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Advanced Technologies for Effluent Water Treatment in Aquaculture: Advancing Environmental Sustainability and Pollution Mitigation

Ganesh Kumar[1*], Jebarson Solomon[2], Priyadharshini[3], Sudhanshu Raman[1], Girija Saurabh Behere[1], Tanuj Misra[1] and Savaliya Bhautik[2]

[1]Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh (284 003), India
[2]ICAR-Central Institute of Fisheries Education, Mumbai, Maharashtra (400 061), India
[3]College of Fisheries, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Tuticorin, Tamil Nadu (628 008), India

Abstract

Aquaculture is becoming a key source of affordable animal protein worldwide. It is also viewed as a sustainable alternative to wild fisheries, which are declining due to overfishing. As the global population grows, the demand for seafood increases, leading to more intensive aquaculture practices. However, this expansion generates various effluents that can harm natural water resources. Traditional treatment methods have struggled to manage the growing number of contaminants effectively. This chapter introduces advanced technologies for treating aquaculture effluents. These include cavitation, high-rate algal pond systems, nanomaterials, Advanced Integrated Wastewater Pond Systems (AIWPS), constructed wetlands and the Sheaffer Modular Reclamation and Reuse System. These innovative methods are increasingly used to improve wastewater management in modern aquaculture operations.

Keywords Advanced methods, Cavitation, Contaminants, Effluent treatment

1. Introduction

Aquaculture is the fastest-growing sector in global food production, with an average annual growth rate of 3.2%. By 2028, aquaculture's contribution to global fish consumption is expected to rise to 58%, driven by the increasing global population and the limitations of wild fisheries. Since 2014, farmed fish consumption has surpassed that of wild fish, highlighting aquaculture's

[*]***Corresponding author's e-mail***: ganeshkaruppaswamy@gmail.com

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vital role in meeting fish demand. To keep pace with this rising demand, aquaculture practices have intensified and diversified to boost productivity (Food and Agriculture Organization, 2018). However, this rapid expansion has also led to significant environmental issues, including land subsidence, mangrove destruction and pollution from nutrient-rich wastewater, pesticides and pharmaceuticals. The release of effluents from aquaculture into natural aquatic ecosystems poses serious sustainability challenges, such as water scarcity and the depletion of natural resources. Aquaculture is carried out using different systems such as pond culture, bio floc, pen and cage culture, raceways and recirculating aquaculture systems (RAS) for varied activities like seed production and species rearing. These activities have intensified competition for essential resources like land, water and other natural resources, which are increasingly strained by human activities and the effects of climate change. Ensuring food security, particularly in aquaculture, depends on access to clean water, energy and maintaining environmental quality (Wang *et al.*, 2020). However, the growing scarcity of high-quality water presents a significant threat to the future sustainability of aquaculture. In response, the development of sustainable wastewater treatment technologies is becoming crucial. To mitigate the environmental impacts of aquaculture, various treatment technologies have been implemented, utilizing biological, physical and chemical processes. Biological treatments harness microorganisms to break down pollutants, while physical methods such as adsorption, membrane filtration and coagulation physically remove contaminants from wastewater. Chemical treatments often employ advanced oxidation processes, which degrade harmful substances into less toxic by-products before discharge. Combining these advanced treatment methods can significantly enhance wastewater purification, offering a more effective solution for addressing the environmental challenges posed by aquaculture (Yahyaa *et al.*, 2020).

2. Impact of Aquaculture Effluents

Natural aquatic resources can be harmed by aquaculture particularly through the discharge of effluents into natural water bodies. These effluents contain a variety of pollutants, including organic matter, excessive nutrients, chemicals and even exotic species, which can lead to the degradation of aquatic ecosystems. The major negative impacts of aquaculture effluents on natural waters are detailed.

2.1. Organic Pollution and Eutrophication

Aquaculture effluents are rich in organic matter and nutrients, particularly nitrogen and phosphorus, which are by-products of feed and fish waste. When these nutrients are discharged into natural water bodies, they can exceed the ecosystem's natural capacity to absorb them, leading to eutrophication. Eutrophication is characterized by excessive algal and phytoplankton growth (commonly cyanobacteria), which can deteriorate water quality by depleting oxygen levels, creating "dead zones," and causing the death of aquatic organisms. This phenomenon not only reduces biodiversity but also disrupts ecosystem functioning and services. Eutrophication is further exacerbated by climate change, as rising temperatures promote the rapid growth of algae and cyanobacteria, contributing to a cycle of ecosystem degradation. Additionally, aquaculture effluents can also alter the composition of phytoplankton communities in natural waters. The nutrient-rich waste from fish pens and ponds can stimulate the growth of harmful algal blooms, including toxic dinoflagellates such as *Alexandrium tamarense*, which are associated with paralytic shellfish poisoning. These blooms not only affect the health of aquatic organisms, but also pose risks to human health through the contamination of shellfish. The high concentration of nutrients and organic matter in effluents can lead to oxygen depletion, especially in densely stocked aquaculture systems. For instance, excessive organic matter from ponds leading to increased biological oxygen demand (BOD) and chemical oxygen demand (COD) severely affecting water quality (Sivaraman *et al.*, 2019; Kumar *et al.*, 2024). Sediments also play a significant role in the accumulation of pollutants from aquaculture systems. Studies have shown that sediment can account for the majority of nutrient output from aquaculture, with intensive shrimp ponds producing thick layers of sludge containing high levels of nitrogen, phosphorus and organic matter. For instance, Shrimp ponds generate a thick sludge layer at a rate of 20-290 metric tons per hectare per crop (mt ha^{-1} $crop^{-1}$), primarily composed of waste feed and fecal matter, which eventually gets discharged into surrounding waters (Justino *et al.*, 2016).

2.2. Chemical Contamination

Aquaculture relies on various chemicals, including antibiotics, disinfectants and pesticides, to enhance growth, prevent disease and maintain water quality. While effective within aquaculture systems, these chemicals pose significant ecological risks when released into natural waters. Antibiotics can lead to the development of antibiotic-resistant bacteria, threatening aquatic organisms and human health (Justino *et al.*, 2016). Disinfectants, while necessary for cleanliness, can introduce toxic effect to wild fish stocks, further endangering biodiversity. Similarly, pesticides accumulate in sediments and aquatic organisms, resulting in long-term environmental contamination. Additionally, the introduction of exotic species for aquaculture production can disrupt local ecosystems, degrade native species and facilitate the spread of diseases and parasites to wild populations. Viral disease like the White Spot Syndrome Virus (WSSV) can easily contaminate the other facility and may cause significant losses in shrimp farming (Cao *et al.*, 2007).

3. Conventional Treatment Methods

In aquaculture, pond culture is being followed as one of the most common and traditional methods of fish production. In extensive and semi-intensive condition, this system acts as a self-sustained system depending on natural processes within the pond for primary production and manages waste. Solid waste tends to settle and accumulate at the bottom and removed by desilting. It involves the periodic removal of settled solids manually after two or more production cycles. For dissolved waste, microorganisms like heterotrophs and detritivores were used to break down organic matter and convert ammonia into less harmful compounds. It is a self-sustaining process and happens as a part of natural process in extensive systems. Bacteria such as Nitrosomonas and Nitrobacter play a crucial role in transforming ammonia into less toxic nitrate. Nitrate, along with phosphate, becomes a nutrient for phytoplankton and algae, which in turn are consumed by zooplankton and finally consumed by fish. However, excessive nutrient buildup can lead to eutrophication, creating a hazardous environment for the fish. This system lacks specialized methods for nitrogen removal except dissolved nutrients and solid waste removal.

Another approach in fish farming is the flow-through system, which is commonly used for culture of high valued fish species. This system operates rapid with less water retention time and involves high rates of water exchange. While it efficiently dilutes dissolved waste and removes solid waste in an external basin, it also shifts waste from the culture unit to the environment. Solid waste removal can be challenging and quite expensive due to the large volume of low-concentration effluent. In contrast, Recirculating Aquaculture Systems (RAS) offer a more sustainable option for managing solid waste compared to flow-through systems. In RAS, solid waste is mainly removed through sedimentation and screening filters, which effectively capture larger particles. While screen and bead filters are good at removing large amounts of waste, they are less effective at capturing smaller particles (less than 50 µm). RAS systems are efficient in removing 85-98% of organic matter and suspended solids and 65-96% of phosphorus. Nitrogen is also managed through biological processes, specifically nitrification, where ammonia is converted to nitrate. Biofilters in these systems provide a surface for microbes to grow, helping convert ammonia to nitrate. However, nitrate can accumulate to high levels (400-500 mg L^{-1}), which can be harmful to fish and is unsafe for discharge into natural water bodies (Ahmad *et al.*, 2021).

4. Advanced Treatment Methods

4.1. Cavitation

Cavitation is a wastewater treatment method that leverages rapid changes in temperature and pressure caused by the collapse of gas-filled bubbles within a very short time frame. A mechanical device creates pressure pulses, causing these bubbles to expand until the vapor pressure of the liquid matches the external pressure. At this point, the bubbles burst and generate high temperatures and pressures. This extreme energy breaks down water molecules into hydrogen and hydroxyl ions. The hydroxyl radicals produced are highly reactive and can quickly oxidize harmful chemicals in the water (Figure 1). This process also helps eliminate pathogens from shrimp farm wastewater (Mancuso *et al.*, 2020). Cavitation has several advantages over conventional oxidation processes. It doesn't require chemicals or ultraviolet light, reducing treatment costs. Additionally, it generates fewer by-products compared to other methods, with the by-products being primarily derived from the contaminants already present in the wastewater. Beyond its effectiveness in removing organic pollutants, the energy released during bubble collapse can completely destroy the cellular structure of bacteria and microorganisms. Hydrodynamic cavitation can eliminate over 90% of Escherichia coli within five minutes and disrupt more than 94% of harmful bacteria. This process significantly enhances the safety of nutrient-rich shrimp wastewater before it is discharged into the environment.

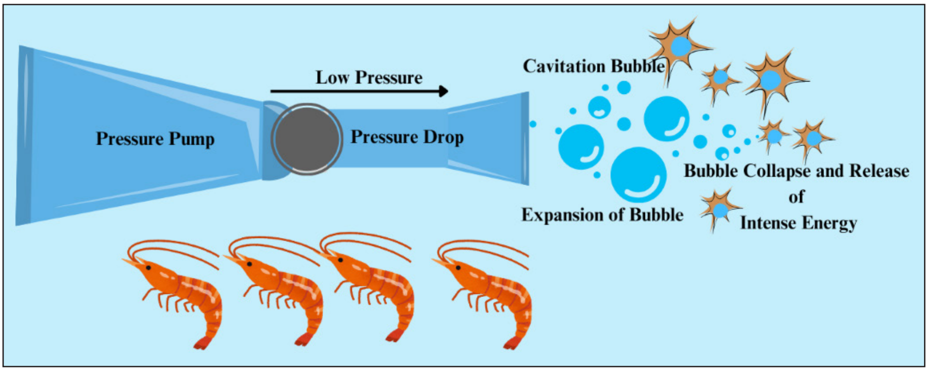

Figure 1: Mechanism of cavitation

4.2. High-Rate Algal Ponds (HRAPs)

High-rate algal ponds (HRAPs) have been adapted to treat wastewater from shrimp aquaculture farms. These ponds are shallow with less than 1 to 1.5 m deep, fitted with a paddle wheel to move water unidirectional circulatory flow. The water is circulated at speeds up to 0.2 m s^{-1} and carbon dioxide (CO_2) is added through a system placed below the paddle wheel, creating a strong water flow. The ponds allow algae to grow and once harvested, these algae can be processed into products like biofuels. The algae metabolize the nutrients from the eutrophicated waters. After treatment, the water can either be reused or safely discharged into the environment. As an added benefit, harvested algae can be converted into valuable products providing extra income for farmers. However, selecting the right type of algal species for cultivation can be challenging. It is an effective, environmentally friendly and profitable method for treating shrimp aquaculture wastewater. In a study using simulated aquaculture wastewater, HRAPs removed 100% of nutrients like ammonium ions, nitrate and phosphate and over 80% of organic residues (Hargan *et al.*, 2020). This clearly highlights the effectiveness of HRAPs in wastewater remediation while emphasizing the added value of the algae produced. An integrated system combining shrimp, mussels and macroalgae culture was found to be highly effective, achieving removal rates of 29% for chemical oxygen demand (COD), 79% for suspended solids, 76% for total nitrogen and 99% for total phosphorus. Beyond pollutant removal, plants like *Ulva lactuca* can be harvested, dried and used in shrimp feed production. A study using agar-alginate blocks with *Picochlorum maculatum* algae found removal rates of 57% for phosphate, 46.4% for nitrate, 89.6% for nitrite and 98.5% for ammonia, making it another effective solution for managing shrimp wastewater (Robles *et al.*, 2020).

4.3. Solid-State Thermophilic Aerobic Fermentation

Methods that use nutrient-rich sludge to grow microalgae carry the risk of accumulating heavy metals and other organic contaminants. This issue is addressed by a technique known as solid-state thermophilic aerobic fermentation. This method produces clean nutrients in the form of ammonium gas from wastewater sludge, allowing algae to be cultivated without the threat of contamination from pathogens or heavy metals. In this process, microorganisms break down organic nitrogen in the wastewater into dissolved nitrogen, which is then transformed into ammonium ions. A portion of the ammonium is released as pure gas, serving as a clean nitrogen source for algae growth. In a combined approach of fermentation and algae production, microalgae like *Chlorella vulgaris* have shown great effectiveness of removing 94.4% of chemical oxygen demand (COD) and 68.8% of ammonium nitrogen from wastewater. This method has also been successful in treating shrimp farm effluents and other wastewater, with different microalgae species achieving up to 75.8% COD removal and 83.4% ammonia removal in municipal wastewater (Koyama *et al.*, 2018). Nevertheless, the difficulty in selecting suitable algae species for cultivation continues to hinder the broader adoption of this technology.

4.4. Nano-Adsorbents and Membrane Filtration

Recent advances in nanotechnology have introduced highly effective methods for treating wastewater, including the use of nano-adsorbents, polymeric nano-adsorbents, nanomaterial-based membranes and nanofiber membranes. Nano-adsorbents are materials that efficiently remove pollutants from wastewater by adsorbing it to active sites on their surface. Compared to traditional adsorption methods, it can offer better surface chemistry, shorter diffusion times and more adsorption sites. As a result, they can effectively remove a broad spectrum of pollutants, including heavy metals and organic compounds. This method is particularly advantageous due to its enhanced pollutant-binding capability. Additionally, polymeric nano-adsorbents have been developed to target specific pollutants in effluent water. These nanomaterials are also called as dendrimers. It is designed with a hydrophobic interior to adsorb organic pollutants and their exterior is engineered to adsorb pollutants with hydroxyl or amine groups. This dual function makes them highly effective in removing heavy metals and other contaminants through complex chemical interactions, such as electrostatic forces and hydrogen bonding. Their specialized design enables more precise and effective treatment of aquaculture wastewater.

Similarly, nanomaterial-based membranes are used to further improve the performance of conventional filtration methods by increasing both permeability and resistance to fouling. These advanced membranes are not only efficient at filtering out viruses, sludge and phosphorus, but also enable the recovery of nutrients from wastewater. Their ease of cleaning through back-flushing enhances their operational efficiency and longevity. Thus, they offer a valuable solution for managing high-nutrient effluents in intensive aquaculture wastewater treatment. Furthermore, it offers an even greater advancement by providing a higher surface area and greater porosity compared to conventional membranes (Do *et al.*, 2019). The diameter and composition of these nanofibers can be tailored, enhancing their versatility for wastewater treatment applications. Nanofiber membranes have demonstrated excellent performance in reducing nitrate and phosphate levels that contribute to harmful algal blooms in natural water bodies. Nanofiber membranes apart from reducing the nitrate and phosphate concentrations can be also used successfully to improve dissolved oxygen and pH levels.

4.5. Advanced Integrated Wastewater Pond Systems (AIWPS)

AIWPS was developed by the University of California. This system uses a series of specially designed, low-cost ponds or reactors. Despite their potential, these systems are still in their early stages and remain relatively unfamiliar to the broader end users (Figure 2). AIWPS enhance conventional waste stabilization ponds by incorporating four advanced stages:

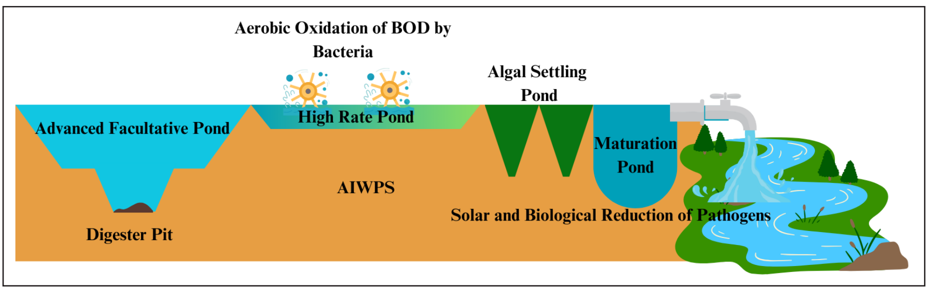

Figure 2: Advanced integrated wastewater pond systems

i) Advanced Facultative Pond (AFP): Contains a digester pit acting as an anaerobic pond within the facultative pond.

ii) High-Rate Pond (HRP): Algae absorb nutrients and provide oxygen for bacteria to reduce BOD.

iii) Algal Settling Pond (ASP): Flocculates the algae produced in the HRP

iv) Maturation Pond (MP): Reduces pathogens through solar and biological processes.

4.6. Bioaugmentation Technology

Bioaugmentation is a technique used to manage nitrogen waste in effluent treatment by introducing a mix of nitrifying and denitrifying bacteria. This method helps convert harmful ammonia and nitrite into less toxic compounds. The bacterial mix used is stable and remains effective for up to 120 days at room temperature. Large amount of water needed in rearing activities can be reduced by using a recirculating aquaculture system. This system improves fish production without requiring water exchange but produces wastewater with high levels of ammonia, nitrite and nitrate. Principle behind this seems similar to biofloc technology but remediation happens here in reactor. A sequencing batch reactor (SBR) can be used to treat this wastewater by processing it in stages, where ammonia is converted to nitrates and nitrates are further broken down. By adjusting the carbon-to-nitrogen ratio and adding molasses, up to 99% of ammonia, nitrite and nitrate can be removed. Another method uses bagasse, a by-product of sugarcane, to lower ammonia (Patil *et al.*, 2021). This method reduces ammonia levels within 24 hours and decreases total ammonia nitrogen by up to 95%. Its effectiveness depends on how much bagasse is used, how long it is left in the water and the starting ammonia levels (Roy *et al.*, 2010).

4.7. Constructed Wetlands

Constructed Wetlands (CWs) are engineered systems designed to replicate the natural processes of wetlands to treat wastewater by combining physical, chemical and biological methods within an ecosystem. These systems have become increasingly popular in recirculating aquaculture systems and aquaculture wastewater treatment due to their various benefits, such as low operational costs, high treatment efficiency, minimal secondary pollution and ease of maintenance. Many studies have focused on the performance of CWs, especially in aquaculture applications. Both vertical and horizontal flow CWs have proven effective in removing key contaminants, including suspended solids, organic matter and inorganic nitrogen from water and effluents in aquaculture ponds. For example, one early study showed that a CW linked to a shrimp pond greatly enhanced water quality in a recirculating aquaculture system. In intensive trout farms, CWs have been successful in treating nutrient levels, such as total nitrogen (TN) and total phosphorus (TP). Research has also demonstrated that horizontal subsurface flow CWs can reduce nitrate concentrations, chemical oxygen demand (COD) and total aerobic bacteria over a 50-day period in shrimp culture. Similarly, vertical subsurface flow CW microcosms have effectively removed organic micropollutants from freshwater aquaculture effluents within four weeks (Parde *et al.*, 2021). However, it is important to note that most of the research on CW purification has been conducted under controlled laboratory conditions for relatively short periods. There is a lack of data on the long-term performance of CW systems at the farm scale in treating effluents from inland freshwater fish farms. Thus, it is essential to assess the stability and effectiveness of farm-scale CWs over extended periods to better understand their practical use in aquaculture wastewater treatment.

4.8. Sheaffer Modular Reclamation and Reuse System

This system effectively removes both suspended and settled sludge, promoting water reuse for irrigation while eliminating odors without depleting essential nutrients. It consists of aerated chambers that integrate a grinder, blower and irrigation chamber. The grinder macerates the solid sewage and pumps it to the bottom of the chamber for anaerobic digestion. The solids partially decompose and settle at the bottom, where they can remain for up to 30 years. Dissolved organic materials are further decomposed through vigorous aeration facilitated by a blower at the surface. This process lasts for 36 days, allowing for continued breakdown of organic matter. As a result, solid components are converted into simple organic acids, methane (CH_2), carbon dioxide (CO_2), sulfides (H_2S), ammonia (NH_2), inorganic compounds and water (H_2O). Nutrients such as nitrogen (N), phosphorus (P) and potassium (K) dissolve into the water, rendering it suitable for agricultural irrigation.

5. Conclusion

To address the pressing issue of wastewater management in aquaculture and prevent the degradation of natural resources caused by the release of aquaculture effluents, advanced treatment technologies are essential. The effluent water primarily contains nutrients, fertilizers, therapeutic chemicals, organic waste, pathogens and exotic species. Various technologies have been proven to provide a holistic approach that integrates technological, legal and environmental factors for effective treatment. Moreover, some technologies, such as integrated algal culture with wastewater, may offer a sustainable and eco-friendly solution, allowing farmers to manage wastewater while enhancing their income. This method minimizes reliance on chemical treatments, which can have harmful residual effects. Therefore, adopting advanced wastewater treatment technologies is vital for promoting environmental sustainability and ensuring the long-term viability of aquaculture practices.

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