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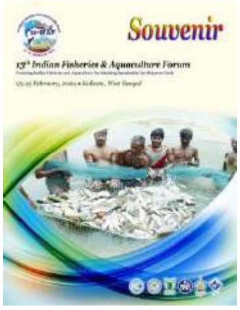

I3th Indian Fisheries and Aquaculture Forum: Fostering Indian Fisheries and Aquaculture for Attaining Sustainable Development Goals

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Edited by
B. K. Das
S. Samanta
Anjana Ekka
P. Mishal
Sangeetha M. Nair
Sajina A. M.
A. K. Das

Editorial Assistance
Shamik Ghosh

Cover Design
Sujit Chowdhury & Shamik Ghosh

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Dr. B. K. Das
President, Inland Fisheries Society of India (IFSI), Barrackpore & Director, ICAR- Central Inland Fisheries Research Institute, Barrackpore, Kolkata - 700120, India

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Sustainability in Mariculture through Innovative Farming Systems

Imelda Joseph and Shoji Joseph
ICAR-Central Marine Fisheries Research Institute, Post Box No.1603, Ernakulam North P.O., Kochi, Kerala
imeldajoseph@gmail.com

Introduction

The 2030 Agenda of UN General Assembly in 2015, encapsulating the 17 Sustainable Development Goals (SDGs), outlines a comprehensive framework for humanity's pursuit of a more prosperous, equitable, and sustainable future. Beyond addressing poverty, hunger, health, and nutrition, the agenda aspires to reduce inequalities and foster peaceful, just, and inclusive societies-all while respecting planetary boundaries. The Food and Agriculture Organization of the United Nations (FAO) projects a global population of 10 billion by 2050 and warns that existing food production systems and nutritional models are insufficient and unsustainable to meet this demand. With the projected global population, and a potential 88% increase in demand for animal proteins (Searchinger*et al*., 2018), there is a pressing need to confront the challenge of providing a healthy and sustainable diet for a growing population, often exceeding recommended consumption levels. To address these challenges, efforts are underway to promote sustainable culture practices, explore alternative protein sources, improve aquaculture sustainability, reduce food waste, invest in genetic improvements, embrace technological innovations, and implement supportive policies. Collaborative actions across governments, organizations, and individuals are essential to build a resilient and sustainable global food system capable of feeding the growing population while minimizing environmental impact.

Fish contributes to over 30% of global protein consumption, with half of this supply originating from aquaculture and mariculture, as highlighted by Costello *et al*. (2020). In 2020, farmed fish production encompassed 57.5 million tons for finfish, 17.7 million tons for molluscs, 11.2 million tons for crustaceans, 5,25,000 tonnes of aquatic invertebrates, and 5,37,000 tonnes of semi-aquatic species including turtles and frogs. The rapid growth of aquaculture, outpacing other major food production sectors, is attributed to the low feed conversion ratio of cultured species (1.1–1.6 kg of feed per kg of edible fish), surpassing ratios for livestock like pork (up to 4.4) or beef (up to 9) (FAO, 2022). Despite this efficiency, aquaculture faces sustainability challenges due to the carnivorous nature of many fish, necessitating diets rich in animal protein. To ensure future viability as a food source, the aquaculture industry must address food waste, promote sustainable practices, and encourage shifts toward healthier diets (Garcia-Oliveira *et al*., 2020). This transformation is crucial to mitigate the environmental impact of the expanding aquaculture sector, projected to persist or even intensify globally (FAO, 2022).

Sustainable aquaculture, irrespective of its scale, is characterized by its economic viability and environmental responsibility. Beyond these criteria, particularly in regions where aquaculture and fisheries hold cultural significance, it must also align with cultural values and not compromise access to vital resources for small-scale fishers and local communities. Examples of environmentally sustainable aquaculture practices include integrated multi-trophic aquaculture, seaweed aquaculture, shellfish aquaculture, and thoughtfully planned fish rearing employing an ecosystem-based approach. These methods emphasize minimizing environmental impact, optimizing resource utilization, and fostering harmony with the cultural and social fabric of the communities involved. In essence, the pursuit of sustainability in aquaculture involves a holistic approach that balances economic, environmental, and socio-cultural considerations for the long-term benefit of both ecosystems and communities.

The diverse nature of the aquaculture sector, spanning various species, production systems, and scales, holds the potential for multifaceted contributions to the Sustainable Development Goals (SDGs). Through the cultivation of different aquatic species and utilization of varied production systems, aquaculture can offer a range of nutritional, economic, and environmental benefits. Methodologies such as Life Cycle Assessments, economic evaluations, and social impact assessments help identify and measure these contributions, ensuring a comprehensive understanding of aquaculture's role in achieving SDGs. However, trade-offs exist, requiring a delicate balance between economic gains, environmental sustainability, and social equity. Effective policies and strategies are crucial to harness the sector's diversity for positive contributions to SDGs, addressing challenges while maximizing its potential to support a sustainable and equitable future.

Sustainable Aquaculture

Sustainability is the capacity of human activities to persist in time while maintaining a healthy environment. It is further defined as "Use of the environment and resources that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland definition). Sustainable biological systems are characterized as diverse, adaptable, resilient, and productive over time. Sustainable aquaculture entails social, economic and environmental sustainability.

Sustainable farming systems

Aquaculture plays a pivotal role in meeting the global demand for animal protein, but ensuring its long-term viability necessitates a transition to sustainability.

Cage fish farming

Cage fish farming, is a method of rearing fish in floating or submerged cages within natural water bodies, such as lakes, rivers, or in sea. This farming technique is widely employed for various species, including salmon, tilapia, and sea bass. The cages are typically constructed with netting or mesh materials, allowing water to flow freely through them while confining the fish within a designated area. Cage fish farming offers several advantages, including efficient space utilization, reduced environmental impact, ease of management and operation, and the potential for high stocking densities and therefore high production. However, challenges associated with cage farming include concerns about water quality, disease management, and the escape of farmed fish, which can impact wild populations. The industry continually explores technological innovations and best management practices to address these challenges and enhance the sustainability of cage fish farming, contributing to the global supply of seafood.

Advantages of cage fish culture

- Productive utilization of water resources
- Diverse species for farming
- Low initial investment is required in an existing body of water.
- Harvesting is simple
- Monitoring of fish is simple
- Management is easier
- Less labour intensive
- Product quality is assured
- Alternate employment and income

Environmental concerns in cage farms

Outputs from cage farms released to the ambient water and,

- Cause eutrophication
- Spread disease in the wild
- Increase BOD, COD
- Increase TAN, TN, TP levels
- Increase sedimentation (TSS), and
- Emission of GHGs

Cage fish farming operations can enhance their overall sustainability, balancing economic viability with environmental and social responsibility by focusing on several key aspects as given below:

Quality Seed*:* Utilizing high-quality seed, preferably produced in hatcheries, is essential for ensuring the health, disease resistance, and overall robustness of the fish stock. Selecting species that are well-suited to the local environment and have desirable market value is crucial for the economic sustainability of the operation.

Good Water Quality: Maintaining optimal water quality is fundamental for the well-being of farmed fish. This involves minimizing waste output, ensuring good water flow within the cages, and preventing pollution. Regular monitoring and management of water parameters contribute to a healthy aquatic environment, reducing the risk of disease outbreaks and promoting sustainable production.

High-Quality Feed: Providing nutritionally complete and cost-effective feed is a key factor in sustainable cage fish farming. Focus on achieving a low Feed Conversion Ratio (FCR), which indicates efficient conversion of feed into fish biomass, and minimizing feed wastage. Additionally, exploring alternatives and substitutions for fish meal and fish oil in the feed, such as plant-based proteins and sustainable sources, supports environmental sustainability and reduces reliance on marine resources.

Fish Meal/Fish Oil Substitution: In the context of achieving a high-protein diet for farmed fish, the sustainable substitution of fish meal and fish oil is crucial. Identifying alternative protein and lipid sources that are both nutritionally adequate and environmentally friendly helps reduce the reliance on wild-caught fish for feed, contributing to the overall sustainability of the aquaculture operation.

Ensuring the sustainability of cage fish farming involves a series of strategic practices and considerations.

a) ***Appropriate Site Selection***: Carefully choose cage installation sites based on environmental conditions and suitability to minimize negative impacts on surrounding ecosystems.

b) ***Adherence to Carrying Capacity***: Install cages in accordance with the carrying capacity of the water resources, preventing overloading and maintaining ecological balance.

c) ***Optimal Stocking Levels***: Stock cages with fish at levels that align with the carrying capacity of the system, ensuring optimum production without exceeding environmental limits.

d) ***Nutritionally Complete Feed***: Provide fish with nutritionally complete and quality feed to minimize waste and control the release of unutilized nutrients, promoting both economic efficiency and environmental sustainability.

e) ***Avoidance of Antibiotics and Drugs***: Minimize the use of antibiotics and drugs to promote fish health, and explore alternative disease prevention and control methods to reduce environmental impact.

f) ***Multi-Species Stocking***: Introduce compatible multi-species in cages, fostering ecological balance and reducing the risk of disease and pest outbreaks.

g) ***Escape Prevention***: Implement measures to prevent fish escape from cage farms, avoiding potential negative impacts on local ecosystems and biodiversity.

h) ***Preference for Local Species***: Prioritize farming species of local importance to prevent adverse effects on biodiversity in case of escape and promote the sustainability of local ecosystems.

i) ***Avoidance of Genetically Manipulated and Exotic Species***: Refrain from farming genetically manipulated species and exotic species in cages to prevent unintended consequences on local biodiversity and ecosystems.

j) ***Protection of Natural Fish Habitats***: Avoid cage installation in areas with natural fish habitats to protect and preserve the diversity of these environments.

k) ***Promotion of Product Certification***: Encourage and participate in product certification programs to inform consumers about the sustainability practices employed in cage fish farming operations.

By implementing these practices, cage fish farmers can contribute to the long-term sustainability of their operations, minimizing environmental impact, promoting ecosystem health, and meeting the increasing demand for responsibly sourced seafood.

Integrated multi-trophic aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) stands out as a pioneering and sustainable approach to aquaculture, emulating the intricacies of natural ecosystems by cultivating diverse species from varying trophic levels within a shared aquatic environment. At its core, IMTA orchestrates symbiotic relationships among species, strategically combining carnivorous fish, primary-producing seaweeds, and filter-feeding bivalves. The system's ingenuity lies in harnessing nutrient cycling, where waste from one species becomes nourishment for another. Fish waste, for example, becomes nutrients for seaweed and bivalves, fostering a balanced and eco-friendly environment. IMTA not only minimizes the ecological footprint of aquaculture, enhancing environmental sustainability, but also optimizes resource usage, boosting economic efficiency.

In IMTA, fed species coexist with extractive species that capitalize on inorganic and organic wastes, transforming them into valuable resources like fertilizer, food, and energy for other crops. This cyclical approach not only recaptures otherwise lost nutrients but also facilitates bio mitigation by removing carbon dioxide and partially extracting nutrients, simultaneously producing oxygen. The extractive component of IMTA serves a dual purpose, generating versatile biomass and rendering waste reduction services. Importantly, every farmed component within IMTA holds commercial value, contributing to both economic viability and environmental stewardship. The intricate mix of organisms across different trophic levels in IMTA mirrors the resilience and functionality of natural ecosystems, presenting a transformative model for sustainable and responsible aquaculture practices.

IMTA systems can be implemented in various aquatic environments, including coastal areas and open water, and they are regarded as a promising solution to address some of the environmental challenges associated with traditional monoculture practices. As the aquaculture industry continues to seek more sustainable practices, IMTA represents a forward-looking approach that aligns with principles of ecological balance and resource efficiency. IMTA is a solution to eutrophication caused by fed aquaculture by extraction and conversion of the excess nutrients and energy into other commercial crops. It is an innovative solution promoted for environmental sustainability, economic stability and societal acceptability.

The by-products and wastes generated by aquaculture operations can be repurposed through circular economy principles, contributing to sustainability and economic throughput. These waste streams can find new life as ingredients in food, cosmetics, or pharmaceuticals, aligning with the circular concept of converting waste into valuable resources. By adopting such circular practices, the aquaculture industry can not only meet protein demands but also contribute to a more sustainable and economically efficient model for the future.

Offshore Cage farming

Offshore cage farming aims to minimize environmental impacts on coastal ecosystems, reduce interactions with wild marine species, and alleviate concerns related to coastal water quality.

Key Considerations for Offshore Mariculture Development:

Disease and Parasite Mitigation: Offshore locations have the potential to reduce the risk of diseases and parasites affecting farmed species. The greater water depth and distance from coastal areas can minimize the transfer of pathogens from wild to farmed populations.

Algal Bloom Avoidance: Offshore locations may experience fewer issues related to algal blooms, which can be a concern in inshore areas. The increased water exchange and distance from nutrient-rich coastal zones can contribute to a more stable and controlled environment.

User Conflicts: Moving mariculture offshore can mitigate conflicts with other coastal users, such as recreational activities or shipping lanes. This may lead to improved social acceptance and reduced regulatory challenges.

Seaweed and Bivalve Profitability: Seaweed and bivalve cultivation can be particularly suitable for offshore development. These organisms do not require feeding, relying on nutrients available in the water column, and operational costs can be lower compared to fed species.

Challenges and Considerations:

Infrastructure and Technology: Developing infrastructure and technology capable of withstanding the challenges of offshore conditions, including strong currents and waves, is crucial for the success of offshore mariculture.

Monitoring and Management: Remote offshore locations pose challenges for monitoring and managing mariculture operations. Advanced technologies for real-time monitoring and adaptive management strategies are essential.

Regulatory Frameworks: The development of appropriate regulatory frameworks is critical to govern offshore mariculture and address environmental, economic, and social considerations.

Environmental Impact: While offshore mariculture can potentially reduce impacts on inshore ecosystems, it is essential to carefully assess and mitigate any potential environmental consequences, such as nutrient discharge and interactions with open ocean biodiversity.The shift toward offshore mariculture development aligns with the goal of expanding the aquaculture industry while addressing environmental and sustainability concerns. Careful planning, technological innovation, and collaboration among stakeholders are essential to navigate the complexities of offshore aquaculture and ensure its long-term success.

Precision Fish Farming (PFF)

Precision Fish Farming (PFF) represents a recent and innovative framework in fish farming that has evolved from the concept of Precision Livestock Farming (PLF). This approach, as outlined by Norton and Berckmans in 2018, leverages advanced hardware such as sensors, observers, and intelligent software to enhance various aspects of fish culture. The primary goals of Precision Fish Farming include improving animal health and welfare, increasing overall productivity, enhancing yield, and promoting environmental sustainability within aquaculture operations.

Key Components and Objectives of Precision Fish Farming (PFF):

Sensor Technology: PFF integrates sensor technologies that monitor and collect data on various parameters such as water quality, feeding behavior, and fish health. These sensors provide real-time information, allowing for prompt and informed decision-making.

Intelligent Software: Advanced software solutions analyze the data collected by sensors, enabling farmers to make precise adjustments in fish farming practices. This includes optimizing feeding regimes, health management strategies, and environmental conditions within the farming system.

Animal Health and Welfare: PFF emphasizes the improvement of animal health and welfare through proactive monitoring. Early detection of diseases, anomalies, or stressors allows for timely interventions, reducing the need for antibiotics and mitigating health challenges.

Productivity and Yield Optimization: By fine-tuning various parameters based on real-time data, PFF aims to enhance overall productivity and yield. This includes optimizing feeding strategies, growth rates, and resource utilization, leading to more efficient and sustainable fish farming operations.

Environmental Sustainability: PFF contributes to environmental sustainability by minimizing resource wastage and reducing the environmental impact of fish farming. Precise control over feeding, water quality, and waste management helps minimize the ecological footprint of aquaculture operations.

Challenges and Considerations in PFF

Technological Adoption: The successful implementation of PFF relies on the widespread adoption of advanced technologies, which may pose challenges for some farmers in terms of investment, training, and infrastructure.

Data Security**:** Handling and managing the vast amount of data generated by PFF systems raise concerns related to data security and privacy. Robust measures must be in place to safeguard sensitive information.

Integration with Traditional Knowledge**:** Integrating PFF with traditional knowledge and practices in fish farming is crucial to ensure that technological advancements complement existing expertise and contribute to sustainable and culturally appropriate aquaculture practices.Precision Fish Farming holds promise as a forward-thinking and sustainable framework, offering the aquaculture industry opportunities to enhance efficiency, reduce environmental impact, and prioritize animal welfare through the integration of cutting-edge technologies and data-driven decision-making.

Circular aquaculture

Circular aquaculture represents a transformative approach to fish farming, embodying principles of sustainability and waste reduction. Unlike traditional linear production systems, circular aquaculture aims to create closed-loop cycles, repurposing waste products as valuable inputs. This innovative model integrates multiple species and components, such as algae or bivalves, to create balanced ecosystems within aquaculture operations. By emphasizing water recycling, minimizing environmental impact, and promoting responsible resource use, circular aquaculture addresses challenges associated with conventional fish farming. This shift towards a holistic and regenerative model aligns with environmental and conservation goals, highlighting the industry's dedication to sustainable practices for long-term viability. The application of circular economy principles in aquaculture further enhances sustainability by optimizing resource use, transforming waste into valuable products like food, feed, bio-based materials, and bioenergy. Circular business models offer the potential to significantly reduce waste, enhance efficiency, and contribute to a more sustainable and resource-efficient future for aquaculture. It is imperative for the industry to lead in adopting circular approaches, guided by regulators and informed by research and innovation, with indicators and reporting methods playing a crucial role in mainstreaming circularity practices into industry norms and policies.

a) **Innovative application of aquaculture sub-products**

Even with the application of the Integrated Multi-Trophic Aquaculture (IMTA) model, aquaculture generates various sub-products. In circular aquaculture, these by-products are systematically repurposed to minimize their quantity and prevent environmental release, aligning with the industry's commitment to sustainable and responsible waste management. Sub-products resulting from the processing of primary fish products, such as fish bone, skin, belly flaps, or trimmings, are recognized for their significant potential. These by-products hold value as they can be reintegrated into the food chain as ingredients for human consumption, maximizing their benefit and reducing waste. The utilization of these sub-products underscores a sustainable approach within the seafood industry, contributing to a more efficient and circular use of resources. Another category of wastes in aquaculture encompasses diverse materials, including manure, non-mineralized guano, and digestive tract content, along with animal by-products containing authorized residues surpassing permitted levels. This category also includes deceased animals, oocytes, and embryos, carcasses, as well as parts of animals slaughtered that are not intended for human or animal consumption due to legal or commercial reasons. Managing these waste categories is essential for maintaining environmental sustainability and regulatory compliance within the aquaculture industry.

b) Human food ingredients

Aquaculture sub-products offer a sustainable reservoir for reclaiming unconsumed compounds like proteins, lipids, and pigments, predominantly repurposed for the production of broths, aromas, fish protein concentrates, among other products. Within the food industry, various compounds crucial for human consumption can be derived from these sub-products, including fish flour, chitosan (a biopolymer sourced from chitin in crustacean exoskeletons), concentrated proteins, collagen (primarily extracted from fish skins), and gelatin (produced through partial collagen hydrolysis). Astaxanthin and chitosan, obtained from aquaculture sub-products, are not only vital in industrial applications but also serve as nutritional supplements for humans. Astaxanthin, a prevalent carotenoid obtained from sub-products, particularly in salmon, trout, krill, shrimps, freshwater crabs, and crustacean shells, is widely recognized for its application as a food ingredient due to its colour-enhancing and antioxidant properties. The cultivation of macro and microalgae has become crucial in this domain, offering a diverse source of pigments that can be recovered from sub-products after processing. Beta-carotene, a yellow pigment known as a precursor to vitamin A, is among the pigments that can be obtained, providing both colour and additional properties, such as antioxidant benefits, to various products destined for human consumption.

c) Animal feeding

Various sub-products stemming from aquaculture, including fish flour, ground shell, chitosan, astaxanthin, concentrated proteins, and silage resulting from fish liquefaction, present valuable opportunities for incorporation into feed formulations. These diverse components can be utilized in the formulation of feeds for aquaculture animals, farm animals, and pets. By integrating these aquaculture-derived sub-products into feed formulations, the industry can enhance the nutritional content of feeds while also contributing to a more sustainable and circular use of resources. This practice aligns with the broader goal of optimizing resource efficiency within the agricultural and aquaculture sectors.Crushed shells, particularly from oysters, serve as a significant source of calcium supplementation ($CaCO_3$), proving highly beneficial when incorporated into hen feeding. Substituting the calcium derived from limestone with oyster shells has been demonstrated to improve egg production, enhance the strength, weight, and thickness of eggs. Additionally, chickens fed with oyster shells exhibited a more rapid increase in weight. This practice underscores the value of utilizing natural and sustainable sources, such as oyster shells, to enhance the nutritional content of poultry feed and promote overall animal health and productivity.

d) Agriculture

Mussel shells serve a valuable role as a liming agent and soil amendment in farming practices. Comprised mainly of calcium carbonate ($CaCO_3$), these mussel shells offer a natural resource that effectively neutralizes acidic and metal-contaminated soils. Simultaneously, they contribute to soil fertility and elevate oxygen levels. The utilization of mussel shells as a natural product aligns with ecological agriculture principles, providing a sustainable alternative to mined-

$CaCO_3$. This practice showcases the potential of repurposing marine by-products for soil improvement, demonstrating a more environmentally friendly approach in agriculture.

e) Industrial uses: food packaging, cosmetic and pharmaceutical

Marine protein-based products, including collagen and gelatine, along with lipids and pigments, have proven to be valuable resources for industries such as food packaging, cosmetics, and pharmaceuticals. These marine-derived compounds offer diverse applications due to their unique properties. Polyunsaturated fatty acids (PUFAs) from marine sources have been subjects of extensive research, showcasing their potential applications, particularly in the realms of nutraceutical and medicine. The exploration of marine biomolecules underscores the rich potential of the oceans as a source of innovative and sustainable ingredients for various industrial sectors.

The food industry is adopting biodegradable active packaging to reduce single-use plastics and enhance product shelf-life. Chitosan, gelatine, and carrageenan are commonly used for biodegradable packaging, while active ingredients from algae extracts, squid, or *Litopenaeus vannamei* by-products are included to improve preservation properties. This sustainable approach aligns with efforts to minimize environmental impact and promote innovative packaging solutions.Pigments serve as colour sources with added bioactive properties. Astaxanthin, known for its antioxidant properties, is reported to stimulate the immune system and prevent various diseases, including diabetes, cardiovascular issues, and neurodegenerative conditions. In cosmetics, astaxanthin is utilized in skincare and anti-aging formulations. Beta-carotene, precursor of vitamin A, exhibits antioxidant activity that counteracts the impact of free radicals, potentially preventing oxidative damage associated with inflammatory processes and chronic diseases like diabetes, cardiovascular issues, and cancer. Pigments from microalgae, suitable for human or animal consumption, offer good digestibility due to a simpler matrix than higher plants, facilitating their incorporation as nutritional ingredients.

The emergence of circular bio-economy aquaculture production systems signifies an innovative approach that not only fosters sustainability but also has the potential to generate new job opportunities. By following circular bio-economy principles, aquaculture can contribute significantly to economic growth while prioritizing resource efficiency and environmental stewardship. This integrated approach aligns with the broader goal of building resilient and sustainable aquaculture production systems that benefit both local communities and the environment.

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