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DEVELOPMENT OF BIOLOGICAL TECHNOLOGY AND NANO TIO_2 MODIFIED CERAMIC MEMBRANES FOR RECIRCULATION OF SHRIMP AQUACULTURE WASTEWATER: BOTTLENECKS AND PROSPECTS

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ABSTRACT
The shrimp aquaculture industry generates wastewater rich in organic matter, suspended solids, nutrients, pathogens, and residual antibiotics, posing environmental challenges. Conventional biological treatments, including constructed wetlands, biofloc systems, microalgae cultivation, and recirculating aquaculture systems (RAS), are widely used due to low cost and environmental compatibility; however, their performance is often constrained by recalcitrant organics and unstable effluent quality under water reuse conditions. This review focuses on recent advances in integrating biological processes with nano TiO_2 modified ceramic membranes. Ceramic membranes provide mechanical strength, chemical stability, and tolerance to saline and harsh conditions, while TiO_2 modification enhances hydrophilicity, antimicrobial activity, and photocatalytic degradation of refractory pollutants. Reported studies show chemical oxygen demand (COD) removal efficiencies of 85-92% and near complete total suspended solids (TSS) removal, while TiO_2 modified membranes achieve over 90% removal of dyes, proteins, and oils and reduce membrane fouling under ultraviolet (UV) irradiation. Membrane fouling mechanisms, photocatalytic performance, bioreactor integration, and economic considerations are discussed. The combination of biological treatment and modified ceramic membranes represents a promising approach for enhancing water reuse and long term treatment stability in shrimp aquaculture.

1. INTRODUCTION

The shrimp farming sector in Vietnam has been developing rapidly, making a significant contribution to aquaculture export value and agricultural economic growth. However, along with the increasing stocking density and production intensity, the volume of wastewater generated has grown substantially. Wastewater from shrimp ponds may contain organic pollutants, suspended solids, nitrogenous compounds, phosphates, pathogenic bacteria, and residual (Szczepanik, 2017). If these components are not effectively controlled, they can degrade the quality of receiving water bodies, cause eutrophication in aquatic environments, and increase the risk of disease outbreaks in farming areas. Therefore, the application of highly efficient, stable, and shrimp farming compatible wastewater treatment technologies is an important research direction. Shrimp aquaculture wastewater can be treated using physical, chemical, and biological methods. Among these, biological treatment stands out due to its environmental friendliness, low operating costs, and effectiveness in removing organic matter and nitrogenous compounds. Current biological treatment technologies of interest include constructed wetlands, biofloc technology, microalgae systems, high-rate algal ponds (HRAP), and RAS. Among them, RAS is considered a promising approach, allowing precise control of culture conditions, enhancing biosecurity, while reducing freshwater demand and limiting environmental discharge (Bohnes & Laurent, 2021).

However, in practical operation, RAS still faces limitations related to the accumulation of dissolved organic matter, recalcitrant compounds, suspended solids, and microorganisms in the recirculating system. When water is reused over multiple cycles, pollutants that are difficult to remove via conventional biological treatment may accumulate, degrading water quality and affecting animal growth.

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To improve effluent water quality in recirculating systems, membrane technologies are increasingly integrated into treatment systems due to their ability to effectively retain suspended solids and microorganisms, providing a more stable water stream for reuse (Banu et al., 2009). Most current systems use polymeric membranes due to low investment costs and versatile fabrication. However, this material type faces several long-term operational limitations, particularly lower mechanical and chemical stability, decreased performance under temperature, cleaning chemicals, or high pollutant loads. Moreover, membrane fouling occurs rapidly, reducing flux, shortening membrane lifespan, and increasing maintenance and replacement costs. To address these limitations, inorganic membranes, particularly ceramic membranes, have attracted considerable attention due to their stable performance under harsh conditions. Ceramic membranes exhibit high chemical and mechanical stability, tolerance to a wide pH range, high temperature, and pressure, long operational lifespan, and lower fouling propensity compared to polymeric membranes (Danfá et al., 2021). Nevertheless, conventional ceramic membranes still have limitations in antibacterial properties, self-cleaning ability, and fouling resistance during long-term operation. To overcome these issues, recent studies have focused on modifying ceramic membranes with nanomaterials, particularly titanium dioxide (TiO_2). Nano TiO_2 modified ceramic membranes retain their inherent mechanical and chemical properties while enhancing antibacterial activity, self cleaning, and fouling resistance through photocatalytic mechanisms, thereby improving the removal efficiency of organic matter and microorganisms in wastewater. In recent years, nano TiO_2 modified ceramic membranes have been widely applied in industrial wastewater, oil-containing wastewater, protein-rich effluents, and dye-laden wastewater due to their high separation efficiency and superior durability (Hemavibool et al., 2022; Shan et al., 2010). The pollutant retention capability of nano TiO_2 ceramic membranes combined with photocatalysis is evident for several typical compounds. Methylene blue (MB, 320 Da) can be retained at over 90% by ultrafiltration membranes with an average pore size of 10-50 nm, while UVA-assisted photocatalysis increases the removal efficiency from 40.8% to 97.7%. Bovine Serum Albumin (BSA, 66 kDa) is retained up to 98% by a 14 nm ultrafiltration membrane and nearly 100% when combined with TiO_2 - Ag photocatalysis under visible light. For oil-contaminated wastewater, TiO_2 coated microfiltration ceramic membranes retain over 90% of oil emulsions, and photocatalysis can enhance oil removal from 91% to 98.5% under UVC irradiation, even for droplets smaller than the membrane pore size. Therefore, nano-TiO_2 modified ceramic membranes demonstrate the combination of mechanical retention and photocatalytic mechanisms, effectively removing recalcitrant organic compounds, from azo dyes and proteins to oil emulsions, while maintaining high permeate flux and membrane lifespan, highlighting their potential for industrial and aquaculture wastewater treatment. Given the characteristics of shrimp aquaculture wastewater, often containing recalcitrant antibiotics and organic pollutants, integrating nano-TiO_2 modified ceramic membranes with biological treatment processes can create an efficient and sustainable recirculating system, optimizing pollutant removal while maintaining stable water quality for reuseIntegrating biological technology with nano-TiO_2-modified TiO_2 modified (Ghamarpoor et al., 2024).

Despite recent advances, studies on integrating biological treatment with nano TiO_2 modified ceramic membranes for shrimp aquaculture wastewater remain relatively limited and fragmented. Most current publications focus individually on pollutant removal efficiency, membrane fouling, or photocatalytic activity, while comprehensive assessments under aquaculture conditions are still lacking. Therefore, this review presents the current status, environmental issues, and technological trends in shrimp aquaculture wastewater treatment, particularly emphasizing the integration of biological treatment with nano TiO_2 modified ceramic membrane filtration toward effective and sustainable water recirculation and reuse.

2. MATERIALS AND METHODS

2.1 Methodology and search strategy

The objective of this study was to evaluate the feasibility and effectiveness of integrating biological treatment technologies with nano-TiO_2 modified ceramic membranes to improve shrimp aquaculture wastewater treatment efficiency and support water reuse objectives in aquaculture systems. The review covered both theoretical and experimental studies published between 2017 and 2024 to ensure the relevance and reliability of the collected data. This period was chosen to encompass the most recent developments in photocatalytic membrane engineering and aquaculture wastewater treatment technologies. To enhance search precision, a Boolean search strategy was employed. Keywords such as "shrimp aquaculture wastewater", "ceramic membrane", "nano-TiO_2", "photocatalysis", "recirculating aquaculture systems (RAS)", and "biological treatment" were systematically combined using logical operators (AND, OR, NOT). This allowed refinement of queries, exclusion of irrelevant records, and expansion of coverage where necessary

The literature search strategy was structured around four main analytical dimensions: research subject, technological approach, operational context, and application objective (Table 1).

2.2 Inclusion and exclusion criteria

To ensure that the review remained focused and relevant, specific inclusion criteria were established. Studies were considered suitable if they addressed biological treatment technologies such as biofloc systems, microalgae cultivation, constructed wetlands, or RAS applied directly

TABLE 1: Search strategy and keyword structure.

Analytical dimension	Search terms
Subject	("TiO_2 photocatalyst") OR ("nano TiO_2") OR ("modified ceramic membrane")
Approach	("wastewater treatment") OR ("photocatalysis") OR ("recirculation") OR ("MBR")

to aquaculture wastewater. Research was also included when it investigated the use of ceramic membranes or nano TiO_2 modifications, particularly in relation to pollutant removal efficiency, fouling resistance, or photocatalytic performance. Furthermore, eligible publications were required to provide quantitative treatment outcomes, including indicators such as COD, BOD, TSS, nutrient removal, or antimicrobial effectiveness. Finally, studies that discussed the integration potential between biological processes and advanced membrane systems were prioritized, as these offered insights into sustainable and scalable wastewater management solutions.

In contrast, several exclusion criteria were applied to filter out studies that did not align with the objectives of this review. Research focusing exclusively on polymeric membranes, without consideration of ceramic or TiO_2 based modifications, was excluded due to its limited relevance to the scope of this study. Similarly, studies that examined wastewater streams unrelated to aquaculture, i.e. municipal, textile, or industrial effluents, were not considered, as their findings could not be directly extrapolated to shrimp aquaculture systems. Publications that lacked experimental validation, relying solely on theoretical models or conceptual frameworks without supporting data, were also excluded to maintain the scientific rigor and reliability of the analysis.

By applying these inclusion and exclusion criteria, the review ensured that only methodologically robust and contextually relevant studies were analyzed, thereby strengthening the validity of the findings and enhancing their applicability to shrimp aquaculture wastewater management.

2.3 Data extraction and categorization

For each study that satisfied the inclusion criteria, a systematic data extraction protocol was implemented to ensure consistency and comparability across sources. Information was collected on the characteristics of aquaculture wastewater, including pollutant type, concentration, salinity, and microbial load, thereby establishing a baseline for understanding the complexity and variability of shrimp aquaculture effluents. Details regarding membrane specifications were also recorded, such as pore size, material composition, TiO_2 coating techniques, and the irradiation source employed to activate photocatalytic processes.

Data concerning the biological treatment technologies applied were documented, covering systems such as biofloc, microalgae cultivation, RAS, and constructed wetlands. To assess treatment efficiency, performance indicators were extracted, including COD and BOD removal, nutrient reduction, antimicrobial activity, fouling resistance, and flux recovery. Operational parameters, i.e. pH, temperature, hydraulic retention time, and exposure to UV or visible light, were noted to contextualize treatment outcomes under varying environmental conditions. In addition, studies were evaluated for economic and scalability considerations, including capital investment, energy requirements, and maintenance demands, which are critical for practical application in aquaculture systems.

To enable structured comparison, the extracted data were organized into four analytical dimensions. The first dimension, research subject, distinguished studies focused specifically on shrimp aquaculture wastewater from those addressing other aquaculture systems. The second dimension, technological approach, classified studies according to whether they employed biological treatment, ceramic membrane filtration, TiO_2 photocatalysis, or hybrid systems integrating multiple methods. The third dimension, operational context, identified whether the research was conducted at laboratory, pilot, or full scale levels. The final dimension, application objective, highlighted the intended outcomes of each study, including pollutant removal, water reuse, fouling mitigation, or antimicrobial enhancement.

This structured categorization provided a coherent framework for comparative analysis, ensuring that both technical performance and practical applicability were critically assessed within the broader context of shrimp aquaculture wastewater management.

2.4 Analytical tools

To explore prevailing research directions and identify critical bottlenecks, VOSviewer software was utilized to construct keyword co occurrence maps. This bibliometric technique enabled the visualization of associations among frequently cited terms, i.e. TiO_2 photocatalysis, shrimp aquaculture, and membrane fouling, and provided valuable insights into emerging thematic clusters within the field.

Complementing this bibliometric analysis, a comparative matrix evaluation was performed to systematically assess differences in treatment performance across technological strategies. The comparison encompassed conventional biological processes versus hybrid biological membrane systems, polymeric membranes versus ceramic membranes, and unmodified ceramic membranes versus those enhanced with nano TiO_2 coatings.

By integrating bibliometric mapping with comparative performance analysis, this dual methodological approach offered both a conceptual overview of research trends and a quantitative assessment of technological efficiency, thereby reinforcing the robustness of the evaluation framework for wastewater treatment strategies in shrimp aquaculture.

3. RESULTS AND DISCUSSION

3.1 Shrimp farming systems and wastewater generation context

3.1.1 Development trends and technological transformation in shrimp farming

Vietnam ranks among the five leading countries in global shrimp production and is a key supplier of shrimp products worldwide. The shrimp farming area has increased by an average of 5% per year, primarily driven by the growth in white-leg shrimp farming. White-leg shrimp production has increased by an average of 13%, while black tiger shrimp production has declined by 8% over six years, with no significant improvement in productivity compared to whiteleg shrimp. Shrimp export is a key sector of Vietnam's economy, contributing significantly to agricultural growth and generating substantial revenue. However, numerous challenges caused a decline in global demand in 2023. Notably, the United States, Vietnam's largest shrimp export market, experienced a 32% decrease, negatively impacting domestic production. Despite this, Vietnamese shrimp exports to other markets such as Japan, South Korea, and China achieved strong growth. The shrimp pond area in Vietnam has rapidly expanded in recent years to meet export demands. Although current profits are high, the success rate remains low, resulting in higher production costs for farmed shrimp than in other countries.

Meanwhile, Vietnam possesses a significant advantage in advanced and deep processing technologies. Therefore, to enhance the competitiveness of Vietnamese shrimp, a clear transformation is needed in the farming sector. The shrimp farming industry in Vietnam is changing, focusing on production growth and sustainability, along with the adoption of new technologies.

Many science and technology enterprises have recently introduced shrimp farming solutions that apply Industry 4.0 technologies, contributing to improved accuracy in environmental monitoring and disease management (Iber & Kasan, 2021). One notable application is the automated feeding system, which supplies feed according to the actual demand of the shrimp. Parameters such as feeding duration and rest intervals can be easily adjusted based on the remaining feed, helping to control appropriate feed amounts, increase feed conversion efficiency, reduce costs, and minimize environmental pollution. Although the initial investment cost is relatively high, the system's durable materials help regulate temperature, withstand weather fluctuations, and prevent water stratification, thereby enabling multiple yearly production cycles. A practical current strategy is the development of ecological and organic shrimp farming models, particularly integrated shrimp-mangrove systems (Ahmed et al., 2017). About 60,000 ha of shrimp ponds in the Mekong Delta region operate under this model. It leverages natural resources to maintain ecological balance and contributes to mangrove forest conservation, creating a sustainable, environmentally friendly farming ecosystem with high economic value. Simultaneously, switching to biological products and probiotics emphasizes reducing antibiotics and chemicals in aquaculture (Zhang et al., 2016). These solutions help control diseases effectively, improve water quality, reduce pollution, and enhance product quality.

Many shrimp broodstock still depend on imports, posing quality and disease control challenges. Therefore, investing in modern broodstock production facilities that meet biosecurity standards and can supply high-quality broodstock is essential. In parallel, long-term selective breeding programs should be implemented with criteria such as fast growth, high survival rates, adaptability to harsh environmental conditions, and especially resistance to serious diseases. In addition to the five main shrimp export markets, China, the United States, Japan, the EU, and South Korea, which account for 76% of total shrimp export value, the country is expanding into potential markets such as the United Kingdom, Canada, and Australia, as well as rapidly growing regions including the Middle East, Africa, and Southeast Asia.

3.1.2 Shrimp farming technologies

Multi-stage shrimp farming technology is divided into stages based on the developmental phases of shrimp - typically two or three stages. It is designed to optimize farming conditions at each stage, minimize risks, and increase production efficiency. The model is currently widely adopted in provinces throughout the Mekong Delta. Characteristics of the 2-phase farming technology model includes a nursery phase (phase 1) and a commercial farming phase (phase 2). In the first phase, shrimp are typically reared in net-covered houses for 20 - 30 days to protect them from adverse weather conditions and other external factors. The pond environment is strictly controlled to minimize shrimp mortality. Characteristics of the 3-phase farming technology model consist of two nursery phases (nursery phase 1 and nursery phase 2), followed by a commercial farming phase. All ponds are covered with tarpaulins during hot weather to help maintain a stable water temperature of approximately 30°C, which is optimal for shrimp growth.

Semi-Biofloc microbiological farming technology in intensive shrimp farming involves cultivating beneficial bacteria outside the pond (also known as microbial incubation) using carbon sources such as molasses and sugarcane molasses. The bacterial strains used are beneficial species of Bacillus. The cultivated bacteria are then introduced to the culture ponds to create a favorable rearing environment (Mangott et al., 2020). This environment can process excess nutrients before they are discharged into the external environment, thereby improving feed efficiency, reducing disease outbreaks, and enhancing biosecurity for the farmed shrimp.

Super-intensive shrimp farming technology in greenhouses is a modern, closed-loop aquaculture model. The farming system is housed within a greenhouse structure, which is covered with durable glass that withstands prolonged exposure to sunlight and rain while allowing sufficient light transmission for shrimp culture. Shrimp are stocked at high densities, typically 300 to 500 individuals per square meter, optimizing space and yield. The water recirculation and waste treatment systems are strictly controlled to minimize environmental pollution and improve resource use efficiency.

Different shrimp farming technologies exhibit distinct strengths and limitations in terms of productivity, biosecurity, investment cost, and operational complexity. Multi-stage shrimp farming technology enables very high stocking densities, typically ranging from 250 to 300 individuals per square meter, which results in high yields of approximately 35-40 tons per hectare and a relatively short and stable culture cycle of 70-85 days per crop. This system also achieves high survival rates, often exceeding 90%, and demonstrates reduced vulnerability to environmental fluctuations and external pathogens. However, these advantages are accompanied by substantial initial and operational costs, particularly for feed, seed stock, and electricity, and the requirement for extensive auxiliary infrastructure, which limits the effective farming area to only 20-25% of the total site.

Semi-biofloc microbiological farming technology applied in intensive shrimp culture offers effective control of excess nutrients, improves feed conversion efficiency, and enhances biosecurity. When combined with other technological innovations, this approach improves pond environmental conditions and promotes the formation of natural bioflocs, thereby reducing feed consumption and simplifying farm operations. In addition, the use of limited external water exchange reduces the risk of pathogen intrusion. Nevertheless, this system requires strict control of multiple operational parameters, including adequate aeration, appropriate water circulation, and precise adjustment of the carbon-to-nitrogen ratio. Maintaining stable and balanced microbial communities across large ponds, typically ranging from 1,500 to 3,000 m^2, remains challenging, and continuous aeration is necessary to sustain sufficient dissolved oxygen levels. Consequently, successful operation depends heavily on experienced personnel and advanced management skills.

Super-intensive shrimp farming in greenhouse systems relies on high-level technological integration to improve traceability of shrimp seed and feed sources, thereby ensuring food hygiene and safety. The incorporation of microbiological approaches without the use of antibiotics contributes to high and stable productivity while significantly reducing land requirements. However, the implementation of greenhouse structures and membrane-based systems results in investment costs that are considerably higher than those of conventional intensive farming models. Moreover, this farming approach demands skilled operators with strong technical and managerial capabilities.

Recirculating shrimp farming systems with minimal water exchange provide effective control of environmental conditions and disease outbreaks, while significantly reducing water consumption and increasing shrimp survival rates. These systems typically operate without antibiotics or chemical additives, thereby minimizing environmental impacts and creating a safer culture environment. High stocking densities, ranging from 150 to 300 individuals per square meter, can be achieved, with reported yields of approximately 7.6-7.8 tons per 1,000 m^2. Despite these advantages, recirculating systems require high capital investment, estimated to be 45-60% greater than that of conventional farming systems, and necessitate operators with appropriate professional training and technical expertise.

Winter shrimp farming in tarpaulin-covered systems enables off-season production and can deliver high productivity and economic value. However, this approach involves substantial investment and extended culture durations. Environmental and disease control during winter farming is generally more complex than in the main production season, and improper management of individual crops may increase the risk of environmental pollution and disease outbreaks. Recirculating aquaculture system (RAS) for shrimp farming with minimal water exchange features filtration systems (mechanical and biological filters), culture ponds, and water supply and drainage channels operating under a mechanism that ensures the reuse of farming water (Halim et al., 2025; Nugraha et al., 2023). Wastewater is treated through sedimentation tanks, biological filtration, and disinfection before being returned to the culture ponds (Arun et al., 2023). The model helps maintain stable water quality, minimizes water exchange, and reduces the risks of disease outbreaks and environmental pollution. With effective environmental control, shrimp exhibit faster growth, higher survival rates, and improved economic efficiency. Winter shrimp farming in tarpaulin-covered systems is an intensive farming model conducted within tarpaulin-covered structures, that helps maintain stable temperatures during colder seasons. The tarpaulin cover provides insulation, blocks wind and rain, and creates a favorable environment for shrimp growth under adverse weather conditions (Kashem et al., 2023).

There are two standard farming methods: (i) Single-Stage Farming, in which shrimp are directly stocked into ponds and reared for 3-4 months before harvest; and (ii) Multi-Stage Farming, which includes 2 phases (Phase 1: Shrimp are reared in indoor nursery tanks for 20-30 days. Phase 2: Once the shrimp reach a size of 3 - 4 cm each, they are transferred to commercial ponds at an average density of 100 shrimp per square meter. After two months, shrimp grow to a size of 50 - 60 individuals/kg and are ready for harvest.

It can be concluded that the shrimp farming industry is increasingly adopting various advanced technologies to improve productivity and minimize risks. Each technological model exhibits characteristics suitable for specific environmental conditions and farming scales. The multi-stage shrimp farming system is appropriate for regions with well-developed infrastructure. By separating each rearing phase, this model improves disease control; however, it requires advanced technical expertise and significant capital investment. In contrast, semi-biofloc technology, which employs beneficial microorganisms for water treatment and improved feed conversion, is commonly applied in small- and medium-scale operations. Despite its advantages in cost reduction, this method poses challenges in managing water quality at high stocking densities. Winter shrimp farming in tarpaulin-covered houses is suitable for northern provinces or areas with distinct cold seasons. This approach allows for the extension of the farming season and supports shrimp survival under adverse climatic conditions. Nonetheless, it remains seasonal in nature and limited in production scale. Super-intensive greenhouse shrimp farming represents a modern, closed farming model characterized by high productivity and strong environmental control. It is particularly suitable for large-scale farms or enterprises due to its high initial investment requirement. Among the technologies, the RAS with minimal water exchange is currently regarded as the most effective and broadly applicable model (Liu et al., 2024). RAS enables water reuse, reduces environmental discharge, enhances control over water quality parameters, conserves water resources, and increases shrimp survival rates (Samui et al., 2024). Compared to other farming systems, RAS offers superior environmental and disease control, resulting in greater productivity and economic efficiency. This model aligns well with the principles of sustainable aquaculture and is expected to play a central role in the industry's future growth.

Water is the primary living medium, directly influencing shrimp growth, physiological health, nutrient metabolism, and disease resistance. Effective water quality management is a fundamental prerequisite for maintaining productivity, optimizing economic performance, and ensuring the long-term sustainability of shrimp farming systems. Shrimp farming, particularly in intensive and super-intensive systems, requires substantial water. The total water consumption during a production cycle can amount to several thousand cubic meters per hectare. During the culture period, periodic water exchange is necessary to maintain a stable pond environment, dilute organic pollutants, and mitigate the accumulation of toxic gases. Modern aquaculture systems like RAS, are increasingly being adopted to reduce water usage and significantly minimize environmental discharge. Shrimp farming infrastructures are typically designed with distinct functional ponds, including sedimentation ponds, treatment ponds, grow-out ponds, and effluent holding ponds, to ensure strict control over water quality, thereby minimizing the risks of disease transmission and cross-contamination. The quality of water supplied to shrimp ponds must conform to the standards specified in the national technical regulation on brackish water shrimp culture farm - Conditions for veterinary hygiene, environmental protection and food safety (QCVN 02-19:2014/BNNPTNT), which is summarized in Table 2.

3.1.3 Characteristics of wastewater generation in shrimp farmings

Shrimp excrete organic and metabolic wastes and uneaten feed during growth and development. These substances accumulate and decompose, resulting in water quality deterioration and the formation of wastewater containing high concentrations of pollutants such as ammonia (NH_3/NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), organic matter and pathogenic microorganisms (Aquino et al., 2019; Vu et al., 2021). Poor water management can result in disease outbreaks, causing shrimp mortality. The prolonged presence of these pollutants in water can lead to oxygen depletion and contamination. Chemicals and pharmaceuticals have been widely applied in shrimp farming due to their critical roles in enhancing productivity, promoting growth, and disease control. These substances include antibiotics, antifouling agents, pesticides, polychlorinated biphenyls (PCBs), polybrominated biphenyl ethers, and disinfectants (Silerio Vázquez et al., 2024). Chemicals discharged into water bodies negatively impact environmental health and human safety (Ahmad et al., 2022; Do et al., 2019). Reports indicate that intensive and semi-intensive shrimp farming uses over 8.2 tons of chemicals. These compounds persist in the aquatic environment for extended periods after discharge (Phuong et al., 2023). To maintain water quality, periodic water exchange is essential for removing accumulated waste within ponds. This practice generates substantial volumes of wastewater, especially when pond water shows signs of contamination or during disease outbreaks (Ayalew, 2022). The discharged water typically contains elevated suspended solids, organic matter, and bacteria levels. Activities such as bottom sludge dredging, pond washing, disinfection, and sediment conditioning produce wastewater during pond preparation. This wastewater may contain residual chemicals (lime, disinfectants, bactericides), sludge deposits, and accumulated debris from previous farming cycles (Do et al., 2018).

Wastewater from shrimp farming is compositionally complex, typically containing high concentrations of pollutants and microorganisms, particularly pathogenic agents (Krishnani et al., 2018). The composition and characteristics of shrimp farming wastewater vary depending on the culture stage, stocking density, feed type, feeding strategies, water exchange regimes, and pond management practices (Chuaicham et al., 2023). Major constituents include uneaten feed, shrimp excretory products, and decomposing organic matter from dead flora and fauna (Tien Nguyen et al., 2024). These organic compounds contribute to elevated BOD and COD levels. Nitrogen- and phosphorus-containing compounds, such as NH_3/NH_4^+, NO_2^-, NO_3^-, PO_4^{3-} are also commonly present. Elevated ammonia and nitrite concentrations are toxic to shrimp and the surrounding ecosystem. In addition, heavy metals and residual chemicals may be present due to improper use of lime, pharmaceuticals, and other chemical agents (Do et al., 2022). Wastewater also harbors heterotrophic bacteria and organic-degrading microorganisms, including pathogenic strains such as Vibrio spp. Algae and plankton can proliferate excessively in nutrient-rich conditions, altering pH levels and dissolved oxygen concentrations in the water (Álvarez & Otero, 2020). The characteristic composition of shrimp pond wastewater is summarized in Table 3. Key

TABLE 2: Quality of water supplied to and present in ponds for black tiger shrimp and whiteleg shrimp (QCVN 02-19:2014).

No.	Parameters	Unit	Permissible Value
1	Dissolved Oxygen (DO)	mg/l	≥ 3.5
2	pH		7-9, daily fluctuations < 0.5
3	Salinity	mg/l	5-35
4	Alkalinity	mg/l	60-180
5	Water Transparency	cm	20-50
6	NH_3	mg/l	< 0,3
7	H_2S	mg/l	< 0.05
8	Temperature	°C	18

TABLE 3: Characteristic parameters of shrimp farming wastewater.

No.	Parameters	Unit	Value Range	QCVN 02 - 19:2014/BNNPTNT
1	Salinity	‰	12-30	-
2	COD	mg/l	65-180	150
3	BOD_5 (20°C)	mg/l	20-100	50
4	NH_4^+	mg/l	1-10	-
5	NO_3^-	mg/l	0.4-3	-
6	NO_2^-	mg/l	0.1-5	-
7	TN	mg/l	5-20	-
8	TP	mg/l	0.1-12	-
9	TSS	mg/l	50-200	100

pollution indicators such as COD, BOD_5, and TSS exceed the permissible limits defined by QCVN 02-19:2014/BNNPTNT. Therefore, appropriate treatment measures must be implemented to treat shrimp farming wastewater before it is discharged into the environment or reused.

The quality of shrimp pond wastewater at Hai Dong Commune, Hai Hau District, Nam Dinh Province indicates that most of the measured parameters exceed the permissible limits. Specifically, TSS exceed the regulatory limit by a factor of 20.8, while COD and BOD_5 exceed the limits by 8.73 and 7.88 times, respectively. These results indicate that shrimp farming activities significantly impact the quality of local water bodies. Analytical results also reveal that the receiving canals are contaminated with elevated concentrations of organic matter.

The characteristics of wastewater from black tiger shrimp (Penaeus monodon) ponds in Cu Lai village (Phu Hai commune, Phu Vang district, Thua Thien Hue province) and from white-leg shrimp (Litopenaeus vannamei) farms on sandy soils in Dien Loc (Phong Dien district, Thua Thien Hue province) show that wastewater from shrimp farming on sandy soils exhibits a pollution profile similar to that of traditional black tiger shrimp ponds. Most parameters are within the permissible discharge limits specified in QCVN 24:2009/BTNMT (Column B); however, COD exceeds the standard by approximately 1.3 to 2.0 times. Compared to the standards for surface water quality (QCVN 08:2008/BTNMT) and coastal seawater quality (QCVN 10:2008/BTNMT), additional treatment is required to reduce TSS, COD, NH_4^+, NO_3^-, and NO_2^- to protect aquatic life.

The pH values of shrimp farming wastewater in Bac Lieu province fall within the permissible range specified by QCVN and are suitable for white-leg shrimp (Litopenaeus vannamei) culture (optimal pH 7.5-8.5) (Table 4). Meanwhile, COD and BOD_5 concentrations in wastewater from super-intensive shrimp farming are 1.5 times higher than those in intensive shrimp farming wastewater, and both exceed the permissible limits by a significant margin. The aggregated results reveal that pollutant concentrations vary considerably across shrimp farming models.

Specifically, intensive and super-intensive farming systems exhibit markedly higher pollutant levels than sand-based farming, black tiger shrimp, and white-leg shrimp models. Parameters such as BOD_5, COD, TSS, total nitrogen (TN), and total phosphorus (TP) in wastewater from intensive and super-intensive shrimp farming exceed the QCVN 40:2011/BTNMT Column B standards, in some cases by multiple folds, reflecting substantial organic matter, suspended solids, and excess nutrients. Additionally, NH_4^+ concentrations and total coliform levels are also considerably elevated. Conversely, shrimp farming on sandy soils and black tiger shrimp and white-leg shrimp systems exhibit significantly lower COD, TSS, and total nitrogen, with most parameters remaining within or near the regulatory limits (Goswami et al., 2022).

3.1.4 Environmental impacts of shrimp farming wastewater

When effectively managed, shrimp farming wastewater can help enhance nutrient concentrations in culture ponds to increase aquaculture productivity. In certain situations, supplementary feeding is not required, which helps reduce production costs. Shrimp farmers can integrate crop cultivation with shrimp farming by establishing adjacent pond sections where nutrient-rich wastewater is used for irrigation. Shrimp farming wastewater can be reused to mitigate environmental degradation and conserve water, enabling more rational use of natural water resources and preventing wastage (Mishra et al., 2018). Additionally, this wastewater is beneficial for restoring nutrient-poor sandy soils, which are known to lack sufficient nutrients for crops. However, if shrimp farming wastewater is not effectively and promptly treated, it can cause negative impacts on water quality, soil health, and human health.

This wastewater contains high levels of organic compounds such as uneaten feed, shrimp feces, and decomposed shrimp carcasses, which increase BOD and COD, significantly reducing DO levels. This leads to oxygen depletion, adversely affecting aquatic organisms. Furthermore, wastewater may contain pathogens such as viruses, bacteria, and parasites. When discharged into rivers, canals, or seas, these pathogens can spread to natural aquatic species or nearby aquaculture areas, increasing the risk of widespread disease outbreaks. Wastewater can cause long-term soil impacts when used for irrigation and agriculture. Crops grown in soils with excessive nitrogen and phosphorus tend to exhibit excessive vegetative growth, which is undesirable for productivity. Moreover, heavy metals absorbed by plants can enter the food chain, potentially reaching humans (Do & Tran, 2023). Soil salinity is elevated near shrimp farms; specifically, for every one-meter de-

TABLE 4: Characteristics of wastewater from intensive and super-intensive shrimp farming in bac lieu province.

No.	Parameters	Unit	Intensive Shrimp Farming Wastewater (n = 20)	Super-Intensive Shrimp Farming Wastewater (n = 20)	QCVN 40:2011/BTNMT Column B
1	pH	-	7.55±0.24	7.87±0.18	5.5-9
2	BOD_5	mg/l	268±41	403±95	50
3	COD	mg/l	291±37	466±92	150
4	TSS	mg/l	492.5±129.5	698.6±350.7	100
5	Total N	mg/l	52.75±23.01	9.63±10.93	40
6	Total P	mg/l	5.63±2.34	17.32±12.05	6
7	N-NHA_4^+	mg/l	8.461±4.36	29.841±24.807	10
8	Total Coliform	MPN/100ml	27585±19558	27105±11800	5000

crease in distance from the shrimp pond to the surrounding land, salinity increases by 0.14% (Amoako Johnson et al., 2016). Another study indicated that shrimp wastewater significantly increases concentrations of total organic carbon (TOC), TN, and TP in coastal soils up to a depth of 10 cm. This wastewater accounts for 30% - 33.6% of TOC in coastal soils and alters carbon and nutrient dynamics in receiving areas.

3.2 Current technologies for shrimp aquaculture wastewater treatment

Various technologies have been applied to treat shrimp aquaculture wastewater depending on pollutant composition and operational conditions. Table 5 summarizes the principal treatment technologies reported for shrimp aquaculture wastewater, highlighting their treatment mechanisms, pollutant removal performance, and major practical constraints.

The following sections present a more detailed description of each technology to illustrate their mechanisms and performance in treating shrimp aquaculture wastewater.

3.2.1 Constructed wetlands

Constructed wetlands (CWs) are treatment systems that mimic natural wetlands but are designed and controlled to improve water quality (Huang et al., 2019). CWs are considered a cost-effective system for treating aquaculture wastewater, especially shrimp farming wastewater (Dinesh Kumar et al., 2020). CWs carry out nitrification, denitrification, and demineralization processes through plants and microorganisms (Yang et al., 2023). The effectiveness depends on design factors (substrate, plants, microorganisms), operational factors (hydraulic retention time, hydraulic loading rate, groundwater depth, flow regime), and environmental conditions (temperature, pH, salinity, moisture, nutrient levels, specific carbon sources).

In Vietnam, studies have shown that constructed wetlands can effectively treat shrimp farming wastewater. One study in Bac Lieu evaluated a 400 m^2 wetland system using native salt-tolerant plants such as Sesbania, Eleocharis, and saltgrass. The system combined biological ponds and wetlands to reuse water from black tiger shrimp ponds – the same source of wastewater (Hiep et al., 2023). Results showed that COD, BOD_5, NH_4^+, and TP removal rates exceeded 50%. The NH_3 concentration in the effluent was low (<0.1 mg/L), making the water suitable for reuse. Internationally, studies have also used constructed wetland models to treat aquaculture wastewater (Kashem et al., 2023). A system using Canna indica combined with 20 mg/L Fe^{2+} showed very high treatment efficiency, with removal rates of TN, TP, and COD reaching 95%, 75%, and 62%, respectively (Zhimiao et al., 2019). Another study investigated the impact of plant physiological characteristics on the treatment efficiency of CWs (de Paula et al., 2024). Results indicated that CWs planted with a mixture of multiple plant species had higher treatment efficiency compared to systems with only one species. Besides removing conventional pollutants, this system could also treat antibiotics in the water. Specifically, removal efficiencies for antibiotics SMX, SMM, SMZ, SDZ, and TMP were 29.8%-76.3%, 20%, 20%, 12%, and 89%, respectively.

The use of constructed wetlands for shrimp wastewater treatment offers several notable advantages. One of the main benefits is their relatively low construction and operating costs compared with conventional treatment technologies. Constructed wetlands rely primarily on natural processes involving aquatic plants and microbial communities to remove pollutants, resulting in low energy consumption and minimal maintenance requirements. Previous studies have shown that these systems are effective in removing organic matter, nitrogen, phosphorus, and, in some cases, residual antibiotics commonly found in shrimp farming effluents. In addition, constructed wetlands can be integrated directly into shrimp farms, contributing to water reuse and promoting more sustainable resource management practices.

However, constructed wetlands also present several limitations. A major constraint is the relatively large land area required for their implementation, which may restrict their applicability in regions with limited space. Treatment efficiency can vary depending on environmental conditions

TABLE 5: Overview of major treatment technologies for shrimp aquaculture wastewater.

Technology	Treatment characteristics	Advantages and limitations
Aerobic/anoxic biological treatment	Based on microbial activity for organic matter degradation and nitrogen conversion; effective removal of COD, BOD, and NH_4^+	Low operating cost and easy implementation, but sensitive to organic loading fluctuations and environmental conditions
Biofloc Technology	Heterotrophic microorganisms assimilate inorganic nitrogen and form biological flocs, contributing to water quality stabilization	Water-saving and nutrient recycling, but difficult to control floc density
Constructed wetland	Combines sedimentation, adsorption, and biodegradation by plants and microorganisms; effective for TSS, nitrogen, and phosphorus removal	Low cost and environmentally friendly, but requires large land area
Recirculating Aquaculture System (RAS)	Integrates mechanical filtration, biological treatment, and water recirculation to maintain stable water quality	Reduces water exchange and improves environmental control, but requires high initial investment
Polymer membrane-based MBR	Combines biological treatment with membrane separation, achieving high removal of COD, NH_4^+, and TSS	Produces high-quality effluent, but membrane fouling remains significant
Nano TiO_2 modified ceramic membrane	Integrates membrane filtration and photocatalysis, enhancing removal of COD, TSS, microorganisms, and refractory pollutants	Good fouling resistance and chemical durability, but requires high investment cost and UV irradiation

such as temperature, pH, and salinity, leading to fluctuations in performance. Moreover, constructed wetlands typically require a long start-up period before reaching stable and optimal treatment efficiency. If not properly designed and managed, these systems may also create favorable conditions for mosquito breeding. Furthermore, constructed wetlands are generally less effective in treating wastewater with very high pollutant concentrations or toxic compounds, and therefore may require pre-treatment or combination with other treatment technologies.

3.2.2 Biofloc technology

Biofloc technology is a new biological approach that is effective in aquaculture, based on the principle of suspended activated sludge (Banu et al., 2011). In Vietnam, this technology has been applied in several localities with promising results, supporting further development and broader adoption. Microorganisms in the biofloc system compete with pathogens in the water, helping reduce disease and improve yields. When an external carbon source is added, heterotrophic bacteria combine with excess suspended organic matter and algae to form floc. These floc particles are rich in protein and serve as a preferred metabolic food source for shrimp (Ahmed & Ambinakudige, 2024). Various factors, such as the C:N ratio, TSS, DO, pH, stocking density, biofloc dosage, and light, affect the efficiency and sustainability of biofloc technology. This method is effective, cost-saving, and easy to operate. However, it also has some limitations: High initial investment cost: farmers need to have a good understanding of the technology; the aeration system must operate continuously, otherwise, dissolved oxygen levels in the pond drop rapidly, leading to shrimp mortality or biofloc die-off, which endangers shrimp health; at high stocking densities, especially in the late stages of shrimp growth, waste accumulation can exceed assimilation capacity. This reduces biofloc efficiency, degrades water quality, and increases risk.

3.2.3 Microalgae and HRAP systems

Microalgae are tiny photosynthetic organisms capable of assimilating nutrients in aquaculture environments (Huang et al., 2022). They offer a cost-effective and practical biological method for aquaculture wastewater, including that from shrimp farms. Microalgae are used not only for wastewater purification but also to synthesize increased amounts of protein, lipids, and natural pigments to replace aquaculture feed and enhance animal immunity (Dinesh Kumar et al., 2016). However, selecting suitable microalgae species requires careful consideration, as pollutant removal efficiency depends heavily on species and environmental conditions. Microalgae technology is an advanced, eco-friendly technology that offers multiple benefits (Zhao et al., 2025). It helps absorb excess nutrients such as nitrogen and phosphorus while releasing dissolved oxygen via photosynthesis, improving water quality and pond stability. Some microalgae species secrete substances that inhibit pathogenic bacteria, helping reduce disease risk. The biomass after treatment can be used as fertilizer, animal feed, or bioproducts, increasing the economic value of the farming system. However, the efficiency depends on light and temperature conditions, that treatment efficiency may decrease during bad weather. Farmers require basic technical knowledge, and initial investment costs in ponds, aeration, and lighting can be relatively high.

Managing shrimp farm wastewater by algal pond systems is effective, profitable, and a green technology (Razaviarani et al., 2023). Algae are maintained at high densities and harvested to process valuable products such as biofuel. Algal growth helps absorb excess nutrients in polluted water, which contributes to water purification before reusing or discharging it into the environment (Rodríguez Leal et al., 2023). A study by Soka University, Japan, using simulated aquaculture wastewater, showed that HRAP could remove 100% of ammonium, nitrate, phosphate, and over 80% of organic matter. Another report found Arthrospira sp. Similarly, Arthrospira sp. was also reported to PCC7413 is effective, removing 84.9% ± 1.9% ammonia by Arthrospira sp. Concentrations drop to as low as 4.9 mg/L during treatment by Nostoc sp. and PCC7413, achieved within 24 hours. In an integrated farming study involving shrimp, clams, and aquatic plants in Romania, algae demonstrated a higher efficiency in removing pollutants. In an integrated farming study involving shrimp, clams, and aquatic plants in Romania, algal-based treatment systems achieved pollutant removal efficiencies of 29%, 79%, 76%, and 99% for COD, suspended solids, total nitrogen, and total phosphorus, respectively; however, the original study did not specify the exact algal species used.

3.2.4 Recirculating aquaculture systems (RAS)

In RAS systems, shrimp are cultured in ponds or tanks equipped with agitators and aerators suited to their growth. Shrimp ponds or tanks collect waste, which is pumped into external mechanical and biological filtration systems for treatment (Chen et al., 2024). The system continuously filters solids like feces, uneaten feed, molted shrimp shells, dead algae, and suspended organic matter in pond water, which are continuously filtered and treated separately in the recirculation tanks. After removing harmful substances, water is biologically treated and recirculated to the shrimp ponds. Continuous waste removal, combined with beneficial microbes, keeps pond water clean. Toxic gases (NH_3, NO_2^-, and H_2S) remain within safe limits, reducing disease, allowing higher stocking densities, and improving yield. The typical operating principle of the RAS farming system is illustrated in Figure 1. The RAS consists of supplementary processes that allow wastewater to be reused for the culture tanks). It is divided into two types: partial water exchange systems (10%-70% water recirculated per day) and full water recirculation systems (less than 10% water replaced per day). RAS includes shrimp culture tanks, settling and mechanical filtration tanks, biological filtration tanks, disinfection equipment, and water supply, drainage, and aeration piping systems. Initially, wastewater is transferred from culture tanks to filtration units. Solid particles settle into a sludge collection pit. Water is then filtered through materials such as sand, gravel, fabric, and mesh (Duong et al., 2019). Large particles are retained and moved to the sludge tank. After this stage, water still contains high concentrations of dissolved ammonia (NH_3) and remains un-

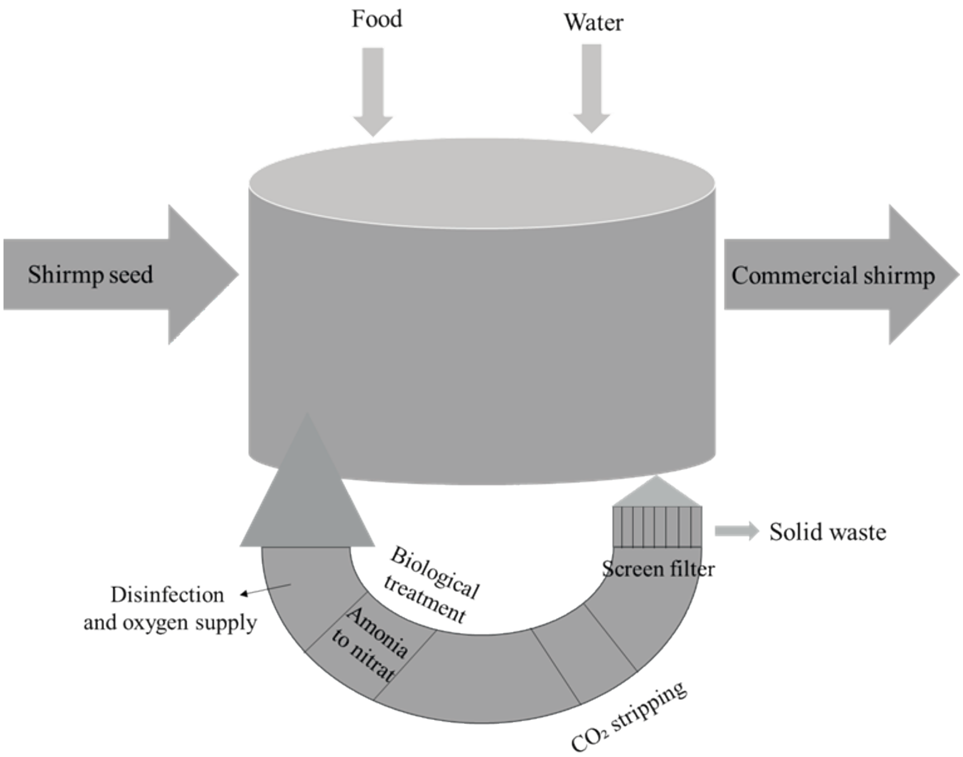

FIGURE 1: Diagram of the RAS system.

treated (Mohammadi et al., 2016). Aerobic, facultative, and anaerobic bacteria in biological filters perform nitrification and denitrification. These bacterial groups convert Nitrogen- and carbon-based compounds into non-toxic forms (Vu et al., 2023). The treated water is pumped back to the culture tanks. Aeration operates continuously to supply sufficient oxygen for bacterial degradation. Disinfection is crucial for eliminating pathogens and controlling microbes to prevent disease in culture ponds. UV light or ozone can be used during this stage.

Throughout the culture period, water circulates in a closed system with no replacement, with only a small amount of fresh water added to compensate for evaporation losses (Hung et al., 2017). The filtration system must operate continuously throughout the culture cycle (3-5 months), and aeration must be maintained daily; therefore, a stable power supply for the water pumps is essential. Among aquaculture wastewater treatment methods, RAS is considered a superior solution due to its integration of multiple outstanding advantages. Therefore, researching and improving the RAS technology process to suit wastewater from whiteleg shrimp farming, while adapting to Vietnam's technical and economic conditions, is essential (Viet Do et al., 2022).

Recirculating aquaculture system (RAS) technology with low water exchange is currently applied on a limited scale and is mainly implemented in research projects and pilot models rather than in widespread commercial shrimp farming. The main advantage of this technology lies in its high treatment efficiency, allowing effective control of water quality under intensive culture conditions. RAS operates without the use of antibiotics or chemical additives, thereby minimizing negative environmental impacts, creating a safe growth environment for shrimp, and significantly reducing the risk of disease outbreaks.

Despite these advantages, RAS technology also presents notable limitations. The most significant drawback is the high initial investment cost, which is approximately 45-60% higher than that of conventional shrimp farming systems. In addition, the operation of RAS requires skilled personnel with professional expertise and appropriate training to ensure stable system performance and effective management. These factors currently limit the large-scale adoption of RAS in shrimp farming practices.

In RAS, treated wastewater is not completely discharged but is reused repeatedly within the same system. This requires the effluent quality to achieve a high standard, not only ensuring the removal of organic matter, toxic compounds, and pathogenic agents, but also maintaining long-term stability to prevent pollutant accumulation during recirculation.

To overcome these limitations, membrane-based treatment technologies have attracted increasing attention because of their ability to provide effective solid–liquid separation and improve effluent quality under recirculating conditions. Among available membrane materials, ceramic membrane is considered particularly suitable for aquaculture applications due to its high mechanical strength, chemical resistance, thermal stability, and tolerance to harsh cleaning procedures, allowing stable long-term operation in complex wastewater environments. In addition, ceramic membranes exhibit superior durability compared with polymeric membranes, making them more appropriate for intensive and continuous operation in RAS.

To further enhance treatment efficiency, recent studies have focused on surface modification of ceramic membranes using nano-Titanium dioxide. Under Ultraviolet light irradiation, TiO_2 coated ceramic membranes can effectively degrade various organic compounds, proteins, and antibiotics resistant to biodegradation, which are characteristic pollutants in shrimp aquaculture wastewater. Moreover, TiO_2 coating improves membrane hydrophilicity, thereby reducing foulant accumulation and microbial attachment on the membrane surface, which helps mitigate membrane fouling one of the major operational challenges in recirculating systems. With these combined advantages, TiO_2 modified ceramic membranes not only improve pollutant removal efficiency but also extend operational cycles, reduce maintenance requirements, and enhance the overall sustainability of RAS operation.

3.3 Advanced membrane based treatment for shrimp wastewater

3.3.1 Ceramic membrane technology in wastewater treatment

In recent years, several innovative technologies have been increasingly applied to mitigate the impact of pollution caused by shrimp farming on surface water bodies, including the RAS. Among these, membrane filtration techniques have shown significant promise in enhancing treatment efficiency and enabling water reuse (Do, Bui, & Vu, 2023; Duong et al., 2020). In particular, ceramic membranes have attracted attention due to their superior properties compared to conventional polymer membranes, such as greater mechanical, thermal, and chemical stability, resulting in extended lifespan and improved fouling resistance (Ayode Otitoju et al., 2020). However, membrane fouling remains a significant challenge (Do & Chu, 2022). To address this, modifying ceramic membranes with photocatalytic nanomaterials has attracted considerable interest, aimed at enhancing both pollutant removal efficiency and antifouling performance (Pereira et al., 2011). Titanium dioxide (TiO_2), owing to its high quantum yield, chemical stability, and cost-effectiveness, is widely used as a coating to enhance photocatalytic activity (Dharma et al., 2022; Radeka et al., 2014).

3.3.2 Nano TiO_2 modified ceramic membranes

In the context of increasing water pollution, TiO_2 photocatalysis has emerged as an effective solution due to its ability to generate highly oxidative hydroxyl (•OH) and superoxide (O_2^-•) radicals, capable of degrading recalcitrant organic pollutants (Hassaan et al., 2023).

Analysis of 4,500 scientific publications from 2019-2024 using VOSviewer indicates two concurrent research trends: improving photocatalytic materials and integrating them with physical treatment platforms, particularly membrane technology (Figure 2). Doping TiO_2 with metal or non-metal elements can improve its adsorption capacity and thus enhance water treatment efficiency. However, recovering dispersed TiO_2 powders from the reaction medium is challenging, limiting reusability and increasing operating costs. To overcome this, various support materials have been used to immobilize TiO_2, facilitating catalyst recovery (Cruz Moreno et al., 2025). Effective substrates include ceramics, activated carbon, glass, composite, stainless steel, and zeolites. Among them, ceramics stand out due to their low cost, natural abundance of clay, tunable porosity, and excellent thermal, chemical, and mechanical

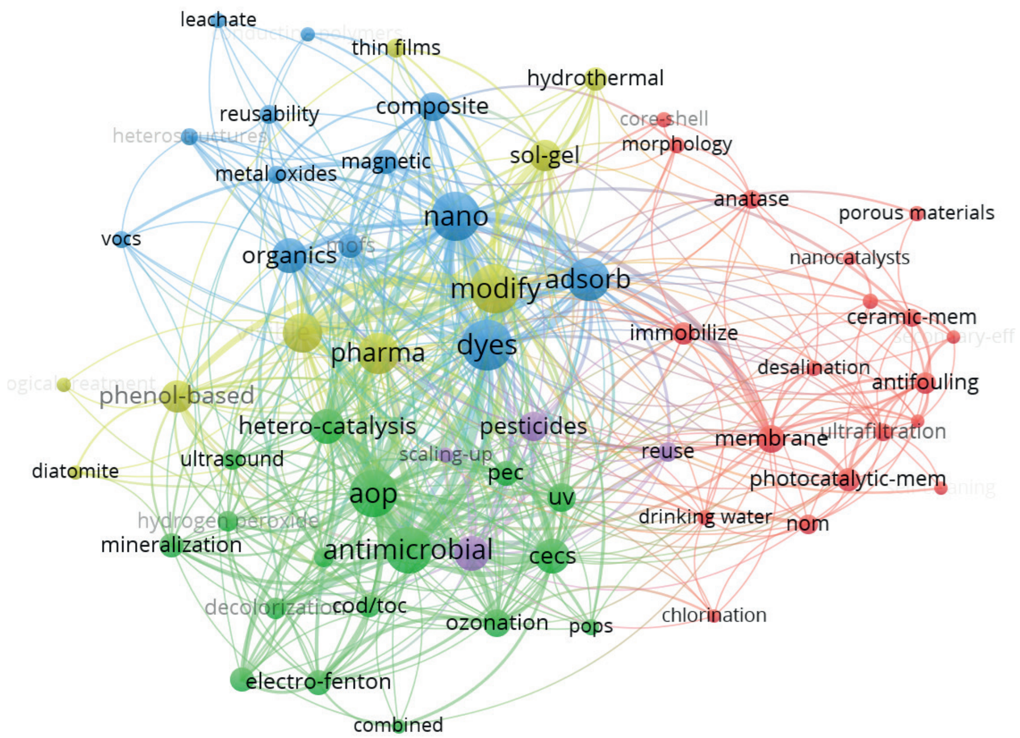

FIGURE 2: Research trends on TiO_2 photocatalysis in water and wastewater treatment.

stability (Morjène et al., 2020; Zendehzaban et al., 2013). Nano TiO_2 coated ceramic membranes have proven effective in degrading pollutants present in shrimp farm wastewater, including organic compounds, antibiotics, and nitrogenous substances (2023; Shi et al., 2013).

Incorporating or coating TiO_2 onto ceramic membranes allows simultaneous physical filtration and photocatalytic oxidation, forming photocatalytic membrane reactors (PMRs). Under UV or visible light irradiation, the generated electron-hole pairs (e^-/h^+) trigger free radical reactions that degrade organic compounds on the membrane surface, reduce fouling, and extend operational lifespan.

The effectiveness of TiO_2 modified ceramic membranes in removing various pollutants has been demonstrated in numerous studies. Table 6 summarizes representative research on the performance of nano TiO_2-coated ceramic membranes for water and wastewater treatment.

From the table, it can be seen that TiO_2 modified ceramic membranes have demonstrated broad applicability in treating a variety of wastewater pollutants, including azo dyes, proteins, oils, and recalcitrant organics. Their effectiveness arises from the synergy between mechanical filtration and photocatalytic degradation: physical retention captures larger contaminants, while photocatalytic activity generates hydroxyl and superoxide radicals under UV or visible light, decomposing smaller or recalcitrant molecules. This dual function not only enhances removal efficiency but also mitigates membrane fouling and prolongs operational lifespan.

Optimal performance depends on pore size, membrane structure, and light exposure. Nano and ultrafiltration membranes (1-50 nm) balance retention and photocatalytic efficiency for dyes and proteins, whereas microfiltration membranes handle larger particles and emulsified oils. Doping TiO_2 with metals or non metals (Ag, Ni, N) further improves antimicrobial activity, broadens light absorption, and enhances pollutant degradation. Reported removal efficiencies are high..., >90% for dyes and proteins, 90-98.5% for oils, and 99.9% bacterial inactivation.

Despite these advantages, challenges remain. Photocatalytic efficiency can be limited by high turbidity or surface fouling, and thick TiO_2 coatings may reduce water flux. Therefore, careful optimization of layer thickness, pore size, and light accessibility is essential for practical applications. Overall, TiO_2 modified ceramic membranes offer a promising, versatile solution for advanced wastewater treatment, effectively combining filtration and photocatalysis for high removal efficiency and reduced fouling.

3.3.3 Integration of membrane bioreactor (MBR) systems TiO_2 modified

In conventional shrimp farming, water is typically sourced and pretreated before being supplied to the culture ponds. In contrast, the proposed system (Figure 3) integrates the shrimp pond with a wastewater treatment unit designed to treat and recirculate the water, thus forming a closed-loop system. The technological layout for the recirculating wastewater treatment system using MBR and nano TiO_2-modified ceramic membranes is illustrated in Figure 4.

Initially, wastewater from the shrimp pond is pumped through a coarse screen to remove solid waste such as shrimp remains and other debris (Figure 4). It then flows into an equalization tank to regulate flow rate and homogenize water quality prior to treatment. The pretreated water is sent to the primary treatment units using physicochemical and biological methods. In the biological treatment stage, the water passes through aerobic and anoxic tanks to remove organic matter and nutrients. Following biological treatment, activated sludge is separated by the TiO_2-modified ceramic membranes (Mozia et al., 2015). To maximize photocatalytic performance, place the mem-

TABLE 6: Studies on TiO_2 nanoparticle modified ceramic membranes for wastewater treatment.

Membrane type	Functionalization method	Target pollutants	Operating conditions	Removal efficiency / Key results
Ceramic membrane coated with TiO_2 nanofibers	Doping, coating, functionalization	Azo dyes (MB, RB5, CR, DR80, AO, CYX)	pH ~8, UVA 365 nm	MB: from 40.84% (retention) to 97.74% with UVA irradiation; optimal pore size 10-50 nm
Ceramic ultrafiltration (UF) TiO_2 membrane	–	Proteins (BSA)	Pore size 6-14 nm, UVA irradiation	Retention 98–100% BSA; TiO_2-Ag composite achieves ~100% under visible light
Ceramic microfiltration (MF) TiO_2 membrane	–	Proteins (BSA)	Pore size 530 nm, UV-A irradiation	Removal 70% BSA, high water flux 3000 LMH.bar $^{-1}$
Ceramic TiO_2 membrane	Ag/TiO_2 nanofiber coating	Bacteria, MB, TOC	UV 100 mW/cm², 98 min	E. coli 99.9%, MB 88%, TOC 99%; flux ~5 L/m².bar
Al_2O_3 tubular membrane coated with TiO_2	Coating	Organic compounds, ink, dyes (humic acid, methyl orange)	UV light 1 W/m²	Fouling-induced flux decline reduced to 27% (vs. 67% without irradiation)
Al_2O_3 / Ti substrate coated with TiO_2 nanostructures	Coating / rod-like	Pesticides (Diuron, Chlorfenvinphos)	UV 10-300 W/m²	Removal: Diuron 78%, Chlorfenvinphos 68%; flux ~15 L/m².bar
Al_2O_3 membrane coated with N-doped TiO_2 (N-TiO_2)	Nitrogen doping	Organic compounds	Pore size 200-800 nm, visible light	Flux decline 12-50%, enhanced organic degradation
Al_2O_3 membrane coated with TiO_2/Ag/HAP	Combined coating	Bacteria (E. coli)	Light intensity 0.3 mW/cm², 60 min	6-log removal (LRV 6) of E. coli; flux decreased 20-25%

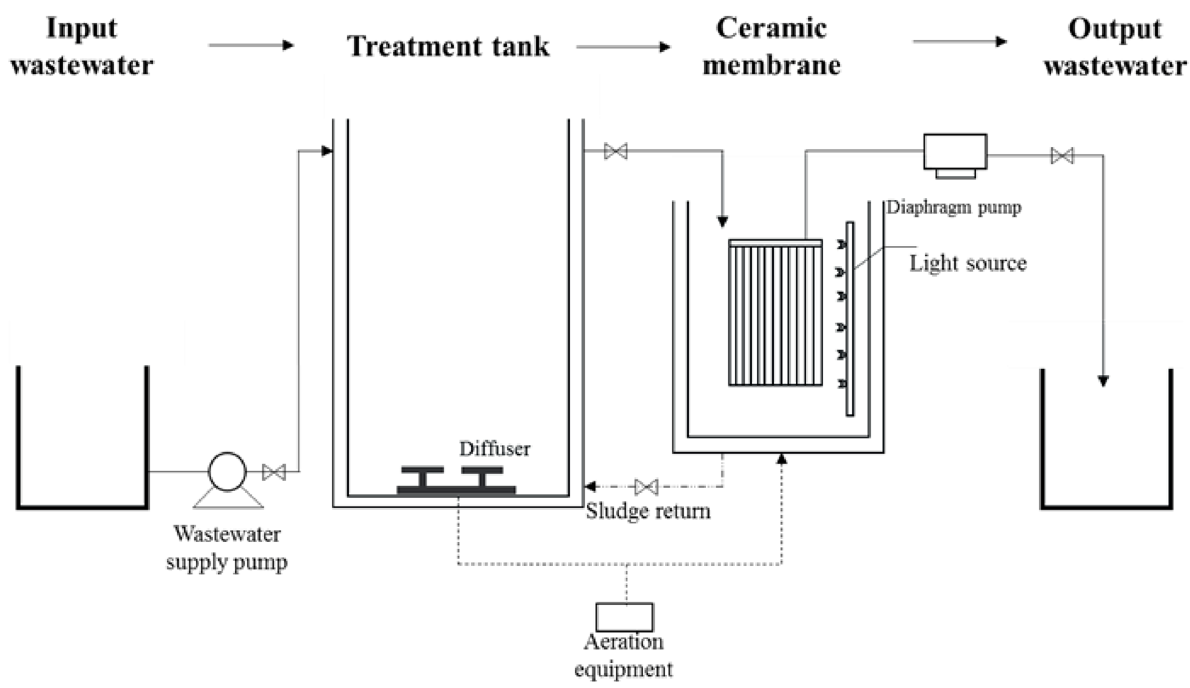

FIGURE 3: Proposed process for the integrated physico-chemical and biological.

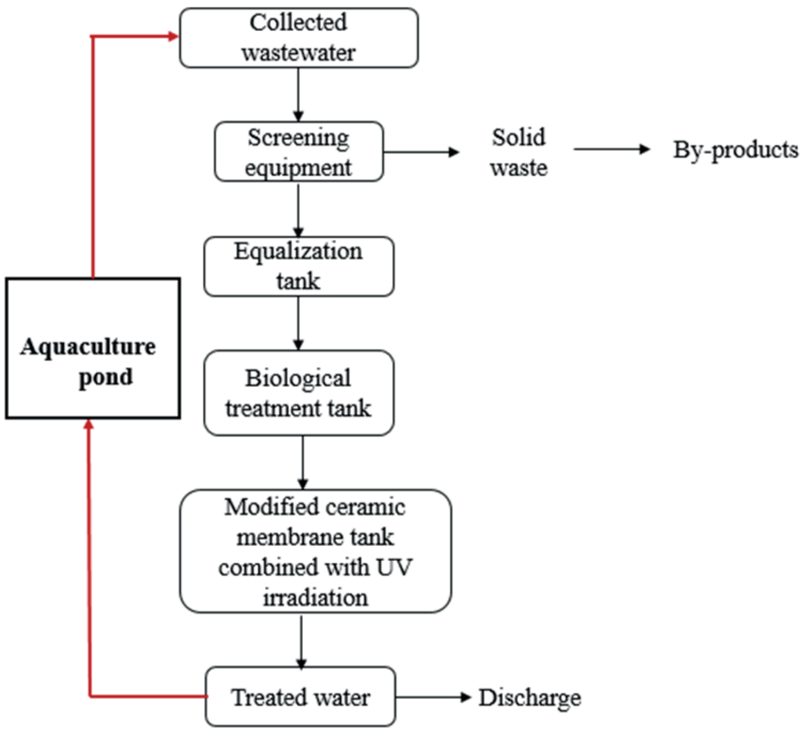

FIGURE 4: Process flow diagram of the recirculating wastewater treatment system for shrimp farming using MBR technology with a modified ceramic membrane.

brane module outside the biological reactor (Loddo et al., 2025; Zheng et al., 2017).

Under UV light, the TiO_2 coating performs physical filtration and degrades refractory organic compounds such as antibiotics used during shrimp farming and residual organics entirely removed in the bioreactor (Kabir et al., 2020). Additionally, UV light also acts as a disinfectant. With the integration of multiple treatment processes, the treated water can be recycled back to the shrimp pond via an intermediate tank or discharged into the environment if regulatory standards are met (Kruse et al., 2020). Furthermore, a supplementary step may be included in reintroducing essential minerals before reusing (Xie et al., 2022). The system - including pumps, aerators, mixers, sensors, and other control equipment - is managed by an automated panel. This setup conserves water, reduces discharge volumes, and maintains water quality suitable for shrimp farming.

3.3.4 Limitations and operational challenges TiO_2 modified

Despite their potential, TiO_2-modified ceramic membranes still face several limitations. Ceramic membranes cost significantly more than conventional polymer membranes.

Though resistant to corrosion and heat, eramic membranes are brittle and prone to cracking. Damaged membranes cannot be repaired and must be entirely replaced, raising costs and causing system downtime. Thus, strict mechanical safety protocols are required during transport, installation, and operation to avoid impact and vibrations. Although nano TiO_2 coatings enhance fouling resistance, membrane clogging remains challenging, particularly in shrimp farm wastewater rich in proteins and polysaccharides (Nannou et al., 2025). A study integrating TiO_2 photocatalysis with ceramic membrane filtration showed promising results in reducing organic pollutants (El Sharkawy et al., 2023). However, regular cleaning was still required to maintain filtration performance. Variations in influent flow and pollutant load can destabilize the microbial community, leading to shock loads and incomplete treatment, accelerating membrane fouling and reducing lifespan. Therefore, stable system performance requires precise influent control, microbial support (through aeration, nutrients, or probiotics), and regular membrane cleaning. TiO_2-modified ceramic membranes are mainly limited to laboratory or small-scale pilot models. High investment and maintenance costs make it unsuitable for smallholder farmers without technical or financial support.

3.3.5 Economic and operational feasibility of nano TiO_2 modified ceramic membrane systems

Economic feasibility is an important factor influencing the practical adoption of advanced wastewater treatment technologies in shrimp aquaculture because treatment costs directly affect production efficiency and long-term operational sustainability. Ceramic membrane systems have attracted considerable attention because of their high chemical resistance, thermal stability, and long operational lifespan compared with polymeric membranes. However, their initial investment cost remains relatively high due to the expensive raw materials and manufacturing processes involved. In general, ceramic membranes may cost approximately 3-5 times more than conventional polymeric membranes. While polymer membranes cost around 200-1.000 US$/$m^2$, ceramic membranes (unmodified) range from 1,000-5,000 US$/$m^2$, representing a fivefold increase. Additionally, the nano TiO_2 material and the surface modification process incur further costs (Davari et al., 2025; Szymański et al., 2018).. To harness the photocatalytic capability of TiO_2, the system must be equipped with UV light sources, increasing capital, energy, and maintenance costs .although their service life can be significantly longer under harsh wastewater conditions. Membrane fouling remains one of the major operational challenges, particularly when treating shrimp wastewater containing suspended solids, organic matter, proteins, and microbial residues. Fouling leads to permeate flux decline and increases the frequency of chemical cleaning, thereby raising operational costs. In membrane bioreactor systems, aeration is commonly applied to control fouling accumulation and may account for a substantial proportion of total energy consumption.

For nano TiO_2 modified ceramic membranes, photocatalytic activity under ultraviolet irradiation improves membrane surface hydrophilicity and promotes degradation of organic pollutants, thereby reducing fouling intensity. However, ultraviolet irradiation also introduces additional energy demand. Depending on irradiation intensity and operating duration, UV related energy consumption may significantly increase total operating cost, particularly in continuous treatment processes.

Compared with conventional biological treatment technologies such as constructed wetlands or biofloc systems, membrane-based systems generally require higher capital investment but provide superior effluent quality and greater potential for water reuse. This advantage is particularly important because water reuse can reduce freshwater demand and improve biosecurity in shrimp farming operations.

To improve economic applicability, hybrid treatment systems combining biological pretreatment with membrane separation have been increasingly recommended. Biological pretreatment reduces pollutant loading before membrane filtration, thereby extending membrane lifespan and lowering cleaning frequency. Although the initial installation cost remains relatively high, long-term benefits such as stable treatment efficiency, reduced environmental discharge, and improved water reuse potential may partially offset the initial investment under practical production conditions.

4. CONCLUSIONS

Vietnam's shrimp farming sector has significantly increased productivity and economic value. However, it also exerts considerable pressure on the environment due to increasing pollution from pond effluents. Shrimp pond wastewater contains high and variable loads of organic matter, nutrients, and pathogenic microorganisms, necessitating more efficient and stable treatment solutions. Combining MBR technology with nano TiO_2-modified ceramic membranes has shown great potential in addressing these challenges. Its advantages, high pollutant removal efficiency, antifouling properties, antibacterial action, and extended membrane life, are well documented in worldwide studies. Integrating biological treatment and advanced membrane technology offers a promising pathway for shrimp wastewater treatment. It builds on current technologies and supports effective practices in shrimp aquaculture. This provides both a scientific and practical basis for the subsequent phases of this research. Developing and evaluating an MBR system using nano TiO_2-modified ceramic membranes for shrimp wastewater would be helpful to design a model that integrates biological treatment with advanced membrane filtration. TiO_2-modified ceramic membranes aim to enhance antibacterial properties, reduce fouling, and extend system longevity.. Future studies should focus on optimizing hydraulic retention time, mixed liquor suspended solids, and membrane operating pressure under practical shrimp farming conditions to improve long-term treatment efficiency and economic feasibility.

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REFERENCES

Ahmad, A. L., Chin, J. Y., Mohd Harun, M. H. Z., & Low, S. C. (2022). Environmental impacts and imperative technologies towards sustainable treatment of aquaculture wastewater: A review. Journal of Water Process Engineering, 46, 102553. https://doi.org/10.1016/j.jwpe.2021.102553

Ahmed, N., Cheung, W. W. L., Thompson, S., & Glaser, M. (2017). Solutions to blue carbon emissions: Shrimp cultivation, mangrove deforestation and climate change in coastal Bangladesh. Marine Policy, 82, 68-75. https://doi.org/10.1016/j.marpol.2017.05.007

Ahmed, Z., & Ambinakudige, S. (2024). How does shrimp farming impact agricultural production and food security in coastal Bangladesh? Evidence from farmer perception and remote sensing approach. Ocean and Coastal Management, 255, 107241. https://doi.org/10.1016/j.ocecoaman.2024.107241

Álvarez, X., & Otero, A. (2020). Nutrient removal from the centrate of anaerobic digestion of high ammonium industrial wastewater by a semi-continuous culture of Arthrospira sp. and Nostoc sp. PCC 7413. Journal of Applied Phycology, 32(5), 2785-2794. https://doi.org/10.1007/s10811-020-02175-4

Amoako Johnson, F., Hutton, C. W., Hornby, D., Lázár, A. N., & Mukhopadhyay, A. (2016). Is shrimp farming a successful adaptation to salinity intrusion? A geospatial associative analysis of poverty in the populous Ganges–Brahmaputra–Meghna Delta of Bangladesh. Sustainability Science, 11(3), 423-439. https://doi.org/10.1007/s11625-016-0356-6

Aquino, R. V. S. d., Barbosa, A. A., Carvalho, R. F. d., Silva, M. G., Nascimento Júnior, W. J. d., Silva, T. D. d., Silva, J. P., & Rossiter Sá da Rocha, O. (2019). Degradation study of tris(2-butoxyethyl) phosphate with TiO2 immobilized on aluminum meshes employing artificial neural networks. Water Science & Technology, 80(6), 1163-1173. https://doi.org/10.2166/wst.2019.363

Arun, J., Nachiappan, S., Rangarajan, G., Alagappan, R. P., Gopinath, K. P., & Lichtfouse, E. (2023). Synthesis and application of titanium dioxide photocatalysis for energy, decontamination and viral disinfection: a review. Environmental Chemistry Letters, 21(1), 339-362. https://doi.org/10.1007/s10311-022-01503-z

Ayalew, A. A. (2022). A critical review on clay-based nanocomposite particles for application of wastewater treatment. Water Science & Technology, 85(10), 3002-3022. https://doi.org/10.2166/wst.2022.150

Ayode Otitoju, T., Ugochukwu Okoye, P., Chen, G., Li, Y., Onyeka Okoye, M., & Li, S. (2020). Advanced ceramic components: Materials, fabrication, and applications. Journal of Industrial and Engineering Chemistry, 85, 34-65. https://doi.org/10.1016/j.jiec.2020.02.002

Banu, J. R., Kaliappan, S., Do, K. U., James, A., & Yeom, I. T. (2009). Combined Treatment of Domestic Wastewater using Anaerobic and Solar Photocatalytic Treatment. Water Quality Research Journal, 44(4), 393-398. https://doi.org/10.2166/wqrj.2009.039

Banu, J. R., Kaliappan, S., Kumar, A., Yeom, I. T., & Do, K. U. (2011). Effect of low temperature thermochemical pretreatment on sludge reduction potential of membrane bioreactor treating primary treated dairy wastewater. Water Quality Research Journal, 46(4), 312-320. https://doi.org/10.2166/wqrjc.2011.026

Bohnes, F. A., & Laurent, A. (2021). Environmental impacts of existing and future aquaculture production: Comparison of technologies and feed options in Singapore. Aquaculture, 532, 736001. https://doi.org/10.1016/j.aquaculture.2020.736001

Chen, F., Qiu, T., Xu, J., Zhang, J., Du, Y., Duan, Y., Zeng, Y., Zhou, L., Sun, J., & Sun, M. (2024). Rapid Real-Time Prediction Techniques for Ammonia and Nitrite in High-Density Shrimp Farming in Recirculating Aquaculture Systems. Fishes, 9(10), 386. https://doi.org/10.3390/fishes9100386

Chuaicham, C., Trakulmututa, J., Shu, K., Shenoy, S., Srikhaow, A., Zhang, L., Mohan, S., Sekar, K., & Sasaki, K. (2023). Recent Clay-Based Photocatalysts for Wastewater Treatment. Separations, 10(2), 77. https://doi.org/10.3390/separations10020077

Cruz Moreno, D., Neri Álvarez, M., Ortiz Rabell, G., Neri Flores, M. A., & Fajardo San Miguel, G. (2025). Functionalized nanoparticles-based surface treatment as an alternative to mitigate deterioration in fired clay materials. Discover Applied Sciences, 7(5), 391. https://doi.org/10.1007/s42452-025-06872-y

Danfá, S., Martins, R. C., Quina, M. J., & Gomes, J. (2021). Supported TiO2 in Ceramic Materials for the Photocatalytic Degradation of Contaminants of Emerging Concern in Liquid Effluents: A Review. Molecules, 26(17), 5363. https://doi.org/10.3390/molecules26175363

Davari, N., Falletta, E., Bianchi, C. L., Yargeau, V., Rodriguez Seco, C., & Boffito, D. C. (2025). Comparing the photocatalytic activity of suspended and floating Ag-decorated TiO2 for dye removal. Tetrahedron Green Chem, 5, 100059. https://doi.org/10.1016/j.tgchem.2024.100059

de Paula, R. Z., Fontana, L., & de Jesus, T. A. (2024). Phosphorus removal by free water surface constructed wetlands for the wastewater treatment: bibliometric and bibliographic review. Discover Water, 4(1), 49. https://doi.org/10.1007/s43832-023-00050-0

Dharma, H. N. C., Jaafar, J., Widiastuti, N., Matsuyama, H., Rajabsadeh, S., Othman, M. H. D., Rahman, M. A., Jafri, N. N. M., Suhaimin, N. S., Nasir, A. M., & Alias, N. H. (2022). A Review of Titanium Dioxide (TiO(2))-Based Photocatalyst for Oilfield-Produced Water Treatment. Membranes (Basel), 12(3). https://doi.org/10.3390/membranes12030345

Dinesh Kumar, M., Gopikumar, S., Uan, D. K., Adishkumar, S., & Rajesh Banu, J. (2020). Constructed Wetlands: An Emerging Green Technology for the Treatment of Industrial Wastewaters. In R. N. Bharagava (Ed.), Emerging Eco-friendly Green Technologies for Wastewater Treatment (pp. 21-44). Springer Singapore. https://doi.org/10.1007/978-981-15-1390-9_2

Dinesh Kumar, S., Santhanam, P., Park, M. S., & Kim, M.-K. (2016). Development and application of a novel immobilized marine microalgae biofilter system for the treatment of shrimp culture effluent. Journal of Water Process Engineering, 13, 137-142. https://doi.org/10.1016/j.jwpe.2016.08.014

Do, K. U., Bui, T. S., & Vu, N. T. (2023). Combination of Membrane-Based Biochar for Ammonium Removal from Domestic wastewater—A Review. In M. P. Shah (Ed.), Microbial Technologies in Industrial Wastewater Treatment (pp. 319-335). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-2435-6_16

Do, K. U., Bui, T. T. N., Tran, H. T., & Chu, X. Q. (2023). Effect of Organic Loading Rates on Performance of Treating Dairy Wastewater in a Lab-Scale Sequencing Batch Reactor. International Journal of Engineering and Technology Innovation, 13(2), 150-159. https://doi.org/10.46604/ijeti.2023.10763

Do, K. U., & Chu, X. Q. (2022). Performances of membrane bioreactor technology for treating domestic wastewater operated at different sludge retention time. In M. Shah, S. Rodriguez-Couto, & J. Biswas (Eds.), Development in Wastewater Treatment Research and Processes (pp. 107-122). Elsevier. https://doi.org/10.1016/B978-0-323-85583-9.00010-7

Do, K. U., Kim, J. H., & Chu, X. Q. (2018). Sludge characteristics and performance of a membrane bioreactor for treating oily wastewater from a car wash service station. Desalination and Water Treatment, 120, 166-172. https://doi.org/10.5004/dwt.2018.22716

Do, K. U., Le, T. L., & Nguyen, T. L. (2022). Application of Zero Valent Iron to Removal Chromium and Other Heavy Metals in Metallurgical Wastewater. In Sustainable Water Treatment (pp. 415-440). https://doi.org/10.1002/9781119480075.ch11

Do, K. U., & Tran, M. H. (2023). Application of Membrane Technology Combined with Sequencing Batch Reactor for Treating Milk Wastewater. In M. P. Shah (Ed.), Sustainable Industrial Wastewater Treatment and Pollution Control (pp. 13-29). Springer Nature Singapore. https://doi.org/10.1007/978-981-99-2560-5_2

Do, T. C. M. V., Nguyen, D. Q., Nguyen, K. T., & Le, P. H. (2019). TiO2 and Au-TiO2 Nanomaterials for Rapid Photocatalytic Degradation of Antibiotic Residues in Aquaculture Wastewater. Materials, 12(15), 2434. https://doi.org/10.3390/ma12152434

Duong, H. C., Ansari, A. J., Cao, H. T., Nguyen, N. C., Do, K.-U., & Nghiem, L. D. (2020). Membrane distillation regeneration of liquid desiccant solution for air-conditioning: Insights into polarisation effects and mass transfer. Environmental Technology and Innovation, 19, 100941. https://doi.org/10.1016/j.eti.2020.100941

Duong, H. C., Tran, T. L., Ansari, A. J., Cao, H. T., Vu, T. D., & Do, K.-U. (2019). Advances in Membrane Materials and Processes for Desalination of Brackish Water. Current Pollution Reports, 5(4), 319-336. https://doi.org/10.1007/s40726-019-00121-8

El Sharkawy, H. M., Shawky, A. M., Elshypany, R., & Selim, H. (2023). Efficient photocatalytic degradation of organic pollutants over TiO2 nanoparticles modified with nitrogen and MoS2 under visible light irradiation. Scientific Reports, 13(1), 8845. https://doi.org/10.1038/s41598-023-35265-7

Ghamarpoor, R., Fallah, A., & Jamshidi, M. (2024). A Review of Synthesis Methods, Modifications, and Mechanisms of ZnO/TiO2-Based Photocatalysts for Photodegradation of Contaminants. ACS Omega, 9(24), 25457-25492. https://doi.org/10.1021/acsomega.3c08717

Goswami, R. K., Agrawal, K., & Verma, P. (2022). Phycoremediation of nitrogen and phosphate from wastewater using Picochlorum sp.: A tenable approach. Journal of Basic Microbiology, 62(3-4), 279-295. https://doi.org/10.1002/jobm.202100277

Halim, M. A., Aziz, D., Arshad, A., W. S. Wong, N. L., Nabi, M. M., Islam, M. A., & Syukri, F. (2025). A systematic analysis of recirculating aquaculture systems (RAS) and biofloc technology (BFT) for white leg shrimp (Litopenaeus vannamei) in the indoor farming system. Aquacultural Engineering, 110, 102544. https://doi.org/10.1016/j.aquaeng.2025.102544

Hassaan, M. A., El-Nemr, M. A., Elkatory, M. R., Ragab, S., Niculescu, V. C., & El Nemr, A. (2023). Principles of Photocatalysts and Their Different Applications: A Review. Topics in Current Chemistry, 381(6), 31. https://doi.org/10.1007/s41061-023-00444-7

Hemavibool, K., Sansenya, T., & Nanan, S. (2022). Enhanced Photocatalytic Degradation of Tetracycline and Oxytetracycline Antibiotics by BiVO4 Photocatalyst under Visible Light and Solar Light Irradiation. Antibiotics, 11(6), 761. https://www.mdpi.com/2079-6382/11/6/761

Hiep, N. T., Anh, L. H. Q., Tuan, P. D., Khang, D. S., Dong, P. D., Han, H. T. N., Thuan, D. D., & Nga, D. T. (2023). Improving the Treatment of Saline Wastewater from Shrimp Farms Using Hybrid Constructed Wetlands Models toward Sustainable Developmen. Environment and Natural Resources Journal, 21(6), 554-562. https://doi.org/10.32526/ennrj/21/20230146

Huang, C., Luo, Y., Zeng, G., Zhang, P., Peng, R., Jiang, X., & Jiang, M. (2022). Effect of adding microalgae to whiteleg shrimp culture on water quality, shrimp development and yield. Aquaculture Reports, 22, 100916. https://doi.org/10.1016/j.aqrep.2021.100916

Huang, X. f., Ye, G. y., Yi, N. k., Lu, L. j., Zhang, L., Yang, L. y., Xiao, L., & Liu, J. (2019). Effect of plant physiological characteristics on the removal of conventional and emerging pollutants from aquaculture wastewater by constructed wetlands. Ecological Engineering, 135, 45-53. https://doi.org/10.1016/j.ecoleng.2019.05.017

Hung, D. C., Nguyen, N. C., Uan, D. K., & Son, L. T. (2017). Membrane processes and their potential applications for fresh water provision in Vietnam. Vietnam Journal of Chemistry, 55(5), 533. https://doi.org/10.15625/2525-2321.2017-00504

Iber, B. T., & Kasan, N. A. (2021). Recent advances in Shrimp aquaculture wastewater management. Heliyon, 7(11), e08283. https://doi.org/10.1016/j.heliyon.2021.e08283

Kabir, J., Cramb, R., Alauddin, M., Gaydon, D. S., & Roth, C. H. (2020). Farmers' perceptions and management of risk in rice/shrimp farming systems in South-West Coastal Bangladesh. Land Use Policy, 95, 104577. https://doi.org/10.1016/j.landusepol.2020.104577

Kashem, A. H. M., Das, P., Hawari, A. H., Mehariya, S., Thaher, M. I., Khan, S., Abduquadir, M., & Al Jabri, H. (2023). Aquaculture from inland fish cultivation to wastewater treatment: a review. Reviews in Environmental Science and Bio/Technology, 22(4), 969-1008. https://doi.org/10.1007/s11157-023-09672-1

Krishnani, K. K., Kumar, N., Meena, K. K., & Singh, N. P. (2018). Bioremediation of Perturbed Waterbodies Fed with Wastewater for Enhancing Finfish and Shellfish Production. In B. B. Jana, R. N. Mandal, & P. Jayasankar (Eds.), Wastewater Management Through Aquaculture (pp. 185-206). Springer Singapore. https://doi.org/10.1007/978-981-10-7248-2_9

Kruse, J., Koch, M., Khoi, C. M., Braun, G., Sebesvari, Z., & Amelung, W. (2020). Land use change from permanent rice to alternating rice-shrimp or permanent shrimp in the coastal Mekong Delta, Vietnam: Changes in the nutrient status and binding forms. Science of The Total Environment, 703, 134758. https://doi.org/10.1016/j.scitotenv.2019.134758

Liu, X., Wang, Y., Liu, H., Zhang, Y., Zhou, Q., Wen, X., Guo, W., & Zhang, Z. (2024). A systematic review on aquaculture wastewater: Pollutants, impacts, and treatment technology. Environmental Research, 262, 119793. https://doi.org/10.1016/j.envres.2024.119793

Loddo, V., Umair, M., Kanwal, T., Palmisano, L., & Bellardita, M. (2025). Efficient photocatalytic removal of drugs in aqueous dispersions by using different TiO2 based semiconductors under UV and simulated solar light irradiation. Journal of Photochemistry and Photobiology A: Chemistry, 468, 116465. https://doi.org/10.1016/j.jphotochem.2025.116465

Mangott, A., Nappi, J., Delli Paoli Carini, A., Goncalves, P., Hua, K., Domingos, J. A., de Nys, R., & Thomas, T. (2020). Ulva lactuca as a functional ingredient and water bioremediator positively influences the hepatopancreas and water microbiota in the rearing of Litopenaeus vannamei. Algal Research, 51, 102040. https://doi.org/10.1016/j.algal.2020.102040

Mishra, A., Mehta, A., & Basu, S. (2018). Clay supported TiO2 nanoparticles for photocatalytic degradation of environmental pollutants: A review. Journal of Environmental Chemical Engineering, 6(5), 6088-6107. https://doi.org/10.1016/j.jece.2018.09.029

Mohammadi, Z., Sharifnia, S., & Shavisi, Y. (2016). Photocatalytic degradation of aqueous ammonia by using TiO2ZnO/LECA hybrid photocatalyst. Materials Chemistry and Physics, 184, 110-117. https://doi.org/10.1016/j.matchemphys.2016.09.031

Morjène, L., Tasbihi, M., Schwarze, M., Schomäcker, R., Aloulou, F., & Seffen, M. (2020). A composite of clay, cement, and wood as natural support material for the immobilization of commercial titania (P25, P90, PC500, C-TiO2) towards photocatalytic phenol degradation. Water Science & Technology, 81(9), 1882-1893. https://doi.org/10.2166/wst.2020.244

Mozia, S., Szymański, K., Michalkiewicz, B., Tryba, B., Toyoda, M., & Morawski, A. W. (2015). Effect of process parameters on fouling and stability of MF/UF TiO2 membranes in a photocatalytic membrane reactor. Separation and Purification Technology, 142, 137-148. https://doi.org/10.1016/j.seppur.2014.12.047

Nannou, C., Maroulas, K. N., Tsamtzidou, C., Ladomenou, K., & Kyzas, G. Z. (2025). Photocatalytic degradation of veterinary antibiotics in wastewaters: A review. Science of The Total Environment, 966, 178765. https://doi.org/10.1016/j.scitotenv.2025.178765

Nugraha, M. A. R., Dewi, N. R., Awaluddin, M., Widodo, A., Sumon, M. A. A., Jamal, M. T., & Santanumurti, M. B. (2023). Recirculating Aquaculture System (RAS) towards emerging whiteleg shrimp (Penaeus vannamei) aquaculture. International Aquatic Research, 15(1), 1-14. https://doi.org/10.22034/iar.2023.1973316.1361

Pereira, J. H. O. S., Vilar, V. J. P., Borges, M. T., González, O., Esplugas, S., & Boaventura, R. A. R. (2011). Photocatalytic degradation of oxytetracycline using TiO2 under natural and simulated solar radiation. Solar Energy, 85(11), 2732-2740. https://doi.org/10.1016/j.solener.2011.08.012

Phuong, N. M., Hung, N. H., Kha, T. M., & Hoa, C. P. (2023). Study on Aquaculture Wastewater Treatment by Aquatic Plants. VNU Journal of Science: Earth and Environmental Sciences, 39(4). https://doi.org/10.25073/2588-1094/vnuees.4995

Radeka, M., Markov, S., Lončar, E., Rudić, O., Vučetić, S., & Ranogajec, J. (2014). Photocatalytic effects of TiO2 mesoporous coating immobilized on clay roofing tiles. Journal of the European Ceramic Society, 34(1), 127-136. https://doi.org/10.1016/j.jeurceramsoc.2013.07.010

Razaviarani, V., Arab, G., Lerdwanawattana, N., & Gadia, Y. (2023). Algal biomass dual roles in phycoremediation of wastewater and production of bioenergy and value-added products. International Journal of Engineering and Technology Innovation, 20(7), 8199-8216. https://doi.org/10.1007/s13762-022-04696-6

Rodríguez Leal, S., Silva Acosta, J., Marzialetti, T., & Gallardo Rodríguez, J. J. (2023). Lab- and pilot-scale photo-biofilter performance with algal–bacterial beads in a recirculation aquaculture system for rearing rainbow trout. Journal of Applied Phycology, 35(4), 1673-1683. https://doi.org/10.1007/s10811-023-02981-6
Samui, S., Mallick, B., & Bailey, A. (2024). Impact of shifting from rice to shrimp farming on migration aspirations in Bangladesh. Regional Environmental Change, 24(4), 150. https://doi.org/10.1007/s10113-024-02312-6
Shan, A. Y., Ghazi, T. I. M., & Rashid, S. A. (2010). Immobilisation of titanium dioxide onto supporting materials in heterogeneous photocatalysis: A review. Applied Catalysis A: General, 389(1), 1-8. https://doi.org/10.1016/j.apcata.2010.08.053
Shi, Z. F., Zhang, S. M., & Guo, S. (2013). Treatment of Waste Seawater from Shrimp Farm Using a Photocatalytic Membrane Reactor. Applied Mechanics and Materials, 409-410, 199-203. https://doi.org/10.4028/www.scientific.net/AMM.409-410.199
Silerio Vázquez, F. d. J., González Burciaga, L. A., Antileo, C., Núñez Núñez, C. M., & Proal Nájera, J. B. (2024). Photocatalytic degradation of antibiotics in water via TiO2-x: Research needs for technological advancements. Journal of Hazardous Materials Advances, 16, 100506. https://doi.org/10.1016/j.hazadv.2024.100506
Szczepanik, B. (2017). Photocatalytic degradation of organic contaminants over clay-TiO2 nanocomposites: A review. Applied Clay Science, 141, 227-239. https://doi.org/10.1016/j.clay.2017.02.029
Szymański, K., Morawski, A. W., & Mozia, S. (2018). Effectiveness of treatment of secondary effluent from a municipal wastewater treatment plant in a photocatalytic membrane reactor and hybrid UV/H2O2 – ultrafiltration system. Chemical Engineering and Processing: Process Intensification, 125, 318-324. https://doi.org/10.1016/j.cep.2017.11.015
Tien Nguyen, N., Tran-Nguyen, P. L., & Vo, T. T. B. C. (2024). Advances in aeration and wastewater treatment in shrimp farming: emerging trends, current challenges, and future perspectives. Aqua Water Infrastructure, Ecosystems and Society, 73(5), 902-916. https://doi.org/10.2166/aqua.2024.328
Viet Do, P., Thao Nguyen, S., Tai Chau, T., Nguyen Tk, L., Touchet, A., Gutter, G., Mahl, P., & Phan, H. (2022). Growth assessment of various formulae of essential minerals and trace elements on whiteleg shrimp at different salinities. Vietnam Journal of Biotechnology, 20(1), 125-133. https://doi.org/10.15625/1811-4989/15781
Vu, N.-T., Ngo, T.-H., Nguyen, T.-T., & Do, K.-U. (2023). Performances of coffee husk biochar addition in a lab-scale SBR system for treating low carbon/nitrogen ratio wastewater. Biomass Conversion and Biorefinery, 13(6), 5273-5282. https://doi.org/10.1007/s13399-021-01788-0
Vu, N. T., Nguyen, T. H. T., & Do, K. U. (2021). Removal of ammonium from aqueous solution by using dried longan peel as a low-cost adsorbent. In M. Shah, S. Rodriguez-Couto, & K. Mehta (Eds.), The Future of Effluent Treatment Plants (pp. 569-588). Elsevier. https://doi.org/10.1016/B978-0-12-822956-9.00029-5
Xie, Y., Wang, J., Ren, F., Shuai, H., & Du, G. (2022). Nonmetallic Mineral as the Carrier of TiO2 Photocatalyst: A Review [Review]. Frontiers in Catalysis, Volume 2 - 2022. https://doi.org/10.3389/fctls.2022.806316
Yang, L., Jin, X., Hu, Y., Zhang, M., Wang, H., Jia, Q., & Yang, Y. (2023). Technical structure and influencing factors of nitrogen and phosphorus removal in constructed wetlands. Water Science & Technology, 89(2), 271-289. https://doi.org/10.2166/wst.2023.414
Zendehzaban, M., Sharifnia, S., & Hosseini, S. N. (2013). Photocatalytic degradation of ammonia by light expanded clay aggregate (LECA)-coating of TiO2 nanoparticles. Korean Journal of Chemical Engineering, 30(3), 574-579. https://doi.org/10.1007/s11814-012-0212-z
Zhang, S., Ban, Y., Xu, Z., Cheng, J., & Li, M. (2016). Comparative evaluation of influencing factors on aquaculture wastewater treatment by various constructed wetlands. Ecological Engineering, 93, 221-225. https://doi.org/10.1016/j.ecoleng.2016.05.029
Zhao, J., Peng, L., & Ma, X. (2025). Innovative microalgae technologies for mariculture wastewater treatment: Single and combined microalgae treatment mechanisms, challenges and future prospects. Environmental Research, 266, 120560. https://doi.org/10.1016/j.envres.2024.120560
Zheng, X., Shen, Z.-P., Shi, L., Cheng, R., & Yuan, D.-H. (2017). Photocatalytic Membrane Reactors (PMRs) in Water Treatment: Configurations and Influencing Factors. Catalysts, 7(8), 224. https://www.mdpi.com/2073-4344/7/8/224
Zhimiao, Z., Xiao, Z., Zhufang, W., Xinshan, S., Mengqi, C., Mengyu, C., & Yinjiang, Z. (2019). Enhancing the pollutant removal performance and biological mechanisms by adding ferrous ions into aquaculture wastewater in constructed wetland. Bioresource Technology, 293, 122003. https://doi.org/10.1016/j.biortech.2019.122003