fishing industrial structure. It reveals that India's fishery industrial structure is experiencing an upward trend in upgrading. However, the level of upgrading in inland fishery areas is higher than that in coastal areas as several government initiatives aimed at improving the industrial structure of the fisheries sector in this region, indicating that the fishery industry in coastal regions is still in its early stages of development. The study proposes recommendations for enhancing the development of India's fishing sector by considering its existing state and identifying prospective avenues for sustainable expansion. This review thus provides a comprehensive understanding of the Indian aquaculture sector, focusing on production trends, species diversity, regulatory frameworks, environmental concerns, and socio-economic impacts. It does this by analyzing existing literature and industry reports and highlighting the sector's accomplishments, challenges, and future prospects.

Keywords India . Fisheries . Upward trend . Sustainable expansion . Current growth . Challenges . Future perspective . Knowledge gaps

Introduction

Aquaculture plays a significant role in India’s economy, food security, and employment generation (Ahmed and Lorica 2002; Kumar et al. 2015). Aquaculture in India provides a vital source of high-quality protein for the growing population of India (Naylor 2016). India has immense potential for freshwater and marine aquaculture due to its diverse coastline, rivers, and inland water bodies, comprising 0.28 million km of rivers and canals, 1.2 million ha of flood plain lakes, 2.45 million ha of ponds and tanks and 3.15 million ha of reservoirs (Béné et al. 2016). Fish and other aquatic products from aquaculture contribute significantly to the country’s seafood production, fulfilling the protein requirements of millions of people. To make the country self-sufficient in food production, country has made remarkable strides in crop production. Despite much benefits from the green and blue revolutions adopted in India, there have been many environmental problems resulting from intensive agricultural practices that led to environmental problems in both terrestrial and aquatic systems (Himaja and Rajagopalasamy 2016). Increasing demand for aquatic resources has also caused inland fisheries to decrease over the past few decades as overfishing, habitat destruction, and water pollution put immense pressure on freshwater ecosystems, leading to reduced fish populations in rivers, lakes, and reservoirs.

Nayan Chouhan
Department of Aquatic Health and Environment, College of Fisheries, Central Agricultural University (Imphal), Lembucherra, Agartala, Tripura (West), 799210, India

Bhavesh Choudhary (✉)
Department of Aquaculture, College of Fisheries, Central Agricultural University (Imphal), Lembucherra, Agartala, Tripura (West), 799210, India
e-mail: bhaveshchoudhary@yahoo.com

Globally, fish is an important source of affordable protein, nutrition, income and livelihood for billions of people. More than 3.3 billion people depend on fish for at least 20% of their total animal protein (FAO 2020). Aquaculture is a major contributor to India's agricultural and rural economy. The sector provides livelihood opportunities to millions of people, especially those living in coastal and rural areas (Ngasotter et al. 2020). It generates employment in various activities such as fish farming, hatcheries, feed production, processing and marketing. Aquaculture also contributes to the country's export earnings through the export of seafood products, plays crucial role in reducing poverty and improving the socio-economic conditions of small-scale farmers/fisherfolks (Béné et al. 2007). Many rural communities, including marginalized and disadvantaged groups, engage in small-scale aquaculture as a means of income generation and livelihood improvement. By providing a steady source of income, aquaculture helps uplift the living standards of these communities. Aquaculture offers opportunities for sustainable food production. India faces challenges of overfishing, declining wild fish stocks, and environmental degradation. By promoting responsible aquaculture practices, such as integrated multi-trophic aquaculture (IMTA) and recirculating aquaculture systems (RAS), India can reduce the pressure on wild fish stocks and conserve aquatic ecosystems while meeting the increasing demand for seafood (Ghose 2014).

India is one of the largest exporters of seafood globally, and aquaculture products constitute a significant share of its export portfolio (Geetha et al. 2020). The country exports a wide range of aquaculture products, including shrimp, fish, mollusks, and value-added seafood items. Aquaculture has contributed to India's foreign exchange earnings and enhanced its position in the global seafood market (Gopalakrishnan et al. 2024). Aquaculture provides an opportunity for diversification of agriculture and reduces the dependence on traditional crops (Adhikari 2013). Farmers can integrate fish farming with agriculture, such as integrating fish ponds with rice cultivation (rice-fish farming) or using fish waste as fertilizers for crop production (aquaponics). This diversification improves farm resilience, increases productivity, and enhances income potential for farmers (Pingali 1995). Aquaculture has stimulated research and technological advancements in India (Kumar 2018). The government, research institutions, and private sector organizations are actively involved in developing improved aquaculture practices, breeding programs, disease management strategies, and feed formulations. These advancements contribute to the growth and sustainability of the aquaculture sector (Ahmed and Lorica 2002). Overall, the objective of the review is to provide a holistic understanding of the current state of aquaculture in India, highlight the challenges and opportunities, and offer recommendations for sustainable and inclusive growth of the sector.

Current status of aquaculture in India

Historical development and growth: Aquaculture in India has a long history and has witnessed significant development and growth over the years. Here is an overview of the historical development of aquaculture in India:

Early beginnings (pre-independence era): Aquaculture practices in India can be traced back to ancient times, where traditional methods such as the cultivation of carp in village ponds and brackish water shrimp farming were practiced. These methods were largely subsistence-based and not commercially oriented (Beveridge and Little 2002). The Fisheries Survey of India was established by the government as a pilot project known as deep sea fishing station (DSFS) in 1946. The aim of DSFS is to improve fish food supply by the development of deep sea fishing.

Initial growth phase (1950s-1970s): The modern aquaculture industry in India started to take shape after independence. The establishment of the Central Marine Fisheries Research Institute (CMFRI) on 3rd February and Central Inland Fisheries Research Institute (CIFRI) on 17th March in 1947 played a crucial role in promoting aquaculture research and development (Gopalakrishnan et al. 2017) with the aim to enhance fishery through knowledge based management and basic or strategic research, conservation of biodiversity, integrity of ecological services and to derive social benefits from inland open waters. During this period, freshwater aquaculture activities gained momentum, particularly in states like West Bengal, Punjab, Haryana, and Andhra Pradesh. Central Institute of Coastal Engineering for Fisheries (CICEF), Bengaluru was established in January, 1968. The main objective for establishing carrying out engineering and economic investigations and preparing techno-economic feasibility reports for the development of fishery harbors at suitable sites along the Indian coast.

Government initiatives (1970s-1990s): The Indian government recognized the potential of aquaculture and initiated various programs and policies to promote its development (Das 2019). In 1971, the CIFRI initiated four All India Coordinated Research Projects (AICRP): Composite Fish Culture, Riverine Fish Seed Prospecting, Air-breathing Fish Culture, and Ecology and Fisheries Management of Reservoirs (http://www.cifri.res.in). The National Institute of Fisheries Post Harvest Technology and Training (NIFPHATT), erstwhile known as 'Integrated Fisheries Project', was established 1972 for development of post-harvest technologies. FISHCOPFED aims to serve, develop and uplift the socio-economic condition of fishers in the country. AICRP on 'Brackish water Fish Farming' by ICAR in 1973 after that the importance in brackish water aquaculture being started in India. The introduction of schemes like the Integrated Fish Farming Development Agency (IFFDA) and the National Project on Brackish water Aquaculture (NPBA) further accelerated the growth of the sector.

Expansion of marine aquaculture (1990s-2000s): In the 1990s, there was a significant shift towards the development of marine aquaculture, particularly shrimp farming. Coastal states like Andhra Pradesh, Tamil Nadu, Gujarat, and Odisha witnessed rapid expansion in shrimp farming through the adoption of improved technologies and better management practices. Export-oriented shrimp farming became a major contributor to the Indian aquaculture industry (Krishnan and Birthal 2002; Jayanthi et al. 2018). With the development and advancement in brackish water farming during 1990s, the brackish water aquaculture area increased by 387% from 1990 to 2000 (Jayanthi et al. 2019).

Technological advancements and diversification (2000s-2010s): The 2000s saw advancements in aquaculture technologies, including the adoption of intensive and semi-intensive farming systems, improved seed production techniques, and better disease management practices (Katiha et al. 2005). The diversification of aquaculture species beyond traditional carps and shrimps also gained attention. Species like genetically improved tilapia, catfish, pangasius, and ornamental fish gained popularity among farmers (Manoj and Vasudevan 2009; Mahapatra 2018; Manyise et al. 2024), as the farmers are willing to adopt fish species having high growth rate, higher survival, and fetching more price in market. Coastal Aquaculture Authority (CAA) 2005, objectives of the Authority are to regulate The Coastal Aquaculture activities in the areas notified by the Central Government as 'coastal areas'. In 2006 GOI established the NFDB for helping in the various development in fisheries sector mainly fishers through various need-based projects for technology up gradation, species diversification in aquaculture, dissemination of new and improved fish varieties, promoting seaweed cultivation, mariculture, shrimp farming, ornamental fisheries, training & capacity building etc (DoF-GOI 2024).

Government support and sustainable practices (2010s onwards): The Indian government continued to support the aquaculture sector through various schemes and initiatives, focusing on sustainable and responsible aquaculture practices. The Blue Revolution Scheme, launched in 2015, aimed to increase fish production and enhance the livelihoods of fish farmers. Emphasis was given to the adoption of eco-friendly practices, certification standards, and promoting aquaculture in inland and hilly regions. During 2020, GOI launched Pradhan Mantri Matsya Sampada Yojana (PMMSY) with an investment of Rs. 20,050 crores for focused and holistic development of the fisheries sector while ensuring socio-economic well-being of fishermen, fish farmers and other stakeholders (DoF-GOI 2025).

Current scenario: Aquaculture has become a vital component of India's fisheries sector. The country is among the largest producers of fish and shrimp globally (Kumaran et al. 2021). Major aquaculture states include Andhra Pradesh, West Bengal, Tamil Nadu, Gujarat, Odisha, and Kerala. The sector provides employment opportunities and contributes to the national economy through exports. In year 2023-24 India exported 17,81,602 MT of Seafood worth US$ 7.38 Billion (Rs. 60,523 Crores) which is all time high export by value (MPEDA 2024). Overall, the historical development of aquaculture in India has been characterized by government support, technological advancements, and a shift towards sustainable practices (Hudson et al. 2016). The industry continues to grow, driven by increased demand, improved farming techniques, and favorable policies.

Major aquaculture production regions: With a vast coastline and numerous freshwater resources, India offers favorable conditions for aquaculture production. The major aquaculture production regions in India are highlighted with the trends in their production over the years. India is endowed with a long coastline (11,098 km) and has a scope for large exploitation of marine wealth. In India, an estimated brackish water area suitable for shrimp culture is 11.91 lakh ha, of which around 1.356 lakh ha area is currently under

shrimp farming. *L. vannamei* is a benefited shrimp production in India (Chellapandi 2021). It is approved by the Coastal Aquaculture Authority of India in the States of Andhra Pradesh, Tamil Nadu, Maharashtra, Gujarat, Orissa, Goa, and Union Territories of Diu and Pondicherry. Andhra Pradesh has 1053.07 km of coastline and 1,75,000 ha of brackish water (Chellapandi 2021). It produces more than half of the country's farmed shrimp. Shrimp exports in India are increased by 16.21% (4,34,484 metric tons) during 2016–17. The Garret ranking and Rank Based Quotient analyses projected severe constraints in the shrimp aquaculture sector in India due to COVID-19 related lockdown (Kumaran et al. 2021).

In recent years, India's aquaculture production has shown a positive trend, driven by technological advancements, improved infrastructure, and supportive government policies. The country has experienced an increasing shift towards shrimp farming due to its high export demand. Additionally, the promotion of sustainable aquaculture practices, disease management strategies, and certification programs has further contributed to growth. Indian aquaculture production has witnessed significant fluctuations due to various factors such as climate change, disease outbreaks, and market dynamics. However, the overall trend has been upward, with production steadily increasing year by year (Handbook of Fisheries Statistics 2023). The industry has strived to address challenges through research and development, including the adoption of advanced feed formulations, biosecurity measures, and water quality management techniques (Mishra et al. 2017). Aquaculture production in India is on the rise, with major regions like Andhra Pradesh, Gujarat, Tamil Nadu, West Bengal, and Kerala contributing significantly (Umesh et al. 2010). The adoption of modern farming practices, sustainable approaches, and technology-driven solutions has been instrumental in the sector's growth. As the demand for seafood continues to increase, India's aquaculture industry is poised to play a crucial role in meeting domestic and global requirements while driving economic development in the country.

Regulatory framework and policies: India has a comprehensive regulatory framework and policies for fisheries, aiming to ensure sustainable and responsible management of its marine and fresh water resources . The Fisheries (Regulation) Act, 2009, and the National Fisheries Policy, 2020, serve as the cornerstone for governing the sector (Jyotsna et al. 2024). These regulations encompass fishing vessel registration, licensing, and catch quotas to prevent overfishing and promote conservation. Additionally, India focuses on modernizing the fishing industry by supporting aquaculture, encouraging the adoption of eco-friendly practices, and promoting research and development. Measures are also in place to safeguard the livelihoods of fisherfolk and foster social welfare. Regular monitoring, surveillance, and collaboration with stakeholders contribute to the effective implementation of these policies, fostering a sustainable fisheries sector for future generations.

Government initiatives and support: The Indian government has been actively promoting aquaculture through various initiatives and support measures. Recognizing the immense potential of the sector, several programs have been launched to encourage sustainable fish farming practices. Financial assistance is provided to farmers for constructing ponds, purchasing equipment, and adopting modern technology. The National Fisheries Development Board (NFDB) plays a crucial role in coordinating these efforts. Additionally, research and training institutes are established to disseminate knowledge and improve skills in aquaculture management. Furthermore, policies are formulated to ensure environmental sustainability and to boost exports, enabling India to become a major player in the global aquaculture industry. The Marine Products Export Development Authority (MPEDA) was established by a parliamentary statute in 1972. The MPEDA operates under the Ministry of Commerce and Industry, focusing exclusively on the promotion and regulation of marine product exports. The Indian government has implemented several initiatives and provided support to promote aquaculture in the country. Here are some key government initiatives and support measures:

National Fisheries Development Board (NFDB): The NFDB is an autonomous organization established in 2006 under the administrative control of the Ministry of agriculture. It plays a vital role in promoting and coordinating aquaculture development in the country. The NFDB provides financial assistance, technical support, training, and capacity building to fish farmers and entrepreneurs.

Rashtriya Krishi Vikas Yojana (RKVY): The RKVY is a centrally sponsored scheme initiated in 2007 aimed at promoting holistic development in agriculture and allied sectors, including fisheries and aquaculture (Vijayan and Nain, 2021). Under this scheme, financial assistance is provided to states for the development of infrastructure, training, extension services, and adoption of best practices in aquaculture.

National Mission for Protein Supplements (NMPS): Launched in 2011-12 by central government of India as part of the RKVY. The NMPS aims to increase the production of animal-based protein and availability of quality protein-rich feed and fodder. This initiative benefits aquaculture by addressing the availability and affordability of quality feed for fish and shrimp farmers.

Pradhan Mantri Matsya Sampada Yojana (PMMSY): The PMMSY is a flagship scheme launched in 2020 to promote the sustainable development of the fisheries sector in India. It integrates the ongoing schemes and initiatives related to aquaculture, fishing infrastructure, modernization, and value chain development. The PMMSY aims to enhance fish production, increase productivity, promote entrepreneurship, and create employment opportunities in the sector. Pradhan Mantri Matsya Kisan Samridhi Sah-Yojana (PM-MKSSY), a Central Sector Sub-scheme under the PMMSY aims at formalizing the fisheries sector and supporting fisheries' micro and small enterprises with an investment of over Rs. 6,000 crores over a period of the next 4 years from FY 2023-24 to FY 2026-27 (DoF-GOI 2025). The government has established the Fisheries and Aquaculture Infrastructure Development Fund (FIDF) in 2018 with a total fund size of Rs 7522.48 crore with the aims to achieve a sustainable growth of 8-9 percent, to strengthen the fisheries sector. FIDF aims to develop robust infrastructure in both marine and inland fisheries, enhancing production capacity and ensuring sustainable growth (MoF 2025).

It's important to note that government initiatives and support measures may evolve over time, so it is advisable to refer to the latest policies and programs announced by the relevant authorities for the most up-to-date information on aquaculture promotion in India.

Legal and regulatory frameworks: Aquaculture in India is governed by various legal and regulatory frameworks at the national and state levels. These frameworks aim to promote sustainable aquaculture practices, ensure food safety, protect the environment, and regulate the industry. Here are some of the key laws and regulations pertaining to aquaculture in India:

The Coastal Aquaculture Authority Act (CAA): The CAA act establishes on 23rd June 2005 to regulate coastal aquaculture activities in specified areas. The CAA set guidelines and regulations for the establishment, operation, and management of aquaculture farms, including the registration and licensing of aquaculture farms and the prevention of environmental pollution (https://caa.gov.in).

The environment (protection) act: This act came into force in country on 19th November 1986. It empowers the central government to take measures for environmental protection and conservation (https://cpcb.nic.in). It includes provisions for regulating aquaculture activities that may have an impact on the environment and mandates obtaining environmental clearances for certain aquaculture projects.

The biological diversity act 2002: This act aims to conserve biodiversity and regulate access to biological resources and it was enacted on February 5th 2003 in India. It requires aquaculture operators to obtain necessary permits and comply with benefit-sharing provisions if they utilize genetic resources from India's biodiversity (http://nbaindia.org).

State fisheries acts and rules: Each state in India may have their own fisheries acts and rules to regulate aquaculture within their jurisdiction. These laws may cover aspects such as licensing, registration, stocking of fish, disease control, water quality, and other specific requirements pertaining to specific area.

Food Safety and Standards Act, 2006: This act establishes the Food Safety and Standards Authority of India (FSSAI) and sets standards for food safety and quality. It applies to aquaculture by regulating the processing, packaging, labeling, and sale of aquaculture products to ensure their safety for consumers (https://www.fssai.gov.in). Indian fisheries act 1897: Indian Fisheries Act, 1897 empowers the state governments to regulate inland fisheries, including aquaculture, within their respective territories (https://www.fao.org).

It is important to note that the legal and regulatory frameworks for aquaculture may evolve over time, and it is advisable to consult the relevant government authorities and seek legal advice for up-to-date and specific information regarding aquaculture operations in India.

Environmental sustainability and certification programs

Environmental sustainability and certification programs in aquaculture are essential for ensuring responsible practices that minimize negative environmental impacts and promote the long-term viability of the industry. Here's a review of environmental sustainability and certification programs in aquaculture in India: Best Aquaculture Practices (BAP): The BAP certification program, developed by the Global Aquaculture

Alliance (GAA) in the year 2002, is widely recognized and implemented in India. BAP certification sets standards for responsible aquaculture practices, covering various aspects such as environmental sustainability, social responsibility, food safety, and animal welfare. It promotes environmentally friendly practices, including habitat protection, effluent management, and responsible sourcing of feed and seedstock.

Global Aquaculture Practices (GAP): It is an internationally recognized certification program that promotes good agricultural practices, including aquaculture. It sets standards for sustainable production systems, environmental conservation, and social responsibility. Although GAP certification is not specific to India, many aquaculture farms in the country have adopted these standards to demonstrate their commitment to responsible practices.

Marine Stewardship Council (MSC): MSC primarily focuses on wild-caught seafood, it also has a certification program for responsible aquaculture practices, launched in the year 1997. The MSC certification ensures that farmed seafood is produced in a manner that minimizes environmental impacts, maintains biodiversity, and follows stringent traceability and sustainability criteria. Some aquaculture farms in India have achieved MSC certification for specific species such as shrimp.

Aquaculture Stewardship Council (ASC): ASC was launched in 2010 by the World Wide Fund for Nature (WWF) and the Dutch Sustainable Trade Initiative (IDH). It is an independent organization that certifies responsibly farmed seafood products globally. While ASC certification is not extensively implemented in India, it provides a framework for promoting responsible aquaculture practices and encourages the conservation of natural resources (Saha 2020).

These certification programs aim to improve environmental sustainability in Indian aquaculture by setting guidelines and assessing farms against defined criteria. They encourage practices such as proper waste management, reduction of chemical use, protection of water quality, and protection of biodiversity. Certification programs also enhance market access and consumer trust by providing assurance that the seafood products meet stringent sustainability standards. However, it's important to note that the effectiveness of these programs depends on factors such as enforcement, transparency, and ongoing monitoring of certified farms. Continuous improvement and regular updates to the certification standards are also essential to keep pace with evolving environmental concerns. Overall, while India has made progress in implementing environmental sustainability and certification programs in aquaculture, there is still room for further development and widespread adoption to ensure the long-term sustainability of the industry.

Challenges in Indian aquaculture

The industry faces several challenges that impact its sustainability and growth. Here are some of the key challenges in Indian aquaculture:

Water quality and pollution: Maintaining good water quality is crucial for the health and growth of aquaculture species. However, pollution from industrial and agricultural activities, as well as untreated wastewater discharge, can contaminate water bodies and negatively impact aquaculture operations. The world's first engineered and largest single wastewater-fed aquaculture system still exists today in Kolkata, India, where almost 4,000 ha of ponds in the East Kolkata Wetlands, provide the only sewage treatment system for the central part of the city which helps to improve water quality dynamics (Mukherjee 2020; Kumar et al. 2023; Ghosh et al. 2024). Poor water quality can lead to disease outbreaks and mortality in fish, affecting production levels. Water quality is an essential factor in the successful expansion of aquaculture, but it is increasingly becoming a significant challenge due to pollution. The quality of water directly impacts the health and growth of aquatic organisms, making it crucial for maintaining optimal conditions. However, pollution from various sources, including industrial waste, agricultural runoff, and improper disposal of chemicals, poses a threat to water quality and, consequently, the expansion of aquaculture. Polluted water contains contaminants such as heavy metals, pesticides, and excess nutrients, which can lead to the deterioration of aquatic ecosystems and the decline of fish and shellfish populations. Moreover, these pollutants can bioaccumulate in the tissues of aquatic organisms, posing risks to human health if consumed. To overcome this challenge, stringent regulations and effective monitoring systems are needed to prevent water pollution and ensure the sustainable growth of aquaculture. Additionally, adopting eco-friendly practices and implementing advanced water treatment technologies can help mitigate the impact of polluted water on aquaculture expansion. It is essential to prioritize water quality management as a fundamental aspect

of aquaculture development to safeguard the health of aquatic organisms, protect human well-being, and sustainably meet the growing demand for seafood.

Disease management: Disease outbreaks can significantly impact aquaculture production and lead to substantial economic losses (Chouhan et al. 2023). The density of fish in aquaculture systems can create an ideal environment for the spread of diseases. Effective disease prevention measures, including regular health monitoring, vaccination, and biosecurity protocols, are necessary to minimize the occurrence and impact of diseases (Choudhary et al. 2025a). Disease management in aquaculture presents a significant challenge in India. With a growing population and increasing demand for seafood, the aquaculture industry plays a crucial role in meeting the country's protein requirements (Choudhary et al. 2025a). However, disease outbreaks pose a severe threat to fish and shrimp farms, leading to significant economic losses and impacting food security (Choudhary et al. 2025b). Several factors contribute to the challenge of disease management in Indian aquaculture (Figure 1).

Firstly, the intensive farming practices and high stocking densities create favorable conditions for the spread of diseases. Overcrowded ponds or cages, coupled with poor water quality management, weaken the immune system of aquatic organisms, making them more susceptible to infections (Ahne et al. 1989). Secondly, the lack of robust disease surveillance and diagnostic facilities hampers timely identification and control of diseases (de la Peña et al. 2022; Pawar et al. 2025). Many farmers in rural areas lack access to proper laboratory testing and diagnostic services, making it difficult to diagnose diseases accurately. This leads to delays in implementing appropriate treatment measures, exacerbating the spread of infections. Furthermore, the limited availability of effective vaccines and therapeutics for aquaculture diseases adds to the challenge (Adams 2019). Unlike in terrestrial livestock farming, where vaccines are commonly used, the development and commercialization of vaccines for aquatic organisms have been relatively slow. Recently, Indian Council of Agricultural Research-Central Institute of Fisheries Education, Mumbai transferred the technologies of two fish vaccine developed against two major bacterial diseases Columnaris caused by *Flavobacterium columnare* and Edwardsillosis caused by *Edwardsiella tarda (icar.org.in).* ICAR-Central Institute of Brackishwater Aquaculture released CIBA-Nodavac vaccine against the viral nervous necrosis (VNN) disease of finfish through recombinant technique (ciba.icar.gov.in). This leaves farmers heavily reliant on prophylactic measures, such as water quality management and biosecurity protocols, which may not always be sufficient to prevent disease outbreaks. Additionally, inadequate knowledge and awareness among farmers regarding disease prevention and management practices further contribute to the challenge. Many small-scale farmers lack access to information, training, and extension services on best aquaculture practices. As a result, they may not implement proper biosecurity measures or may unknowingly introduce pathogens to their farms, leading to disease outbreaks. Addressing the challenge of disease management in Indian aquaculture requires a multi-faceted approach (Datta 2012). It involves strengthening disease surveillance systems, enhancing diagnostic capacities, and promoting research and development for vaccines and therapeutics specific to aquaculture diseases (Pawar et al. 2025).

There is a need for increased farmer education and training programs, coupled with improved access to extension services, to enhance disease prevention and management practices at the grassroots level. By

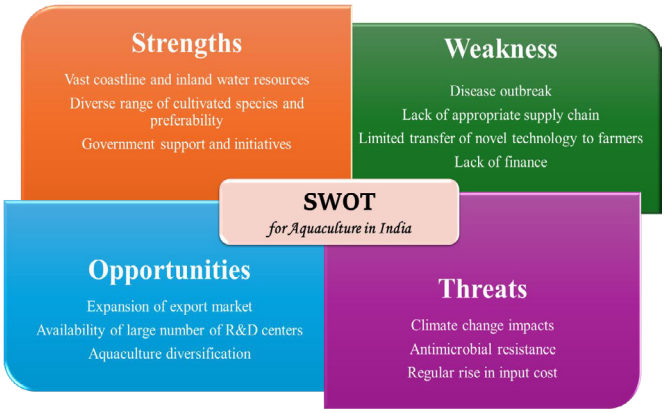


Fig. 1 SWOT analysis of the fisheries and aquaculture in indian perspective

adopting a comprehensive approach and investing in infrastructure, research, and farmer empowerment, India can overcome the challenges associated with disease management in aquaculture (Singh et al. 2024). This will not only safeguard the sustainability and profitability of the aquaculture industry but also ensure a consistent supply of safe and healthy seafood for the country's growing population.

Feed availability and quality: The availability and affordability of quality fish feed are crucial for the success of aquaculture. At present in India, the targeted fish production by 2025 is 22.0 million tons. Currently, India heavily relies on imported fish feed ingredients, which can make it expensive. Supply chain, including promoting alternative feed ingredients and improving feed conversion efficiency, is essential for the growth of the aquaculture sector. In India, the availability and quality of feed for aquaculture play a crucial role in the success of the industry. As aquaculture continues to expand and meet the growing demand for seafood, ensuring a consistent supply of nutritious feed is essential for the health and growth of farmed fish and shrimp.

Traditionally, the main source of feed for aquaculture in India has been fishmeal and fish oil derived from marine resources (Hodar et al. 2020). However, due to concerns over overfishing and sustainability, alternative sources of feed have gained importance. One such alternative is plant-based feed, which is produced using various agricultural commodities like soybean, corn, wheat, and rice bran (Jiang et al. 2022a). These plant-based feeds are formulated to provide the necessary nutrients for fish and shrimp growth and have been proven to be effective replacements for fishmeal-based feeds. Another emerging alternative source of feed is insect meal, which involves using insects such as black soldier flies or mealworms as a protein source. Insect meals have shown great potential as a sustainable and environmentally friendly feed option, as insects can be reared using organic waste or byproducts, reducing the pressure on traditional feed resources (Ojha et al. 2020).

Additionally, research is being conducted on the use of single-cell proteins (SCP) and algae in aquafeed formulations (Jones et al. 2020). SCP, produced from microbial sources like bacteria or yeast, can provide a highly nutritious and sustainable protein source. Algae, on the other hand, are rich in omega-3 fatty acids and can be cultivated to supplement the nutritional content of aquafeeds (Kanoje et al. 2023). To improve feed availability and quality, India has been investing in research and development, promoting sustainable aquafeed production practices, and encouraging collaborations between the public and private sectors (Jayasankar 2018). Efforts are being made to enhance the domestic production of aquafeed ingredients, reduce dependence on imports, and optimize feed formulations to meet the specific nutritional requirements of different aquaculture species. Ensuring the availability and quality of feed for aquaculture in India is crucial for the sustainable growth of the industry. Alternative sources such as plant-based feeds, insect meals, single-cell proteins, and algae are being explored to reduce reliance on fishmeal and fish oil (Hadi and Brightwell 2021). These efforts aim to promote a more sustainable and environmentally friendly aquaculture sector while meeting the increasing demand for seafood in the country. Recent research highlights the potential of leaf meals as a cost-effective and sustainable alternative in fish feed formulation. Plant-derived feedstuffs, including leaf and seed meals, are being explored as viable substitutes for conventional ingredients (Ghosh et al. 2019). Several terrestrial plant leaves have shown promise as sources of protein, vitamins, and essential fatty acids (Agrawal et al. 2014; Uddin et al. 2014). Notably, Acharya et al. (2025) reported that leaves of *Albizia lebbeck* and *Bauhinia acuminata* could serve as substitutes for low-protein vegetal meals such as rice bran, wheat flour, wheat bran, corn meal, and sorghum in carp diets. However, further research is essential to assess digestibility, anti-nutritional factors, and long-term impacts on fish health and growth performance.

Lack of infrastructure and technology: Many aquaculture farms in India lack basic infrastructure and technology, such as proper hatcheries, efficient water management systems, and advanced monitoring equipment. The lack of infrastructure hampers productivity, quality control, and overall efficiency of the operations. Investments in infrastructure development and the adoption of modern technologies can enhance the productivity and sustainability of Indian aquaculture. Recently, Government of India stepped up investments in fisheries sector and approved Fisheries and Aquaculture Infrastructure Development Fund (FIDF) in 2018-19. Under this FIDF GOI immerse in developing new Fishing Harbor's and Fish Landing Centre's across the country. Also, GOI takes initiatives to improve post-harvest infrastructure facility. To support small and marginal farmers GOI providing transportation facilities including motorcycles/bicycles with ice box, auto rickshaws, refrigerated and insulated trucks and live fish vending centers (https://pib.

gov.in). Inadequate cold chain infrastructure and poor post-harvest facilities hamper the marketability of aquaculture products. The absence of well-equipped processing and storage facilities leads to significant post-harvest losses and a lack of value addition, limiting the profitability of fish farmers. Furthermore, the absence of a robust regulatory framework and institutional support for aquaculture development further compounds the challenges. Limited access to credit, insurance, and technical assistance hampers the growth and expansion of the sector, particularly for small-scale farmers who form a significant portion of the aquaculture community (Figure 1).

Addressing these challenges requires concerted efforts from the government, private sector, and research institutions. Investments in infrastructure development, including the construction of modern hatcheries, well-designed ponds, and water management systems, are crucial. Promoting research and development to develop and disseminate appropriate aquaculture technologies tailored to local conditions can boost productivity and sustainability. Additionally, capacity building initiatives and knowledge transfer programs need to be implemented to educate fish farmers on modern farming practices and the efficient use of resources. Encouraging public-private partnerships, facilitating access to credit and insurance, and establishing market linkages can also enhance the viability of aquaculture ventures and attract more investment in the sector. By addressing the infrastructure and technology gaps in aquaculture, India can unlock its immense potential and contribute to meeting the growing demand for seafood, both domestically and internationally. This would not only enhance food security and rural livelihoods but also promote sustainable economic growth in the country.

Regulatory framework and governance: The aquaculture sector in India is governed by various agencies at the central and state levels, leading to a complex regulatory framework such as coastal aquaculture authority (CAA). Inconsistent policies, bureaucratic hurdles, and a lack of coordination between different agencies can hinder the growth of the sector (Farrington et al. 2014). Streamlining regulations, providing clarity on licensing and permits, and promoting transparency can improve the investment climate and facilitate the development of aquaculture.

Sustainability and environmental impact: Aquaculture can have environmental implications, such as habitat degradation, water pollution, and escape of farmed fish into natural ecosystems (Holmer 2010). Ensuring sustainable practices, such as proper waste management, minimizing the use of antibiotics and chemicals, and reducing the ecological footprint of aquaculture operations, is necessary to mitigate these environmental impacts and maintain the long-term viability of the sector. The use of antibiotics in Aquaculture is strictly prohibited as their use may result in development of pathogens resistant to such drugs and the transfer of these pathogens into human body. To maintain market access for Indian shrimp exports, as many importing countries have strict regulations on antibiotic levels in seafood products, CAA released the list of banned chemicals and regulation in coastal aquaculture. CAA, MPEDA, and FSSAI have banned certain antimicrobials to regulate antibiotic use in Indian aquaculture, but antibiotic resistance remains a huge concern for scientific community. Addressing these challenges requires a multi-stakeholder approach involving the government, aquaculture industry, research institutions, and local communities. By implementing sustainable practices, investing in infrastructure and technology, and improving regulatory frameworks, Indian aquaculture can overcome these challenges and achieve its potential as a significant contributor to food security and economic growth.

Socio-economic issues and livelihoods

It is crucial to examine the socio-economic issues and livelihoods associated with aquaculture to ensure its sustainable development. One key socio-economic issue in aquaculture is the unequal distribution of benefits (Krause et al. 2015). Large-scale aquaculture operations often dominate the industry, leading to the concentration of wealth and power in the hands of a few major players. This can marginalize small-scale fish farmers and coastal communities, who may struggle to compete in the market or face limited access to resources and support. Addressing this imbalance is essential to promote inclusive growth and reduce inequalities.

Another challenge is the environmental impact of aquaculture practices. Unsustainable farming methods, such as the excessive use of antibiotics, inadequate waste management, and habitat destruction, can degrade water quality, harm wild fish populations, and damage coastal ecosystems. Balancing the economic

benefits of aquaculture with environmental stewardship is crucial to ensure the long-term viability of the industry and protecting natural resources. The livelihoods of aquaculture workers and communities are influenced by various factors (Manlosa et al. 2021). In some cases, aquaculture provides employment opportunities and income diversification, particularly in rural and coastal areas where alternative livelihood options may be limited. However, decent working conditions, fair wages, and social protection measures must be ensured to prevent exploitation and improve the well-being of workers. Access to credit, technical knowledge, and markets also plays a vital role in shaping the livelihoods of aquaculture practitioners. Limited access to capital and information can hinder the growth and productivity of small-scale farmers, impeding their ability to invest in better technologies or expand their operations (Figure 1). Strengthening support mechanisms, such as training programs, cooperative networks, and market linkages, can enhance the capacity of fish farmers and enable them to participate more effectively in the aquaculture value chain.

While aquaculture holds immense potential for meeting global food demands and reducing pressure on wild fisheries, it is essential to address the socio-economic challenges associated with the industry. By promoting inclusive growth, environmental sustainability, and improved livelihoods, aquaculture can contribute to the well-being of communities, alleviate poverty, and ensure the long-term viability of this important sector. By fostering sustainable production practices can serve as an essential economic lifeline in areas without other dependable revenue streams, apart from fishing and associated businesses. Sustainable aquaculture mitigates poverty by generating job opportunities and bolstering local economies, while concurrently guaranteeing the enduring sustainability of aquatic resources and livelihoods (SDG 1: No Poverty) (Troell et al. 2023) and enhance food security (SDG 2: Zero Hunger) by providing a reliable source of nutrition and employment (Meharoof et al. 2023). Furthermore, sustainable aquaculture methods minimize environmental impact (SDG 14: Life Below Water), ensuring the long-term viability of aquatic ecosystems and reducing biodiversity loss (Moretti et al. 2024). Additionally, responsible aquaculture development supports gender inclusivity (SDG 5: Gender Equality) by creating diverse employment opportunities, particularly in rural and coastal communities (Misk et al. 2021). Investing in innovation, governance, and resource-efficient techniques will ensure the resilience of this sector, contributing to a more sustainable management of natural resources (SDG 12: Responsible Consumption and Production).

Market access and trade barriers

Market access and trade barriers in aquaculture in India have been subjects of concern for the industry (Chakraborty 2009). While India boasts a vast coastline and abundant water resources, it faces several challenges in realizing its full potential in aquaculture trade (Le and Chen 2020). One of the primary obstacles is the existence of trade barriers, both domestic and international. Domestically, the aquaculture industry in India grapples with regulatory complexities and bureaucratic hurdles. Inconsistent and fragmented policies across different states create an uneven playing field, hindering market access and inhibiting the growth of the sector. Inadequate infrastructure, such as poor transportation and storage facilities, further exacerbate the challenges faced by aquaculture producers in reaching the market efficiently. Internationally, Indian aquaculture products encounter various trade barriers, including tariffs, non-tariff measures, and sanitary and phytosanitary requirements. In India, fish marketing is mostly executed via traditional fish markets, retail establishments, and internet channels. Fish Farmer Producer Organisation (FFPO) is integral to India's fish marketing strategy, facilitating small-scale fish farmers in collectively aggregating their produce, negotiating superior prices with buyers, accessing broader markets, and attaining economies of scale, thereby enhancing income for fish producers by diminishing dependence on intermediaries and bolstering their bargaining power (Mondal et al. 2024). Department of Fisheries under the Ministry of Fisheries, Animal Husbandry and Dairying initiated "fishery e-platform" {National Fisheries Digital Platform (NFDP)} intended to digitize the Indian fishing industry by linking fishermen, fish producers, and purchasers via an online marketplace. Nowadays, fishery-based e-commerce platforms like Odaku, BitNut Technologies, Manjha etc. have emerged in India, aiming to reach a broader audience and enhance accessibility to aquatic products (Dhenuvakonda and Sharma 2020). The India's first application dedicated to the fisheries and aquaculture was the AquaBrahma launched in 2015 provides real time market data, expert advice and dynamic trading platform at competitive prices. ICAR-CIFA developed Matsya Setu app aims to disseminate the latest freshwater aquaculture technologies/schemes and market place to aqua farmers of the country.

Aqua Exchange, Sagar Vani etc., were designed to provide ease solutions for fish farmers of the country. High import duties imposed by some countries limit the competitiveness of Indian aquaculture products in global markets. Additionally, non-tariff barriers like stringent quality standards and certification processes pose challenges for exporters, especially small-scale producers who often lack the necessary resources and expertise to comply with these requirements.

To address these issues, the Indian government has recognized the importance of promoting market access for aquaculture products. Efforts are being made to streamline regulatory frameworks, harmonize policies across states, and enhance infrastructure development to facilitate efficient trade. Bilateral and multilateral negotiations are also underway to reduce trade barriers and create favorable conditions for Indian aquaculture exports (Madan and Shyam 2012). Moreover, the government is actively working on capacity building initiatives to improve the quality and safety standards of Indian aquaculture products, ensuring compliance with international norms. These efforts aim to enhance the competitiveness of Indian aquaculture in the global market and foster sustainable growth of the sector. As aquaculture in India holds significant potential, market access and trade barriers pose challenges to its growth and development (Madan and Shyam 2012). Addressing these issues requires a comprehensive approach, encompassing regulatory reforms, infrastructure development, and capacity building initiatives. By creating an enabling environment for the aquaculture industry, India can unlock its full potential and emerge as a key player in the global aquaculture trade.

Opportunities for future growth

Technological advancements and innovation

Recirculating Aquaculture Systems (RAS): RAS technology allows for intensive fish farming in controlled environments, reducing water usage and environmental impacts. India has seen the adoption of RAS for high-value species like shrimp and fish. These closed-loop systems monitor water quality, temperature, and feeding to optimize production (Das et al. 2022).

Biofloc Technology: The biofloc technology (BFT) system is a very effective technology that may address the environmental and economic issues encountered in conventional aquaculture production systems. This revolutionary aquaculture method is considered very ecofriendly since it relies on the activity of microorganisms to function (Dekari et al. 2024a).

Aquaponics: Aquaponics is a method of combining fish farming with hydroponic crop cultivation, where the nutrient-rich water from the fish tanks is circulated to fertilize the plants. The efficiency of nutrient conversion for plants depends on the presence and optimal functioning of microorganisms.

IMTA: IMTA involves the cultivation of multiple species in close proximity, utilizing waste and by-products from one species as nutrients for another (Nardelli et al. 2019). By combining fish, shellfish, and seaweed, IMTA systems create symbiotic relationships and reduce environmental impacts. India has explored IMTA systems, especially in coastal areas, to maximize resource utilization and minimize pollution (Choudhary et al. 2025c).

Genetic Improvement: Selective breeding and genetic improvement programs have been implemented to enhance the growth rate, disease resistance, and other desirable traits of farmed fish and shrimp. These efforts aim to develop improved strains that are well-suited to local conditions, leading to increased productivity.

Automated Feeding and Monitoring: Automation and sensor technologies are being deployed in aquaculture operations to optimize feeding and monitoring. Automatic feeders dispense feed at precise intervals, reducing labor requirements and improving feed efficiency. Monitoring systems measure water quality parameters, detect diseases, and enable real-time adjustments, enhancing production control (Antonucci and Costa 2020).

Data analytics and decision support systems: Digital technologies and data analytics are increasingly used to collect, analyze, and interpret large amounts of data from aquaculture operations. This helps farmers make informed decisions about feeding, stocking density, water quality management, and disease prevention (Prapti et al. 2022). Such decision support systems improve productivity and profitability. The integration of information technology and data analytics has revolutionized aquaculture practices in In-

dia. Farmers are now able to collect and analyze real-time data on various parameters, including feeding patterns, growth rates, and environmental conditions. This data-driven approach enables them to make informed decisions regarding feed management, disease prevention, and production optimization (O'Donncha and Grant 2019). Additionally, remote sensing and satellite imaging technologies are being utilized to monitor and manage aquaculture operations over large areas, ensuring efficient resource allocation and environmental sustainability.

Value addition and processing: Efforts are being made to enhance the value of aquaculture products through processing and value addition (Katiha et al. 2005). This includes activities like filleting, freezing, packaging, and development of ready-to-cook products. Advanced processing technologies help maintain product quality and extend shelf life, facilitating market access and diversification.

Sustainable Aquafeed: Research is ongoing to develop sustainable and cost-effective aquafeed options (Chauton et al. 2015). This includes exploring alternative protein sources, such as insect meal and plant-based ingredients, reducing reliance on fishmeal and fish oil. Sustainable feed formulations help improve the efficiency and sustainability of aquaculture operations.

Public-private partnerships and entrepreneurship: The Indian government, along with private sector participation, has initiated several programs and schemes to support aquaculture innovation and entrepreneurship. This includes financial assistance, technical training, and incubation centers to foster technology adoption and startups in the aquaculture sector.

These technological advancements and innovation in aquaculture have the potential to increase productivity, improve environmental sustainability, and contribute to the growth of India's aquaculture industry. Continued research, development, and collaboration between various stakeholders will further drive the progress in this sector.

Diversification of species and culture systems

India's aquaculture sector has primarily focused on a few species such as carp, shrimp, and catfish (Singh 2014). Diversifying the range of species cultivated can open up new market opportunities, reduce risks associated with disease outbreaks, and cater to the preferences of different consumer segments. For example, introducing high-value species like seabass, tilapia, or certain shellfish species can boost profitability and meet the demand for premium seafood products. India has a rich diversity of indigenous fish species that have not been widely cultivated. Promoting the culture of indigenous species can help conserve biodiversity, preserve traditional knowledge, and offer unique products to domestic and international markets. These species are often well-suited to local environmental conditions and require less intensive management practices, making them suitable for small-scale farmers. Diversification in cultural practices can be achieved by adopting advanced novel aquacultural practices with their sustainable approach with embracing technological advancements such as remote sensing, satellite imagery, big data analytics, and artificial intelligence can facilitate better monitoring, management, and decision-making in aquaculture Rowan 2023; Choudhary et al. 2025b). These tools can help optimize feed management, disease control, and environmental sustainability. Additionally, the adoption of biotechnological interventions like selective breeding, genetic improvement, and disease-resistant strains can enhance the productivity and profitability of aquaculture systems.

Overall, diversification of species and culture systems in aquaculture, combined with technological advancements and capacity building, can augment the growth of the sector in India (Jayasankar 2018; Metian et al. 2020; Kim et al. 2022). By tapping into the vast potential of indigenous species, implementing innovative production systems, and leveraging advancements in aquaculture technology, India can expand its aquaculture sector, meet increasing seafood demand, generate employment opportunities, and contribute to food security and economic development. The primary concerns of many indigenous species are the slow growth rates, which makes them less competitive than commercially farmed fish species having wider market acceptance and the higher growth rates (Mohanta et al. 2008). However, technical difficulties further complicate indigenous fish farming, including the lack of hatcheries and suitable feed formulations. Unlike exotic species, indigenous fish do not have well-developed selective breeding programs or readily available commercial feeds, leading to lower productivity till date. According to Sarkar and Lakra (2010), the culture, species diversification, up-scaling of breeding practices for the available indigenous fish species is needed to be done with proper enforcement of the laws to protect the natural habitats with public awareness for

wise management (Figure 1).

Value addition and processing

Value addition and processing of fish play a crucial role in the future expansion of aquaculture. As the demand for seafood continues to rise globally, it is essential to enhance the value of fish products and improve their marketability. By implementing value addition and processing techniques, aquaculture can meet the diverse needs of consumers, increase profitability, and contribute to sustainable development. Value addition refers to the process of enhancing the quality, appearance, and value of fish products through various methods. One of the key aspects of value addition is product diversification. Aquaculture farms can focus not only on producing whole fish but also on developing a range of processed products such as fillets, steaks, smoked fish, canned fish, fish sausages, and fish-based ready-to-eat meals. This diversification allows for a wider consumer base and enables the utilization of different parts of the fish, reducing waste and maximizing profitability.

Processing techniques in fish production involve activities such as cleaning, gutting, scaling, filleting, freezing, and packaging. These processes help improve the shelf life and quality of fish products, ensuring they reach consumers in optimal condition. Proper handling and processing techniques also minimize post-harvest losses, which are significant challenges in aquaculture. Value addition and processing also enable the development of value-added products, such as fish-based extracts, protein concentrates, fish oils, and fish meal. These products have various applications in the food, pharmaceutical, and cosmetic industries. By utilizing fish waste and by-products, aquaculture farms can minimize waste generation and maximize the utilization of available resources (Stevens et al. 2018). Moreover, value addition and processing create employment opportunities and support rural and coastal communities. Processing plants, cold storage facilities, and packaging units require skilled labor, providing job opportunities for local communities and contributing to economic growth.

To expand aquaculture in the future, it is crucial to invest in infrastructure, technology, and research and development in value addition and processing. This includes the establishment of modern processing facilities equipped with advanced machinery and quality control systems. Research and development efforts should focus on developing innovative and sustainable processing methods, improving product quality, and ensuring food safety standards are met. In conclusion, value addition and processing of fish are vital for the future expansion of aquaculture. By diversifying fish products, implementing efficient processing techniques, and developing value-added products, aquaculture can meet the growing demand for seafood, increase profitability, minimize waste, create employment opportunities, and contribute to sustainable development in the industry.

Export potential and market development

One of the major factors driving the export potential of Indian aquaculture is its diverse range of high-quality seafood products. The country produces a wide variety of fish and shrimp species, including rohu, catla, tilapia, vannamei shrimp, and black tiger shrimp, which are highly sought after in international markets. Additionally, Indian aquaculture has implemented best practices in terms of quality control, disease management, and sustainable farming techniques, ensuring that the exported seafood meets international standards and regulations. The Indian government has played a pivotal role in supporting the growth of the aquaculture industry. Initiatives such as the Blue Revolution and the National Fisheries Development Board have provided financial assistance, technical expertise, and infrastructure development to aquaculture farmers and entrepreneurs. These efforts have not only boosted production but have also encouraged the adoption of modern technologies and sustainable practices, further enhancing the export potential of Indian aquaculture (Figure 1).

In recent years, India has witnessed a surge in demand for seafood both domestically and globally. As a result, the market for Indian aquaculture products has expanded significantly. The country's strategic location provides easy access to major international markets, and with the improvement of logistics and transportation infrastructure, Indian aquaculture products can be efficiently delivered to customers worldwide. Furthermore, India has been successful in building strong trade relationships and securing lucrative

contracts with countries such as the United States, European Union, Japan, and the Middle East, thereby opening up new avenues for market development. To fully exploit the export potential and further develop the market for aquaculture in India, continuous investments in research and development, infrastructure, and marketing strategies are crucial. Efforts should be directed towards improving the quality and productivity of aquaculture farms, promoting sustainable practices, and enhancing the traceability and certification processes. Trade barriers in the global aquaculture market often include strict regulatory standards, tariffs, market access restrictions, and compliance with sustainability certifications. These challenges can limit the ability of producers to compete internationally. However, collaborations between government agencies, industry stakeholders, and research institutions can help overcome these barriers by fostering technological innovation, streamlining regulations, and improving compliance with international standards (Bradley et al. 2019). Additionally, investment in capacity-building programs, infrastructure, and sustainable practices can enhance market access and economic resilience (Wescott 2002). Strengthening trade policies and facilitating knowledge exchange will be key to improving global competitiveness in the aquaculture sector.

India's aquaculture industry holds significant export potential and offers ample opportunities for market development. With its diverse range of seafood products, government support, and growing demand, the country is well-positioned to expand its presence in international markets. By focusing on quality, sustainability, and innovation, India can establish itself as a key player in the global aquaculture sector, benefiting both the economy and the livelihoods of those involved in the industry.

Integration with other sectors (agriculture, tourism)

Integrating aquaculture with other sectors such as agriculture or tourism can indeed enhance profitability by creating synergies, diversifying income streams, and optimizing resource utilization. Here are some potential ways to integrate aquaculture with these sectors:

Agriculture-aquaculture integration: Integrated agriculture-aquaculture is becoming more and more important as a sustainable approach to maximize resource usage, improve food security, and slow the effects of climate change (Jana and Jana 2003). For small and marginal farms especially, IFS offers a method of diversifying risks, creating self-sufficient employment, and producing regular revenue. It guarantees sensible and sustainable use of the resources at hand. The farmers owing to adopt this system are holding high degree of nutritional and food security (Haobijam and Ghosh 2023). The predominant models favored in India, particularly effective in waterlogged conditions, include pond-dyke integration, as well as combinations of fish-rice-duck or poultry-vegetable, and fish-cow or pig-duck or poultry-vegetable systems. Implementing aquaponics systems where fish waste provides nutrients for growing crops, and the crops filter the water for the fish. This integrated approach can increase productivity and reduce inputs (Paramesh et al. 2019; Wei et al. 2023). Utilizing livestock manure as a feed source for fish or incorporating fish farming in livestock wastewater treatment systems (Paramesh et al. 2019). This integration can enhance nutrient recycling and reduce environmental pollution.

Tourism-aquaculture integration: Integrating aquaculture with local cuisine and promoting seafood-focused culinary experiences. This can attract tourists who are interested in unique dining experiences and contribute to the local economy by supporting local restaurants and producers. Some fisheries institutes within protected areas of developing countries as it efficiently closes the gap between the need for local economic growth and environmental preservation. Establishing sustainable aquaculture practices in environmentally sensitive areas, such as coral reef restoration projects or through ornamental fishery, mangrove restoration programs, sport fishery and fish-based eco-tourism, fish sanctuaries, can enhance tourism by offering visitors the opportunity to observe and learn about marine life conservation efforts (Pandey et al. 2023; Choudhary et al. 2024). Several researchers and state governments are now exploring the integration of fisheries with tourism as a means to develop innovative tourism experiences while also creating new revenue streams. This approach aims to enhance the profitability and sustainability of the fisheries sector (Baruah and Sarma, 2018; Dash and Balamurugan 2024). The prospect of development of eco-tourism centers holds great potential, particularly in the northeastern states, hilly regions, and coastal areas, which offer ideal locations for this initiative (Chand et al. 2015; Baruah 2018). Fishing tournaments have successfully engaged the local people in promoting eco-tourism in a concealed area of Arunachal Pradesh (Baruah and Sarma 2018).

Circular economy approach: The current linear economic model has resulted in growing waste generation and resource depletion, therefore creating major environmental and public health hazards. Another model known as the circular economy idea has become well-known in the worldwide business sector in order to go above these challenges. Implementing a circular economy model like integrated multi trophic aquaculture and the integration of aquaculture, agriculture, and tourism can create a self-sustaining system (Das et al. 2023). The output of fish waste and by-products increases with the growing population, presenting significant opportunities for a circular economy strategy. (Jasrotia et al. 2024). Circular bioresource efficiency, characterized by the intelligent and effective use of resources, reduces and repurposes waste, potentially resulting in stress-resilient fisheries and aquaculture (Lakra and Krishnani 2022). The incorporation of microalgal RAS into the biorefinery framework adheres to the tenets of a circular economy, fostering sustainable resource use and waste reduction (Méndez et al. 2022).

Renewable energy: Aquaculture facilities can be integrated with renewable energy production systems such as solar, wind, or tidal power (Behera et al. 2015). By locating aquaculture farms near renewable energy installations, the energy requirements of the aquaculture operations can be met sustainably. To augment the livelihood of fishing community and refine the quality of dried fish at Sagar Island, India walk-in solar thermal dryer was installed at a fishing cooperative it also alleviates the limitations of open sun drying (Andharia et al. 2021). Additionally, aquaculture infrastructure, such as floating platforms, can be designed to incorporate solar panels or wind turbines, contributing to clean energy generation. In India, the cumulative installed capacity of floating solar photovoltaic systems is 2.7 MW, with significant potential for expansion (Kumar and Majid 2023). Integrating these systems with aquaculture can enhance land and water resource utilization, offering a sustainable approach to energy generation while supporting fish farming activities. The country's achievement of the world's lowest investment cost for floating solar installations further strengthens the feasibility of this integration (Kumar and Majid 2023).

Waste Management: Aquaculture can be integrated with waste management systems to improve resource efficiency and minimize environmental impact (Nenciu et al. 2022). For example, organic waste from food processing industries can be used as feed or fertilizer for aquaculture operations, reducing waste disposal and providing a cost-effective source of nutrients. In return, the aquaculture system can help purify wastewater or treat effluents, mitigating pollution and enhancing water quality.

By integrating these sectors, we can optimize resource utilization, reduce waste, create new market opportunities, and enhance overall profitability. However, it's important to consider the specific conditions, regulations, and market demands of our location to ensure successful integration.

Sustainable aquaculture practices

Best management practices and standards

Best management practices (BMPs) in aquaculture play a crucial role in ensuring sustainable and responsible production of aquatic organisms (Kumar et al. 2018). These practices, coupled with stringent standards, help mitigate the environmental, social, and economic impacts associated with aquaculture operations. One key aspect of BMPs is site selection and design. Aquaculture facilities should be located in areas that have suitable water quality, appropriate hydrodynamic conditions, and minimal impacts on sensitive ecosystems. The design of the facility should incorporate measures to minimize effluent discharge and prevent the escape of farmed species into the wild.

Environmental impact mitigation

Some ways in which aquaculture can contribute to environmental sustainability:

Reduced habitat destruction: Wild fish populations often face habitat destruction due to activities like bottom trawling or dredging. Aquaculture reduces the need for such destructive practices, as fish can be raised in specially designed tanks, ponds, or offshore cages, minimizing impacts on natural habitats.

Water and land use efficiency: Compared to traditional livestock farming, aquaculture generally requires less land and water in comparison to cattles (Nijdam et al. 2012). Fish can be farmed in tanks or cages, utilizing available water resources more efficiently. Additionally, some aquaculture systems can utilize

wastewater from other industries, reducing the demand for freshwater inputs.

Waste management and nutrient recycling: Properly designed aquaculture systems can effectively manage waste and prevent its release into the environment. Waste generated by farmed fish can be collected, treated, and used as fertilizers in agriculture, reducing the need for synthetic fertilizers and preventing nutrient pollution in water bodies.

Carbon footprint reduction: Aquaculture can be more resource-efficient compared to traditional livestock farming. The study conducted by Dineshbabu et al. (2024) showed that emission from Indian fishing industry during 2023 were 1.52 kg CO_2e/kg of fish, which is 30% lower than corresponding global estimates. For example, raising fish requires less feed, land, and water per unit of protein produced compared to raising cattle or pigs (Nijdam et al. 2012). Fish retain around 30% of the protein in the consumed feed, whereas chicken and pork retain around 25% and 13%, respectively (Åsgård et al. 1999) By promoting the consumption of seafood from sustainable aquaculture practices, carbon emissions associated with food production can be reduced (Jiang et al. 2022b).

Restoration of ecosystems: Some forms of aquaculture, such as shellfish farming and seaweed cultivation, can contribute to ecosystem restoration efforts. Shellfish act as natural filters, improving water quality by removing excess nutrients. According to Kreeger et al. (2018), investing in bivalve populations can be considered an innovative BMP for enhancing water quality by effectively removing excess nutrients from the water column. A *Penaeus japonicus* (Bate) shrimp farm was stocked with plants and oyster (*Saccostrea commercialis*), to manage water quality by removing waste nutrients and serving as natural biofilters (Jones et al. 2002). Seaweed cultivation helps sequester carbon dioxide from the atmosphere and provides habitat for various marine species (Choudhary et al. 2024).

However, it is important to note that not all forms of aquaculture are environmentally sustainable. Poorly managed operations can lead to water pollution, disease outbreaks, and the escape of farmed fish, which can have negative impacts on local ecosystems. To ensure the environmental sustainability of aquaculture, it is essential to promote responsible farming practices, such as proper site selection, waste management, disease prevention, and regular monitoring of water quality. Regulatory frameworks and certifications, such as the Aquaculture Stewardship Council (ASC) and Best Aquaculture Practices (BAP), help establish and enforce these standards.

Recommendations for sustainable growth

In the Indian perspective, aquaculture holds immense potential for sustainable growth and can contribute significantly to the country's food security, economic development, and rural employment. However, to ensure the long-term sustainability of the aquaculture sector, certain recommendations need to be considered. First and foremost, it is crucial to promote responsible and environmentally friendly aquaculture practices. This includes adopting sustainable farming techniques such as IMTA, RAS, biofloc technology, polyculture, and integrated fish farming to enhance productivity while ensuring environmental and economic sustainability (Choudhary et al. 2025c). Implementing good water management practices, reducing the use of antibiotics and chemicals, and promoting organic feed options can also contribute to sustainable growth.

Improving the infrastructure and providing better access to technology and knowledge is another key recommendation. Developing robust hatchery systems and promoting the production of high-quality seeds will enhance production efficiency and reduce dependence on wild-caught seeds. Encouraging research and development in areas like disease management, feed formulation, and breeding programs can further optimize production processes. Strengthening the regulatory framework is essential to ensure sustainable growth. The government should establish stringent regulations and guidelines to monitor and control the sector's operations, addressing issues like water pollution, disease outbreaks, and overuse of resources. Promoting certification and eco-labeling schemes can help consumers identify and choose sustainably produced aquaculture products.

Investing in capacity building and training programs for farmers and stakeholders are vital. Providing technical assistance, educating farmers about best practices, and facilitating knowledge sharing platforms can enhance the skills and knowledge required for sustainable aquaculture. Additionally, supporting entrepreneurship and providing financial assistance to small-scale farmers can encourage their active participation in the sector. Collaboration and partnerships between various stakeholders, including government

agencies, research institutions, NGOs, and industry players, are crucial for the sustainable growth of aquaculture. These partnerships can foster information exchange, promote innovation, and facilitate the implementation of best practices. To enhance fish production in India, it is essential to establish demonstration sites for novel technologies such as IMTA, RAS, Biofloc, and other integrated fish farming practices at a commercial scale. These sites will serve as practical models, showcasing the managerial, economic and environmental viability of these systems while providing stakeholders with the necessary technical know-how for successful implementation. Lastly, creating market opportunities and promoting sustainable consumption of aquaculture products is essential. Developing domestic and international markets, promoting value addition and branding of Indian aquaculture products, and raising awareness among consumers about the benefits of sustainable aquaculture can drive demand and ensure economic viability. By implementing these recommendations, India can achieve sustainable growth in its aquaculture sector, while safeguarding the environment, improving livelihoods, and meeting the growing demand for nutritious seafood.

Future research directions

As we look into the future, several research directions can significantly contribute to the sustainable expansion of aquaculture in India. There is a need to focus on the development of improved aquaculture systems and technologies. Research should aim to enhance the efficiency of production methods, such as recirculating aquaculture systems (RAS) and integrated multitrophic aquaculture (IMTA). These innovative approaches can optimize resource utilization, reduce environmental impact, and increase overall productivity. The primary limitations of RAS and IMTA include the substantial investment required, high capital and operating costs, and extended payback periods (Badiola et al. 2012). Additionally, achieving a cost-effective and environmentally friendly solution remains challenging, particularly in managing accumulated sludge (mainly drum filter waste) and meeting oxygenation demands (Ende et al. 2024). To make sustainable RAS with value-added co-production a reality, continuous innovation in bio-based treatment strategies is essential, ensuring a balance between economic feasibility and environmental responsibility. A holistic approach to overcoming these challenges includes integrating renewable energy sources and utilizing cost-effective filtration technologies, such as microalgae-based treatment systems (Méndez et al. 2022; Zhang et al. 2024). Furthermore, securing cooperative investments can help alleviate financial burdens and enhance the viability of RAS.

The efforts should be directed towards the development of high-quality, disease-resistant aquatic species. Disease outbreaks pose a significant threat to aquaculture production, leading to substantial economic losses. The emergence of new hosts for viruses, parasites, and bacteria in Indian aquaculture is a growing concern, necessitating advancements in disease diagnosis and prevention for sustainable aquaculture (Dekari et al. 2024b). TiPV detection in tilapia including its eggs from Tamil Nadu by Badhusha et al. (2025) underscores the risk of vertical transmission. The first reports of bacterial diseases in freshwater fishes of the Andaman Islands with *Aeromonas veronii*, *Aeromonas sp.*, and *Pseudomonas alcaligenes* contribute to disease, affecting productivity (Praveenraj et al. 2024) and *Micrococcus luteus* infections in Nile tilapia in Andhra Pradesh (Suresh et al. 2025) necessitates proper disease surveillance and strategic mitigarion of disease. Arumugam et al. (2024) reported the first occurrence of *Paracapillaria philippinensis* (parasitic nematode) in flowerhorn cichlid (*Cichlasoma* sp.) from Chennai, India highlights the need for enhanced surveillance and biosecurity measures. Viral outbreaks, including lymphocystis disease virus in Asian seabass (Nair et al. 2024), infectious spleen and kidney necrosis virus (ISKNV) in *Etroplus maculatus* (Kushala et al. 2024) emphasize the importance of early detection and pathogen characterization. Additionally, *Ichthyophthirius multifiliis* infections causing mortality in ornamental fish (Banu et al. 2025) necessitate improved biosecurity and treatment strategies. Addressing these emerging challenges through rapid diagnostics, effective vaccination, and sustainable management practices will be critical for the future of Indian aquaculture.

Through advanced genetic selection techniques, such as selective breeding and genetic engineering, researchers can develop disease-resistant strains that are better suited to Indian environmental conditions. Sustainable feed development is critical for the growth of aquaculture. Currently, feed for farmed fish often relies heavily on wild-caught fishmeal and fish oil, contributing to overfishing and ecological imbalance. Research should focus on alternative protein sources, such as plant-based proteins and microbial biomass,

to reduce the dependence on marine resources. Additionally, optimizing feed formulations to improve digestibility and nutrient utilization can enhance growth rates and minimize environmental impacts. Harnessing the potential of emerging technologies can revolutionize aquaculture practices. Automation, artificial intelligence (AI), and the Internet of Things (IoT) can enable real-time monitoring, efficient resource management, and precise control over water quality parameters. Integrating these technologies into aquaculture operations can enhance production efficiency, reduce costs, and improve environmental sustainability (Das et al. 2022).

Finally, collaboration between researchers, industry stakeholders, and policymakers is crucial for the future growth of aquaculture in India. Research institutions, private enterprises, and government agencies should work together to facilitate knowledge transfer, support technology adoption, and establish favorable policies and regulations. This collaboration can drive innovation, create employment opportunities, and ensure sustainable development of the aquaculture sector.

Conclusion

In conclusion, aquaculture plays a crucial role in India's food security, economic development, poverty alleviation, and sustainable use of aquatic resources. It provides employment, income, and nutritional benefits to millions of people while promoting sustainable agriculture and contributing to the country's export earnings. The continued development and responsible management of aquaculture can help meet the growing demand for seafood, alleviate poverty, and support sustainable development in India. To support the growth of aquaculture, the government and private sector have collaborated to establish research and development institutes, training centers, and technology transfer initiatives. These platforms promote knowledge exchange, capacity building, and the dissemination of innovative techniques among farmers and industry stakeholders. Moreover, financial incentives, subsidies, and favorable policies have been introduced to encourage the adoption of advanced technologies, making them accessible to small-scale farmers and entrepreneurs. India has witnessed significant progress in aquaculture. The inland fisheries sector has shown remarkable expansion, with production rising from 7.5 lakh tons in 1950-51 to 139.07 lakh tons in 2023-24. Similarly, the marine fisheries sector has grown from 5.34 lakh tons in 1950-51 to 44.95 lakh tons in 2023-24. The future aquaculture targets for upscaling present initiatives to achieve >40 MT in 2047 under the Viksit Bharat@2047 plan by the GOI. This substantial growth highlights the sector's potential and underscores the need for sustainable management strategies to ensure long-term productivity and environmental balance in both marine and inland fisheries and emerged as one of the world's leading producers of fish and seafood. However, several challenges need to be addressed to ensure sustainable growth and maximize the potential of this sector. While aquaculture in India faces several challenges, including environmental sustainability and productivity enhancement, the industry holds tremendous opportunities for growth and development. By addressing these challenges head-on, adopting sustainable practices, and seizing emerging opportunities, India can harness the full potential of aquaculture and emerge as a global leader in the production of fish and seafood.

Another challenge lies in improving the productivity and efficiency of aquaculture operations. Enhancing feed efficiency, disease management, and genetic selection can significantly boost production levels while minimizing resource inputs. Additionally, the adoption of innovative technologies, such as recirculating aquaculture systems and automation, can help optimize production processes and reduce costs. Investing in research and development and promoting knowledge exchange among farmers are vital for enhancing productivity and competitiveness. By prioritizing sustainability, the aquaculture industry can mitigate its impact on ecosystems and ensure the long-term viability of fish production. The growing popularity of sustainable and organic aquaculture practices presents a niche market that can be tapped into for higher value-added products. To capitalize on these opportunities, it is crucial to invest in infrastructure development, including hatcheries, processing facilities, and cold chains. Improving market linkages and ensuring fair pricing mechanisms can also enable small-scale farmers to access lucrative markets and improve their livelihoods. However, in the fisheries sector in India, effective management proficiency is gained through experience, as technical or engineering expertise alone does not always guarantee success. Practical knowledge, adaptive strategies, and an understanding of ecological and socio-economic factors play crucial roles in sustainable fisheries management. Additionally, capacity building programs, training, and financial sup-

port for farmers can enhance their technical skills and empower them to adopt the best available practices.

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