

IntegInnovation and Emerging Technologies for Sustainable Aquaculture



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INTRODUCTION

Aquaculture is one of the fastest-growing food production areas in the world. In recent years, it has become a focus of more attention because it helps produce a lot of aquatic food and meets the growing need for fish and seafood. Right now, the amount of fish people eat is partly because aquaculture is growing. But this quick growth has also led to some environmental problems. These problems are mostly about the safety of the food from aquaculture and other environmental issues. Some big environmental problems include the release of untreated wastewater, which is not properly treated, and the high use of water (Xie et al., 2004; Xie and Yu, 2007). These problems can make aquaculture less sustainable and can hurt the aquatic environment. China is the top producer of aquaculture products and also the biggest consumer of fish and seafood in the world (FAO, 2008). It produces a large part of the world's aquaculture. However, the fast growth of aquaculture in China has brought many challenges, such as a lack of land and water, damage to aquatic ecosystems, frequent disease problems, and difficulties in handling sediments and wastewater (Cao et al., 2007). To deal with these issues, sustainable aquaculture practices are needed. So, better farming methods and the development of new techniques are important to reduce environmental effects and help aquaculture grow in a long-term way (Zhang et al., 2011).



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Recirculatory Aquaculture systems (RAS)

Recirculatory Aquaculture Systems, or RAS, are a good way to help reduce environmental issues in fish farming. These systems are used on land, and they use treated water that has gone through mechanical and biological filters. The main goal of RAS is to save energy, use less water, and lower the amount of nutrients that get released into the environment. This helps stop problems like eutrophication. RAS was created to help make fish farming more sustainable, especially in places where there is not much land or water, and where environmental rules are very strict. RAS can be used to raise many types of fish, including both sea and freshwater species. They can be used in different parts of the fish farming process, like raising fish from the beginning, growing young fish, and raising them to full size.

Recent developments in RAS mainly focus on two areas:

1. Improving the technology used for water treatment and recirculation.
2. Recycling nutrient through integrated farming systems, such as the use of **constructed wetlands (CWs)** (Martins et al., 2010).

Integration of constructed wetlands (CWs) with RAS

Recently, constructed wetlands have been widely applied in aquaculture systems for reusing wastewater and treating (Konnerup et al., 2011; Li et al., 2007; Zachritz et al., 2008; Zhang et al., 2010). However, the complete role of constructed wetland were combine with a primary biological pond and ecological ditch and connected with an almost closed RAS system. This integrated systems was used to maintain good water quality for farming of:

Channel catfish (*Ictalurus punctatus*)

Fifteen-spined stickleback (*Spinibarbus sinensi*)

Yellow catfish (*Pelteobagrus fulvidraco*)

The study focused on two main objectives:

1. To evaluate how the combined treatment system improves water quality in RAS.
2. To study the relationship between improved water quality and the growth performance of cultured fish species.

Biofloc Technology (BFT)

Biofloc technology (BFT) is an advanced aquaculture technique which used to improve water quality by maintaining a proper balance between carbon and nitrogen in the culture system (Crab et al., 2012). In this system, uneaten feed and fish waste are not removed but converted into bioflocs, which act as natural food source for fish (Avnimelech, 2009). Bioflocs are small group of microorganism containing bacteria, algae, protozoans, and organic particles such as left over feed and fish waste. Microorganism held together by a sticky substance produced by bacteria, forming small floating particles called flocs. In BFT, adding a carbon source to the pond encouraging the growth of beneficial bacteria. These bacteria absorb nitrogen waste and convert it into microbial protein, which can be consumed by fish.

When carbon and nitrogen levels are properly balanced, harmful ammonia produced from fish waste is reduced through bacterial activity. BFT requires the addition of carbon-rich feed or extra carbon either through external carbon sources. The growth of heterotrophic bacteria helps to remove ammonia faster than traditional nitrification processes (Avnimelech, 2009). Therefore, Biofloc technology provides a sustainable farming method that:

- Improves water quality
- Reduces water exchange
- Converts waste into useful feed
- Increases fish production in an eco-friendly way

Mono-sex Culture/ Neo-female Technology

Mono-sex culture is a fish farming method where only one sex (all male or all female fish) is cultured cause one sex usually grows faster and provides better production. This method improves:

- Growth rate
- Feed utilization
- production efficiency

Generally, all-female culture is practiced in species like carp and salmon, while all-male culture is preferred in giant freshwater prawn and tilapia because males often grow faster. In freshwater prawn (*macrobrachium rosenbergii*), males reach market size faster than females. Therefore, all-male culture is preferred for higher production. Mono-sex culture is achieved by identifying the sex of fish and selecting the required population for farming (Jena et al., 2017).

Neo-female Technology

Neo-female technology is a modern method used to produce all-male fish population. In this technique, normal males are changed into functional females by using:

- Removal of androgenic gland (a hormone-producing organ)
- Gene silencing methods (RNA interference)

These changed females are called neo-females. They have male genetic characteristic but show female features. When neo-female mate with normal males, they produced all male offspring (Jena et al., 2017). This technology is useful because all-male populations generally show:

- Faster growth

- Better production
- Higher economic benefits

In India, neo-female technology is being used for producing all-male scampi seeds through research programs, and these seeds are supplied to farmers.

Compensatory Growth Technology

Compensatory growth is a process in which fish show faster growth than normal after a period of slow growth or limited feeding, when proper feeding is provided again. It occurs when fish experience a period of underfeeding or starvation and later receive enough food (Ali et al., 2003). During this recovery period, fish started growing rapidly and can reach the same or even higher weight compared to normally fed fish (Biswas et al., 2016). In this method, fish used to kept without feeding up to certain period (for example, 3 weeks) and then provided with normal feed for next period. Re-feeding show more effective than continuous feeding due to rapid weight gain and may achieve growth equal to or greater than fish that received continuous feeding. Advantages of these technology:

- Carp fish show rapid growth during the second year of culture.
- Improves survival rate in grow-out ponds.
- Fish become more resistant to disease.
- Fish can tolerate environmental change. Minimize the time requirement to reach market size (around 5-6 months).
- Weak and unhealthy fish may be removed during the slow growth period, leaving healthier fish for culture.
- Increases overall fish production and productivity (Jena et al., 2017).



Application of Microalgae Biotechnology

Microalgae are natural food sources used for many small aquatic animals such as shrimp larvae and fish larvae. Many microalgae species are commercially used as live feed or dried algal feed. Commonly used microalgae species include *Chlorella*, *Tetraselmis*, *Pavlova*, *Chaetoceros*, *Nannochloropsis*, *Skeletonema*, and *Thalassiosira*. Different microalgae species are often combined to provide a balanced source of nutrients such as proteins, essential micronutrients and lipids. In older fish and shellfish, adding algae-based biomass to fishmeal or grain-based feed improves nutritional quality. It also provides important pigments like astaxanthin, which give colour to the flesh of salmon and shellfish. Microalgae contain bioactive compounds that can help control harmful bacteria, viruses, and other disease-causing organism in aquaculture.

Future applications of microalgae

Advanced genetic engineering can improve microalgae by modifying algal cells to produce useful substances. Engineered microalgae can produce bioactive compounds such as vaccines, growth-promoting substances, antimicrobial agents. The algal cells function as natural carriers to deliver these useful compounds directly into aquatic animals.

Chloroplast engineering in microalgae helps in the stable production and storage of these useful compounds inside algal cells. Thus, integrating microalgae into aquaculture systems supports healthy, eco-friendly, and sustainable aquaculture production.

Organic Aquaculture

Organic aquaculture is a farming system that focuses on producing aquatic animals using natural and eco-friendly methods. It promotes biodiversity, natural biological cycles, healthy ecosystem management. This system uses minimum external inputs and follows sustainable practices that maintain and improve species diversity and environmental

balance (Prein et al., 2010). The main aim of organic aquaculture is to improve the health, growth, and productivity of fish and other aquatic organism while maintaining social, environmental, and economic sustainability. Organic aquaculture supports natural resource conservation and produce safe, high-quality aquatic products. Its follow different practices such as:

- Regular monitoring of environmental impacts.
- Use of polyculture systems (culturing multiple species together)
- Integration of natural plants into farming systems. Preference for native/local species.
- Avoiding the use of hormones, radiation, and antibiotics. maintaining proper stocking density for sustainable production.

Organic aquaculture is an innovative and sustainable approach that balances fish production with environmental protection. It helps achieve long term aquaculture development by reducing pollution, conserving biodiversity, and producing healthy aquatic foods.

IoT Based Smart Aquaculture system

Internet of Things (IoT) based automation system are modern technologies used in fish farming to continuously monitor and manage water quality. The collected data helps farmers understand changes in water conditions and make better management decisions. These systems use sensors to measure important water quality parameters. Different sensors use in IoT such as:

Wireless sensor Network (WSN) in aquaculture are used to monitor fish farm condition in real time (Simbeye et al., 2014). The information is sent wirelessly to farmers, allowing quick action to maintain suitable conditions for fish growth. These systems can detect water quality changes, oxygen levels, pH changes and water level variations. Automatic Monitoring and Control Systems

different researchers have developed automatic aquaculture monitoring systems using wireless sensors. Some system use technology like GPRS and ZigBee for communication between sensors and central servers (wang et al., 2011). These systems:

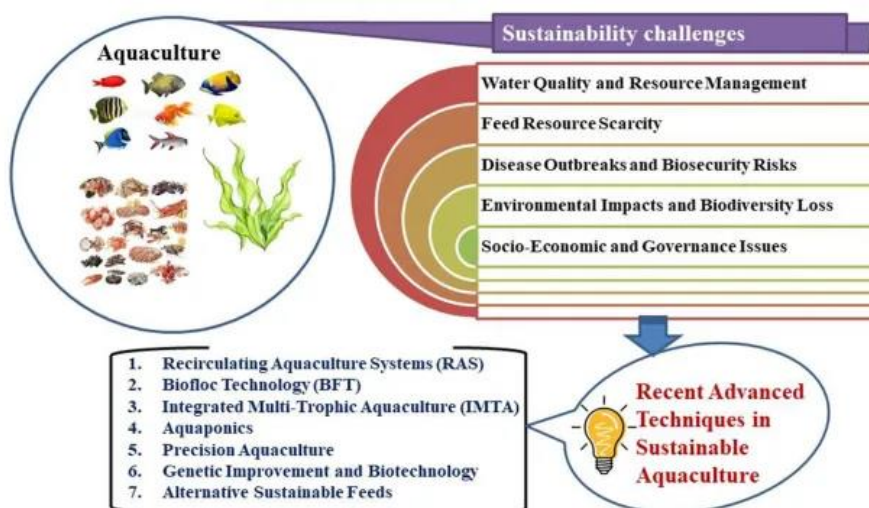
- Collect real-time water quality data.
- Reduce manual monitoring work.
- Improve communication between sensors and control units.
- Help in energy-saving management

LoRa (long Range) technology is used for long-distance data transmission with low

power consumption. LoRa-based systems help maintain fish health and ensure food safety. It helps in

- Sending sensors data from farm areas over long distance.
- Reducing energy use, building low-cost monitoring networks.

IoT and smart sensors technologies are important innovation in modern aquaculture. They help farmers maintain good water quality, improve fish production, reduce losses, and support sustainable fish farming (Gao et al., 2019).



Integrated multi-Trophic Aquaculture (IMTA)

IMTA is a sustainable aquaculture approach that combines fed species like fish and shrimp with extractive species such as seaweed and shellfish. The system allow recycling of nutrients by converting waste from one species into resources for another. Fish waste provides nutrients for seaweed growth, while shellfish utilizing organic particles from fish farming. This natural recycling process reduces environmental pollution, improves resource efficiency, and increase overall farm productivity. Therefore, IMTA supports sustainable aquaculture by balancing economic

benefits with environmental protection. In IMTA systems, fish and shrimp are usually placed at the highest trophic level (Barrington et al., 2009). They consume feed and produce waste materials such as:

- Dissolved inorganic nutrients (ammonia and phosphorus)
- Organic waste (fecal matter and leftover feed)
- Advantages:
- Provides higher food production and improves food security.
- Converts waste materials and unused feed into useful product.

- Reduces nutrient pollution and eutrophication.
- Improves economic benefits by producing multiple crops (Jena et al., 2017).
- It is an eco-friendly and sustainable farming method.
- Improves biodiversity and ecosystem stability.

CONCLUSION

Emerging technologies represent a promising pathway for achieving sustainable aquaculture by improving resource utilization, reducing environmental pollution, and increasing productivity. The adoption of these innovative approaches can support climate-resilient, economically viable, and eco-friendly aquaculture systems. Future developmental should focus on improving technology accessibility, reducing operational costs, and promoting their application among farmers to ensure long-term sustainability of the aquaculture sector.

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