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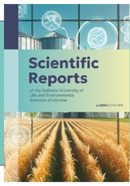

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Optimisation of biofiltration in closed aquatic systems for the sustainable development of aquaculture: Environmental aspects and technological innovations

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Abstract. The aim of the study was to establish the theoretical and applied foundations for optimising biofiltration in closed-loop aquaculture water systems, taking into account environmental requirements, technological innovations and the stability of biofilter operation. The study was conducted within a theoretical and applied framework, utilising scientific analysis, biochemical generalisation, comparative technological analysis, ecological generalisation and the systematisation of current data on biological water treatment. It was established that biofiltration ensured the conversion of ammonium nitrogen, nitrites, and nitrates through the sequential action of bacterial and archaeal communities, and that its stability was determined by temperature, pH, alkalinity, dissolved oxygen, salinity, organic load and the condition of the biofilm. Six main groups of aquatic pollutants, nine biofilter control parameters, seven biofiltration process options, six environmental effects and six innovative areas for optimisation were systematised. A review of the literature showed that the choice of biofilter type should depend on the nitrogen load, salinity, the need for CO_2 degassing, the level of automation and the complexity of operation. Reactors with a moving biofilm bed are suitable for intensive recirculating aquaculture systems (RAS), denitrification modules are suitable for controlling nitrate accumulation, and combined treatment is suitable for comprehensive water quality management. Design improvements, sensor monitoring, automated control and predictive models enhance the manageability of the nitrogen cycle and reduce the risk of toxic compound accumulation. It has been demonstrated that biofiltration helps to reduce the need for water exchange, limit contaminated effluent, minimise the risk of eutrophication and improve the efficiency of aquatic bioresource utilisation. The practical significance of the results lies in the fact that these results can be used by engineers at aquaculture enterprises, environmentalists,

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designers of closed-loop aquatic systems and specialists at fish farms to select the type of biofilter, set up water quality monitoring and reduce the environmental impact of production

Keywords: alkalinity; dissolved oxygen; nitrates; denitrification modules; toxic compounds

Introduction

Closed-loop aquaculture systems are currently regarded as the technological basis for the intensive rearing of aquatic organisms under conditions of restricted water intake, reduced discharge volumes and improved control over the production environment. In such systems, water quality is maintained not by a one-off renewal of the water volume, but by continuous circulation through mechanical, biological and physicochemical treatment units. Biofiltration plays a central role in this process, as it ensures the conversion of toxic forms of nitrogen formed as a result of the release of metabolic products, the decomposition of feed residues and the accumulation of organic matter. The relevance of research into biofiltration stems from the fact that closed aquaculture systems operate at high stocking densities, with intensive feeding rates and limited water exchange. Under such conditions, ammonium nitrogen and nitrites rapidly affect the physiological state of fish, shrimps, and other farmed organisms, whilst the accumulation of nitrates places a long-term nitrogen load on the system. Therefore, the stability of the biofilter depends on the activity of colonies of nitrifying and denitrifying microorganisms, temperature, pH, alkalinity, dissolved oxygen, salinity and the operating conditions of the biofilm.

In the literature, biofiltration in recirculating aquaculture systems (RAS) is primarily regarded as a controlled microbiological process of nitrogen compound transformation. In the work by P.P. Preena *et al.* (2021), the role of ammonium-oxidising, nitrite-oxidising and denitrifying microorganisms in maintaining the nitrogen balance in a RAS was systematised; it was shown that the system's efficiency depended not only on nitrification but also on the subsequent control of nitrates through denitrification processes. The temperature adaptation of microbial communities was examined in detail in the study by A. Neissi *et al.* (2022), which assessed the removal of ammonium and nitrite under low-temperature conditions. At 9°C, enriched microbial communities increased ammonium removal by 288% and nitrite removal by 181% compared with conventional biofilter communities, indicating the importance of pre-adapted microbiota for cold-water aquaculture systems. The technological aspects of biological treatment are discussed in detail in a review by A. Shitu *et al.* (2022) on moving-bed bioreactors. In this study, moving bed biofilm reactor (MBBR) technology was characterised as a solution for nitrification, simultaneous nitrification-denitrification and combined nitrogen removal, with the stability of such reactors being linked to salinity, organic loading, start-up duration and the operating regime of the biofilm.

The microbiological complexity of RAS extends beyond individual groups of nitrifiers, as confirmed by the analysis by S. Moschos *et al.* (2022). Based on next-generation sequencing studies, it has been shown that water, biofilm, biofilters and sludge form distinct prokaryotic niches, and the functional role encompasses not only nitrogen transformation but also the decomposition of organic matter and the maintenance of the system's microbial balance. The choice of filter medium has a direct impact on the start-up of the biofilter, as established by A. Nędzarek *et al.* (2022) in a rainbow trout rearing system. Following an initial increase in NH_4^+-N to 0.728-1.29 mg N/dm^3 and NO_2^--N to 0.982-5.198 mg N/dm^3, the concentrations of both parameters decreased to below 0.1 mg N/dm^3, and the removal efficiency of ammonium and nitrite nitrogen exceeded 90%. The complex of factors determining the operation of a recirculating system is summarised in the review by H. Li *et al.* (2023). This paper emphasises that temperature, dissolved oxygen, pH, salinity, stocking density, feeding, lighting and disinfection do not act in isolation, but rather have a combined effect on water quality, the accumulation of nitrogen compounds and the stability of the biofilter.

A separate area of current research concerns the management of biofilm between production cycles. S. Al Dakdouki *et al.* (2025) demonstrated that standard purification without proper control of the biofilter medium does not eliminate the microbiological 'memory' of the tank and preserves inter-tank heterogeneity, whereas the specialised T1 protocol ensured the equalisation of the initial microbial composition whilst preserving functionally significant communities. The management of microbial communities and water quality in RAS is elaborated upon in the study by Z. Lu *et al.* (2024), in which the RAS was considered as a tool for stabilising the aquatic environment during the larval rearing of *Scylla paramamosain*. The authors' findings confirm that the effectiveness of RAS depends not only on the technical organisation of water circulation, but also on the system's ability to maintain a balanced microbial structure and control key water quality parameters. The practical effectiveness of MBBR in marine aquaculture was confirmed in a study by J. Sun *et al.* (2026), carried out on a compact *Penaeus vannamei* rearing system. During the first 6 hours of operation, the MBBR achieved an NH_4^+-N removal rate of 0.513 $mg \cdot l^{-1} \cdot h^{-1}$, reducing its concentration from 1.99 ± 0.04 to 0.66 ± 0.03 mg/l, which corresponded to a 66.8% removal rate, whereas the sand filter removed 56.3% of suspended solids, and the foam separator reduced chemical oxygen demand by 58.3%. The latest insights into the spatiotemporal dynamics of microbial communities in RAS are presented in the paper by C. Hu *et al.* (2026). It was found that denitrification, anammox and nitrification together accounted for 45.2% of the functional genes of the nitrogen cycle, whilst the shift from r-strategists to K-strategists was associated with salinity, total dissolved solids, electrical conductivity, temperature, redox potential, pH and dissolved oxygen.

A synthesis of the cited sources demonstrated that biofiltration in closed aquatic systems is a complex microbiological and technological system. The main scientific findings focused on four interrelated areas: the selection of microbial communities, the control of the physicochemical parameters of the water, the choice of biofilter design, and the management of the biofilm during start-up, operation and disinfection. At the same time, the literature has not sufficiently integrated the theoretical mechanisms of processing marine aquaculture waste products with practical solutions for making aquaculture more environmentally friendly, reducing discharges and improving the efficiency of water bioresource utilisation.

The aim of the study was to provide a theoretical justification and applied analysis of approaches to optimising biofiltration in closed-loop aquaculture systems, taking into account environmental performance, technological innovations and the conditions for the stable operation of the biofilter. To achieve this aim, the following objectives were set: to elucidate the mechanisms of biofiltration-mediated transformation of waste products from marine aquaculture in closed aquatic systems, in particular the role of bacterial colonies in nitrification, denitrification, and the stabilisation of the nitrogen cycle. To determine the physicochemical parameters that ensure the stable operation of the biofilter, in particular temperature, pH, alkalinity, dissolved oxygen, salinity, and the concentrations of ammonium, nitrite, and nitrate nitrogen. To characterise practical approaches to the implementation of biofiltration and technological innovations that reduce the environmental impact of aquaculture and improve the efficiency of aquatic bioresource utilisation.

Materials and Methods

The study was conducted within a theoretical and applied framework, as its aim was to systematise current scientific approaches to optimising biofiltration in closed-loop aquaculture systems. The object of analysis was biofiltration processes in RASs, whilst the subject was the microbiological, technological and ecological factors determining the stability of biofilters, the efficiency of nitrogen compound conversion and the reduction of aquaculture's impact on the aquatic environment.

The methodological procedure for the study involved several consecutive stages: searching for relevant sources, the preliminary selection, content analysis, grouping into thematic blocks and the subsequent systematisation of the results. The search for publications was carried out in scientific databases and search engines such as Google Scholar, Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI, Frontiers, and on the official resources of the Food and Agriculture Organisation. The search utilised keywords and combinations thereof in Ukrainian and English: "biofiltration", "closed water systems", "recirculating aquaculture systems", "aquaculture", "nitrification", "denitrification", "nitrogen cycle", "biofilm", "water quality", "recirculating aquaculture system", "RAS", "biofiltration", "biofilter", "nitrification", "denitrification", "nitrogen removal", "biofilm", "water quality monitoring", "IoT sensors in aquaculture", "moving bed biofilm reactor", "MBBR".

The main time frame for the selection of sources was 2020-2026, which allowed taking into account the current state of development of biofiltration technologies in RAS. Individual works published prior to 2020 were included only where these works were of methodological or conceptual significance for explaining the basic mechanisms of biofiltration, nitrification, denitrification or the ecological role of RASs. A total of 32 sources were analysed, including peer-reviewed scientific articles, review papers, experimental studies, analytical materials and relevant documents from international organisations.

The inclusion criteria for the sources were: a direct link to biofiltration or RASs; the availability of data on the transformation of nitrogen compounds, biofilter stability, microbial communities, biofilter design types, water quality control parameters or the environmental effects of RAS; scientific relevance and practical applicability for analysing the sustainable development of aquaculture. Sources that dealt with aquaculture in general but did not contain information on biofiltration processes, closed-loop water systems, water quality control or the environmental impacts of RAS operation were excluded from the analysis. Publications lacking clear scientific reasoning, duplicates, popular materials without references to research data and sources, and those whose content did not correspond to the aim of the study were also excluded. The study's source base comprised peer-reviewed scientific articles, review papers and specialist analytical materials directly relating to biofiltration in RASs. The general environmental and technological context of RAS development was determined on the basis of materials from the Food and Agriculture Organization (2024a; 2024b) on the sustainable development of aquaculture. The biochemical aspects of nitrogen compound transformation and water quality control were examined using studies analysing TAN, NH_4^+, NH_3, NO_2^-, NO_3^-, pH, alkalinity, salinity and dissolved oxygen in closed aquaculture systems (Jafari *et al.*, 2024; Sarosh *et al.*, 2024). The microbiological section was compiled based on studies focusing on the role of biofilm, nitrifying microorganisms, Nitrospira and comammox in biofilter stability (Costigan *et al.*, 2024; Godzieba *et al.*, 2025). Technological options for biofiltration were systematised based on studies on modern types of biofilters and combined treatment schemes in RAS (Gupta *et al.*, 2024; Hashmi *et al.*, 2025). Innovative approaches to optimisation were summarised based on sources addressing sensor monitoring, automated control and the use of predictive models in closed water systems (Fan *et al.*, 2024; Flores-Iwasaki *et al.*, 2025; Malandrakis *et al.*, 2025).

Theoretical analysis, biochemical generalisation, microbiological generalisation, a systems approach, comparative technological analysis, ecological generalisation and technological systematisation were applied to review the sources. Theoretical analysis was used to determine the role of biofiltration in the functioning of closed aquaculture water systems. Biochemical generalisation was applied to explain the transformation of major nitrogen compounds in the biofilter, in particular the conversion of ammonium nitrogen to nitrite and nitrate, as well as to account for the dependence of the toxicity of non-ionised ammonia on pH, temperature and salinity. The microbiological analysis focused on characterising the role of ammonium-oxidising bacteria, ammonium-oxidising archaea, Nitrospira, comammox microorganisms and other biofilm components in the stability of the biofilter.

A systematic approach made it possible to consider the biofilter not as an isolated technical element, but as part of a unified water treatment circuit, interacting with mechanical filtration, aeration, oxygenation, CO_2 degassing, pH regulation, alkalinity control and feed load management. A comparative technological analysis was applied to examine the main types of biofiltration technologies: moving-bed biofilm reactors, trickling biofilters, submerged and fixed biofilters, sand biofilters, denitrification modules and combined treatment systems. The comparison criteria were the operating principle, type of filter medium, capacity for nitrification or denitrification, resistance to changes in organic and hydraulic load, operational complexity, and suitability for marine, brackish-water or freshwater RAS.

The analytical categories of the study were formed through repeated content coding of the sources. In the first stage, recurring indicators, processes and technological solutions related to biofiltration were identified from the sources. In the second stage, these were grouped according to the functional purpose. As a result, five main categorical blocks were formed: groups of aquatic pollutants; parameters for monitoring biofilter stability; types of biofiltration technologies; environmental effects of biofiltration; and innovative approaches to optimising closed aquatic systems. The groups of pollutants included ammonium nitrogen, nitrite, nitrate, dissolved organic matter, suspended solids and CO_2. The control parameters included temperature, pH, alkalinity, dissolved oxygen, salinity, TAN, nitrite, nitrate and suspended solids. The biofiltration process options were grouped according to the design principle and function within the water treatment system. The environmental effects were determined by the impact of biofiltration on water abstraction, discharges, eutrophication, biosafety, feed utilisation and the management of operational risks. Innovative approaches were categorised according to the expected impact on biofilter stability, nitrogen cycle control and reduction of environmental impact.

Separately, current approaches to the use of digital monitoring, sensor networks, automated dosing and predictive models in RAS were summarised. In this study, predictive models were neither developed nor tested experimentally; the models were considered solely as one of the current technological approaches to optimising biofiltration, based on an analysis of scientific publications.

The study did not involve conducting laboratory experiments, field trials of a specific recirculation system, or independent measurements of TAN, NO_2^-, NO_3^-, pH, temperature, salinity, alkalinity or dissolved oxygen; nor did it involve statistical modelling or testing the effectiveness of digital models. The results were derived through the synthesis, comparison, and systematisation of contemporary scientific and analytical sources, which enabled the role of biofiltration to be identified as a fundamental technological prerequisite for the environmentally oriented development of intensive aquaculture in closed aquatic systems.

Results and Discussion

Biofiltration in closed-loop aquaculture systems is a central component in maintaining stable water quality, as it is the biological transformation of dissolved metabolic products that ensures the continuous reuse of the aquatic environment. In recirculating systems, water is not completely discharged after passing through tanks or reservoirs containing aquatic organisms, but is returned to the process circuit following mechanical, biological and, where necessary, physicochemical treatment. This organisation of the water cycle reduces the need for a constant intake of fresh water and limits the volume of contaminated effluent, which is of direct importance for the environmental safety of intensive aquaculture (Food and Agriculture Organization, 2024a; Gupta *et al.*, 2024).

Within the structure of a closed water system, the biofilter serves to convert toxic nitrogen compounds formed as a result of the metabolic activity of marine cultures, the decomposition of feed residues and organic particles. The most important metabolic product is ammonium nitrogen, which in an aquatic environment consists of the sum of the ionised form NH_4^+ and non-ionised ammonia NH_3. It is precisely non-ionised ammonia that is the most toxic form for fish, crustaceans, and other farmed organisms. The ratio between NH_4^+ and NH_3 depends on pH, temperature and salinity; therefore, controlling these parameters is not merely auxiliary but a fundamental requirement for the stable operation of a biofilter (Jafari *et al.*, 2024; Sarosh *et al.*, 2024).

The main process of biofiltration is nitrification. It occurs in two consecutive stages. In the first stage, ammonium nitrogen is oxidised to nitrite by ammonium-oxidising bacteria and archaea. In the second stage, nitrite is converted to nitrate by nitrite-oxidising microorganisms. Nitrate is a less toxic form of nitrogen; however, in closed systems it accumulates gradually, so long-term operation of the system requires combining nitrification with water exchange, denitrification, plant or algal modules, as well as other nitrogen removal technologies (Gupta *et al.*, 2024; Dai *et al.*, 2026). This finding is supported by data from N. Ramli *et al.* (2020), who demonstrated the feasibility of integrating algal reactors into recirculating systems for the uptake of inorganic nitrogen. In the studies the authors analysed, the maximum nitrogen removal rate achieved by an algal reactor reached 1.4 g N m^{-2} day^{-1}, although the practical effectiveness of this approach depended on light intensity, hydraulic retention time, system configuration and reactor area.

The microbial communities in biofilters are not limited to the classic groups of nitrifiers. In marine and brackish water recirculation systems, ammonium-oxidising archaea, Nitrospira and comammox full nitrifiers play an important role, being capable of ensuring the complete conversion of ammonium to nitrate within a single microbial taxon (Yang *et al.*, 2024; Costigan *et al.*, 2024; Godzieba *et al.*, 2025). This refines the understanding of the biofilter as a complex microbial ecosystem, in which treatment efficiency depends not only on the loading area or flow rate, but also on the maturity of the biofilm, the ratio of autotrophic to heterotrophic microorganisms, the stability of the substrate load, and the absence of abrupt changes in the environment (Table 1).

Table 1. *Main metabolic products of marine cultures and biofiltration mechanisms for the transformation*

Component of the aquatic environment	Source of entry into the system	Main risk to aquaculture	Biofiltration or related control mechanism
Ammonium nitrogen (TAN)	Excretion via gills, feed decomposition, faeces	Toxic effects of NH_3, respiratory and metabolic disorders	Oxidation of ammonium to nitrite by ammonium-oxidising bacteria and archaea
Nitrite NO_2^-	Intermediate product of nitrification	Impaired oxygen transport, nitrite poisoning	Oxidation of nitrite to nitrate by nitrite-oxidising bacteria
Nitrate NO_3^-	End product of nitrification	Accumulation during low water exchange, risk of chronic exposure	Denitrification, water exchange, plant or algal modules
Dissolved organic matter	Feed residues, slime, metabolic products	Growth of heterotrophic bacteria, oxygen depletion	Mechanical filtration, biofiltration, control of feed loading

Table 1. *Continued*

Component of the aquatic environment	Source of entry into the system	Main risk to aquaculture	Biofiltration or related control mechanism
Suspended solids	Faeces, feed residues, biofilm fragments	Biofilter clogging, increased bacterial load	Drum filters, clarifiers, flotation tanks, regular sludge removal
Carbon dioxide CO_2	Respiration by aquatic organisms and microorganisms	Decrease in pH, impact on the buffer system	Degassing, aeration, alkalinity control

Source: compiled by the author based on L. Jafari *et al*. (2024), S. Sarosh *et al*. (2024), E. Costigan *et al*. (2024), X. Yang *et al*. (2024), M. Godzieba *et al*. (2025)

This classification shows that the metabolic by-products of marine aquaculture pose not isolated but interrelated risks to a closed aquatic system. Ammonium nitrogen, nitrite, and nitrate form a sequential chain of nitrogen loading; therefore, the effectiveness of biofiltration depends not only on the oxidation of ammonium, but also on the subsequent control of nitrite and the accumulation of nitrates. At the same time, organic matter, suspended solids and CO_2 affect the operation of the biofilter indirectly: these factors alter the oxygen regime, pH, the condition of the biofilm and the balance of microbial communities. Consequently, the biofilter in an RAS should be regarded not as a separate unit for nitrogen removal, but as part of a comprehensive water quality management system, where biological treatment must be combined with mechanical filtration, degassing, aeration and feed load control.

The findings indicate that the biofilter cannot be considered in isolation from other elements of the system. Its stability depends on the prior removal of solid particles, oxygen saturation of the water, regulation of pH and alkalinity, CO_2 removal, and the uniformity of the hydraulic load. If mechanical filtration is insufficient, organic particles enter the biofilter, stimulating the growth of heterotrophic microflora and reducing the proportion of nitrifying microorganisms. As a result, the rate of ammonium and nitrite oxidation decreases, and the system loses its ability to respond rapidly to changes in the feed load (Liu *et al.*, 2024; Fernandes *et al.*, 2026).

The stability of a biofilter is determined by a combination of physical, chemical and microbiological factors. Temperature directly affects the metabolic rate of fish and microorganisms, as well as the toxicity of ammonia. As the temperature rises, the activity of biological processes generally increases; however, the proportion of non-ionised NH_3 also increases at the same time. As the temperature decreases, nitrification slows down, creating a risk of ammonium nitrogen accumulation following an increase in feed load or the biomass of aquatic organisms (Sarosh *et al.*, 2024). pH is the second key parameter, as it determines the activity of nitrifying bacteria. Nitrification is accompanied by the consumption of alkalinity and a gradual decrease in pH. In closed systems, this means that the biofilter simultaneously purifies the water and alters its buffer state. Without regular monitoring of alkalinity, the system enters a state in which the microbiological oxidation of nitrogen becomes less stable. Research by L. Jafari *et al.* (2024), conducted using data from brackish-water systems with Atlantic salmon, confirmed that the stability of the biofilter depends not only on TAN and nitrite concentrations, but also on the interrelationship between alkalinity, CO_2 levels, pH and the carbonate equilibrium of the water.

Dissolved oxygen meets the energy requirements of nitrifying microorganisms and aquatic organisms. Nitrification is an aerobic process; therefore, oxygen deficiency reduces the rate of ammonium and nitrite conversion. In systems with high stocking densities, competition for oxygen arises between fish, the bacterial biofilm and heterotrophic microorganisms that degrade organic matter. Consequently, oxygen levels must be monitored not only in the rearing tanks but also directly within the biofilter zone. Salinity is of particular importance for marine and brackish-water systems. Sudden changes in salinity affect the osmotic state of aquatic organisms and the structure of the biofilter's microbial community (Table 2).

Table 2. *Parameters for monitoring biofilter stability in closed aquaculture systems*

Parameter	Functional significance	Consequence of deviation	Technical control method
Temperature	Regulates the metabolism of aquatic organisms and microorganisms	Change in nitrification rate, increased NH_3 toxicity	Temperature sensors, heat exchangers, automatic control
pH	Determines the activity of nitrifiers and the proportion of NH_3	Disruption of nitrification, changes in nitrogen toxicity	Buffering, alkalinity control, dosing of correctors
Alkalinity	Maintains carbonate equilibrium and pH stability	pH drop, unstable biofilter operation	Addition of carbonate buffers, regular analysis
Dissolved oxygen	Ensures aerobic nitrification	Accumulation of ammonium and nitrite	Aeration, oxygenation, hydraulic control
Salinity	Affects the osmotic state of aquatic organisms and the structure of the biofilter's microbial community	Changes in the activity of nitrifying microorganisms, disruption of biofilm stability	Gradual adaptation of the system, control of electrical conductivity, monitoring of salinity
TAN	Reflects the primary nitrogen load	Risk of toxic effects from ammonia	Biofiltration, optimisation of feeding, biomass control
Nitrite	Indicates incomplete nitrification	Nitrite poisoning	Enhancement of the second phase of nitrification, oxygen control
Nitrate	Indicates the accumulation of the end product of nitrification	Chronic nitrogen load	Denitrification, water exchange, integrated biomodules
Suspended solids	Affect the biofilm and bacterial load	Clogging of media, growth of heterotrophs	Mechanical filters, clarifiers, flotation units

Source: created by the author based on H. Li *et al*. (2023), L. Jafari *et al*. (2024), S. Sarosh *et al*. (2024), E. Costigan *et al*. (2024)

This summary demonstrates that biofiltration is not a standalone technical unit, but a process that requires a constant balance between load, oxygen conditions, the water's buffering capacity and the structure of the microbial community. In practical terms, this means that an increase in biomass or feeding rate must be accompanied by a review of the biofilter's nitrification capacity. If the biofilter does not have sufficient surface area for biofilm formation or operates under conditions of unstable pH, an increase in production intensity will not be accompanied by a corresponding improvement in water treatment quality.

The practical implementation of biofiltration in closed aquaculture systems is based on selecting the type of biofilter in accordance with the species of aquatic organisms, stocking density, feeding regime, salinity, temperature, permissible water exchange rate and the desired level of automation. In modern RAS systems, submerged biofilters, trickle biofilters, moving-bed reactors, fixed-bed reactors, sand biofilters, membrane bioreactors and combined treatment schemes are used (Gupta *et al*., 2024; Hashmi *et al*., 2025). Moving-bed biofilm reactors are widely used due to the combination of a large specific surface area of the carrier, constant contact between the biofilm and the water, and the ability to maintain the carriers in a suspended state through aeration or hydraulic mixing. In such systems, the biofilm forms on the surface of plastic or mineral carriers, whilst turbulence limits excessive fouling and ensures oxygen access to active zones. Innovative modifications to moving-bed biofilters are aimed at improving nitrogen removal efficiency, stabilising the microbial composition and reducing energy consumption (Zhou *et al.*, 2024; Zhang *et al.*, 2026).

Drip biofilters facilitate contact between water, air, and the biofilm on the surface of the media. The functional advantage lies in the simultaneous oxidation of nitrogen compounds and partial degassing of CO_2. However, such systems are susceptible to clogging, uneven water distribution and the accumulation of organic particles. Submerged fixed biofilters have a simpler design but require control of the hydraulic regime and periodic maintenance, as excessive accumulation of biomass reduces the permeability of the media. In systems with high packing density, biofiltration is combined with mechanical removal of solid particles. This is of fundamental importance, as suspended solids not only impair water quality but also alter the microbiological profile of the biofilter. The accumulation of organic particles increases the proportion of heterotrophic microflora, which competes with nitrifiers for oxygen and space within the biofilm (Liu *et al.*, 2024; Fernandes *et al.*, 2026). Consequently, an effective biofiltration system requires preliminary mechanical treatment, sludge removal and control of the feed coefficient (Table 3).

Table 3. *Process options for biofiltration in closed aquatic systems*

Type of biofilter	Basic operating principle	Advantage for RAS	Limitations or conditions for stability
Moving-bed biofilm reactor	Biofilm forms on moving carriers	High surface area, good aeration, adaptability to load	Requires stable aeration and control of carrier loss
Drip biofilter	Water passes through the media in contact with air	Combination of nitrification and degassing	Susceptible to clogging and uneven water distribution
Submerged biofilter	The biofilm-coated media is fully submerged in water	Simple design, stable contact with water	Risk of excess biomass accumulation
Fixed bed	Water flows through a stationary bed	High biofilm density	Requires control of hydraulic resistance
Sand biofilter	Biofilm forms on granular material	Combination of fine filtration and biological activity	Risk of silting up, need for backwashing
Denitrification biofilter	Anaerobic conversion of nitrate to gaseous nitrogen	Reduction in NO_3^- accumulation within the system	Requires control of the carbon source and anaerobic conditions
Combined biofilter	Combination of several types of treatment	Flexibility for different types of aquacultures	More complex operation and higher monitoring requirements

Source: compiled by the author based on W. Liu *et al.* (2024), S. Gupta *et al.* (2024), X. Zhou *et al.* (2024), Z. Hashmi *et al.* (2025), B. Zhang *et al.* (2026), P. Fernandes *et al.* (2026)

A comparison of biofiltration process options shows that the choice of biofilter type should depend on the production load, the type of aquatic organisms, salinity, feeding regime, available space, degassing requirements and the acceptable level of operational complexity. Moving-bed biofilm reactors are suitable for intensive systems with high or variable nitrogen loads, as the moving carriers provide a large contact area between the biofilm and the water, as well as a stable supply of oxygen. Trickling biofilters are suitable for use where, in addition to nitrification, additional aeration and partial CO_2 removal are required, although the efficiency depends on uniform water distribution and the prevention of clogging. Submerged and fixed biofilters may be suitable for systems with a stable hydraulic regime, but require control of excess biomass accumulation. Sand biofilters are appropriate when biological treatment needs to be combined with fine mechanical filtration; however, the operation requires regular backwashing. Denitrification biofilters are of particular importance in systems with low water exchange rates and a risk of NO_3^- accumulation, whilst combined treatment schemes are best suited to intensive RAS systems, where it is necessary to simultaneously control suspended solids, nitrogen compounds, CO_2, pH, alkalinity and the overall environmental load.

The practical efficiency of biofiltration depends on the maturation of the biofilm. A new biofilter does not provide full nitrification capacity immediately after start-up, as colonies of nitrifying microorganisms form gradually. The start-up period is characterised by fluctuations in TAN and nitrite levels; therefore, in industrial systems, pre-colonised media, bacterial inoculants, a gradual increase in biomass and controlled feeding are employed. Studies on rapid nitrification start-up show that the long-term performance of a biofilter is linked to the controlled development of the microbial community and the limitation of excessive organic loading (Liu *et al.*, 2024). For marine aquaculture, the adaptation of the biofilter to salinity is of particular importance. In brackish-water RAS systems, particularly in post-smolt salmon farming systems, the biofilter must operate under conditions where salinity and carbonate equilibrium alter the activity of nitrifiers. In such systems, it is important to maintain not only regulatory concentrations of TAN and nitrite, but also a stable relationship between alkalinity, CO_2, pH and degassing (Jafari *et al.*, 2024).

The ecological significance of biofiltration lies in the fact that it shifts intensive aquaculture from a model of continuous water intake and discharge to a model of controlled internal water circulation. Under such conditions, major pollutants do not enter natural water bodies directly, but pass through a system of local transformation, removal or accumulation, followed by controlled management. This reduces the risk of eutrophication, local organic pollution, the spread of pathogens and uncontrolled impacts on coastal or inland aquatic ecosystems (Food and Agriculture Organization, 2024a; Hashmi *et al.*, 2025). This conclusion is supported by the findings of E. Villar-Navarro *et al.* (2021), who investigated the potential use of six species of marine microalgae and a natural bloom to process nutrients from simulated water in a RAS. The study utilised 18-litre bubbled photobioreactors operating in batch and semi-continuous modes; *Isochrysis galbana* demonstrated the highest biomass productivity on aquaculture effluent, whilst *Tetraselmis chuii* proved most effective for the treatment of marine effluent.

Biofiltration also improves the efficiency of bioresource utilisation. In closed systems, water losses are reduced, rearing conditions are stabilised, and control over temperature, oxygen and nitrogen compounds is enhanced. This creates the conditions for more predictable growth of aquatic organisms, a reduction in stress factors and a more efficient use of feed. As feed residues are one of the sources of organic and nitrogen loading, optimising feeding directly affects the load on the biofilter and the ecological profile of the system.

At the same time, biofiltration does not automatically eliminate all environmental risks. The accumulation of nitrate, concentrated sludge, spent filter media and biomass requires separate management. A synthesis of the analysed sources showed that the environmental performance of RAS depends not only on reducing water intake and discharges, but also on the stability of biofiltration, control of nitrate accumulation, sludge treatment, energy consumption and the technical complexity of operation. This is consistent with the findings of N. Ahmed & G. Turchini (2021), who considered RASs as a technological solution for reducing the direct impact of production on aquatic ecosystems and for adapting aquaculture to climate risks. However, a comparison with this study clarifies that the environmental advantage of closed-loop systems is not automatic, as energy consumption, greenhouse gas emissions and the high cost of complex engineering solutions remain factors limiting the scaling up of such systems in aquaculture practice. Therefore, the environmental performance of RAS depends on the entire technological chain, which encompasses mechanical removal of solids, biological nitrogen transformation, CO_2 control, pH stabilisation, partial or complete nitrate removal, sludge treatment and energy-efficient water circulation (Table 4).

Table 4. *Environmental effects of biofiltration in RASs*

Area of environmental impact	Outcome of biofiltration	Conditions for achieving the result
Reduction in water intake	Water is reused multiple times after treatment	Stable operation of the mechanical and biological circuits
Reduction in discharges	Pollutants are converted or removed within the system	Monitoring of TAN, NO_2^-, NO_3^-, organic matter and sludge
Reduction of eutrophication	Less nitrogen and organic matter enter natural water bodies	Denitrification or controlled water exchange
Biosafety	Reduced contact with external sources of pathogens	Closed water circuit, disinfection, biofilm control
Efficient use of feed	Reduced organic load on the water	Optimisation of feeding and control of the feed conversion ratio
Control of production risks	Water parameters are maintained within a controlled range	Sensors, automation, and alarm notifications

Source: created by the author based on Food and Agriculture Organization (2024a; 2024b), S. Gupta *et al*. (2024), Z. Hashmi *et al*. (2025), E. Malandrakis *et al.* (2025)

Thus, biofiltration not only purifies water but also forms the ecological basis for sustainable aquaculture. Its effectiveness is demonstrated by the reduction of resource losses, the minimisation of impact on water bodies and the improvement of production process control. This is of particular importance for industrial systems, as the growth in global aquaculture production is accompanied by increasing demands for environmental responsibility, traceability, and the safety of aquatic food products (Food and Agriculture Organization, 2024a; 2024b).

Current innovations in the field of biofiltration are aimed at improving the controllability of microbiological processes, the accuracy of monitoring and the energy efficiency of closed systems. Three areas are of particular significance: improvements to biofilter design, the development of digital water quality monitoring and the application of predictive models for nitrogen cycle management. The first area encompasses the use of media with a high specific surface area, moving-bed biofilm reactors, compact bioreactors, and combined nitrification and denitrification systems. Such solutions increase the contact area between microorganisms and water, improve oxygen access and allow the system to adapt to variable loads. In marine RAS systems, nitrate control is becoming increasingly important, as nitrification does not result in the complete removal of nitrogen, but merely converts more toxic forms into less toxic ones. Denitrification reactors, solid-phase denitrification and integrated systems combining aerobic and anaerobic processes therefore hold great promise (Xu *et al.*, 2025; Dai *et al.*, 2026).

The second area relates to the digital monitoring of water parameters. The Internet of Things, automated sensor networks and cloud-based platforms make it possible to monitor temperature, pH, dissolved oxygen, electrical conductivity, turbidity, ammonium, nitrite, and nitrate in near real time. This changes the logic of biofilter management: instead of periodic laboratory monitoring, a continuous monitoring system for high-risk parameters is established. According to a review by M. Flores-Iwasaki *et al.* (2025), sensor systems are increasingly being used to monitor the physicochemical parameters of water in RAS, biofloc systems and aquaponics. This primarily involves monitoring temperature, pH, dissolved oxygen, electrical conductivity, turbidity, and concentrations of nitrogen compounds. E. Malandrakis *et al.* (2025) regard digital monitoring as a tool for more precise management of the aquatic environment, as it enables not only the recording of the system's current state but also a timely response to deviations that may affect the stability of biofiltration. Consequently, sensor networks should be regarded as one of the key tools for proactive water quality management in closed aquaculture systems.

The third area covers the use of predictive models. For closed systems, predicting nitrate accumulation is particularly important, as this parameter changes gradually and depends on feed loading, nitrification rate, water exchange, denitrification, and the biomass of aquatic organisms. Machine learning models, in particular hybrid neural networks, demonstrate the ability to predict nitrate concentrations based on a set of water quality parameters (Fan *et al.*, 2024). This provides the basis for a transition from reactive to proactive management of biofiltration (Table 5).

Table 5. *Innovations for optimising biofiltration in closed water systems*

Area of innovation	Solution description	Expected technological outcome	Environmental impact
Moving biofilm reactors	Carriers with active biofilm are in constant motion	Improved nitrification stability	Reduced accumulation of toxic nitrogen compounds
Denitrification modules	Anaerobic conversion of nitrate to N_2	Control of long-term accumulation of NO_3^-	Reduction of nitrogen load in effluents
Sensor networks	Continuous monitoring of pH, oxygen, temperature, and nitrogen compounds	Early detection of anomalies	Prevention of emergency discharges and losses of biological resources
Automated dosing	Regulation of buffers, oxygen, and water exchange	Stabilisation of pH, alkalinity and oxygen	Reduced risk of disruption to biological treatment
Predictive models	Forecasting of TAN, NO_2^- and NO_3^- based on monitoring data	Preventive management of the biofilter	Optimisation of resources and reduction of environmental risks
Combined treatment	Combination of mechanical, biological, chemical, and physical treatment	Comprehensive water quality management	Reducing multifactorial environmental impacts

Source: created by the author based on S. Gupta *et al*. (2024), X. Fan *et al.* (2024), X. Zhou *et al*. (2024), Z. Hashmi *et al.* (2025), M. Flores-Iwasaki *et al*. (2025), E. Malandrakis *et al*. (2025), P. Xu *et al*. (2025), H. Dai *et al.* (2026), B. Zhang *et al.* (2026)

Innovative developments in biofiltration also involve more precise control of the biofilm. A mature biofilm not only performs a nitrification function but also plays a stabilising role in the system's microbial environment. Research by J.N. Azizah *et al.* (2026) shows that the type of biofilter substrate influences microbial dynamics, TAN and nitrite concentrations, and the overall stability of water quality in RAS. This confirms that biofilm management should be viewed not merely as biofilter maintenance, but as a prerequisite for maintaining the microbiological equilibrium of a closed system.

For the sustainable development of aquaculture, the optimisation of biofiltration must combine technological efficiency with environmental soundness. The most functionally complete model is one in which the biofilter is integrated with mechanical treatment, degassing, oxygenation, denitrification, digital monitoring and feed load management. Such a model makes it possible to maintain water quality within a controlled range, reduce the need for water exchange, limit the generation of polluted effluent and improve the efficiency of bioresource utilisation. A summary of the results shows that biofiltration in closed aquatic systems is a multi-stage process encompassing the microbiological transformation of nitrogen compounds, the physicochemical stabilisation of water, the technological integration of treatment modules and the digital control of environmental parameters. The most stable operation of a biofilter is achieved when temperature, pH, alkalinity, oxygen, salinity, organic load and the concentrations of TAN, NO_2^- and NO_3^- are controlled. In aquaculture practice, this means that biofiltration is not merely a supplementary element, but a fundamental technological prerequisite for the environmentally sustainable development of intensive farming of marine and freshwater organisms in closed systems.

Conclusions

This study, based on a theoretical and applied design, substantiated the role of biofiltration as a fundamental technological mechanism for maintaining water quality in closed aquaculture systems. A synthesis of the analysed sources showed that biofiltration ensures the sequential transformation of ammonium nitrogen, nitrites, and nitrates with the participation of bacterial and archaeal communities. The stability of this process is regarded as the result of the combined control of temperature, pH, alkalinity, dissolved oxygen, salinity, organic load and concentrations of nitrogen compounds. This provided grounds for treating the biofilter not as an isolated technical element, but as a component of a unified treatment circuit linked to mechanical treatment, degassing, oxygen supply, pH regulation and feed load management. Within the scope of the study, six main groups of aquatic pollutants, nine biofilter control parameters, seven biofiltration process options, six environmental effects and six innovative areas for optimisation were systematised.

Based on a comparative and technological analysis, the following were identified as functionally significant solutions: moving-bed biofilm reactors, denitrification modules, combined treatment systems, sensor-based monitoring, automated regulation of water parameters and predictive models for the accumulation of nitrogen compounds. These are considered as areas that can improve the controllability of biofiltration, reduce the risk of accumulation of toxic forms of nitrogen, contribute to a reduction in water abstraction, limit discharges, lower the risk of eutrophication and promote a more rational use of aquatic bioresources. The limitations of the study stem from its theoretical and applied nature, as no in-house laboratory or field trials of biofilters were conducted. Further research should focus on an empirical comparison of different types of biofilters for specific marine and freshwater aquaculture species, the assessment of the energy efficiency of such systems, and the development of digital models for early warning of nitrogen balance disturbances.

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Conflict of Interest

None.

References

[1] Ahmed, N., & Turchini, G.M. (2021). Recirculating aquaculture systems (RAS): Environmental solution and climate change adaptation. *Journal of Cleaner Production,* 297, article number 126604. doi: 10.1016/j.jclepro.2021.126604.

[2] Al Dakdouki, S., Nivelle, R., Ledoré, Y., Fontaine, P., & Changey, F. (2025). Effects of biofilter management modalities on the microbiological status in RAS water to avoid recording capacities of biofilms. *Aquacultural Engineering,* 110, article number 102522. doi: 10.1016/j.aquaeng.2025.102522.

[3] Azizah, J.N., Rahardjo, S.S., Maimunah, Y., Zakaria, M.H., Rangkuti, R.F., Fakhri, M., Yuwanita, R., Pratiwi, A., & Prayogo, T.B. (2026). Biofilter substrates influence microbial dynamics and water quality in the *Cherax quadricarinatus* recirculating aquaculture system. *Journal of Ecological Engineering*, 27(7). doi: 10.12911/22998993/216359.

[4] Costigan, E.M., Bouchard, D.A., Ishaq, S.L., & MacRae, J.D. (2024). Short-term effects of abrupt salinity changes on aquaculture biofilter performance and microbial communities. *Water*, 16(20), article number 2911. doi: 10.3390/w16202911.

[5] Dai, H., Dong, D., Sun, Z., Li, M., Li, Y., Gan, E., Song, X., Xiao, J., & Li, M. (2026). The overlooked NO_3^--N reducing pathways in biofilters of marine recirculating aquaculture system (RAS): Insights from metagenomics and ^{15}N-membrane inlet mass spectrometry. *Aquaculture,* 616, article number 743705. doi: 10.1016/j.aquaculture.2026.743705.

[6] Fan, X., Lia, J., Wang, Y., Qu, Y., Li, H., Qu, K., & Cui, Z. (2024). A hybrid neural network model for predicting the nitrate concentration in the recirculating aquaculture system. doi: 10.48550/arXiv.2401.01491.

[7] Fernandes, P.M., Fiksdal, L.W., Rojas-Tirado, P.A., Stenhaug, S.R., Khadka, S., Calabrese, S., Powell, M.D., Dahle, H., Bakke, I., Hess-Erga, O.-K., & Fredriksen, S. (2026). Biofilter performance, water quality, and microbial dynamics in RAS operated under high or low suspended solids load. *Aquaculture,* 614, article number 743559. doi: 10.1016/j.aquaculture.2025.743559.

[8] Flores-Iwasaki, M., Guadalupe, G.A., Pachas-Caycho, M., Chapa-Gonza, S., Mori-Zabarburú, R.C., & Guerrero-Abad, J.C. (2025). Internet of Things (IoT) sensors for water quality monitoring in aquaculture systems: A systematic review and bibliometric analysis. *AgriEngineering,* 7(3), article number 78. doi: 10.3390/agriengineering7030078.

[9] Food and Agriculture Organization. (2024a). *Guidelines for sustainable aquaculture*. Retrieved from https://www.fao.org/guidelines-sustainable-aquaculture/en.

[10] Food and Agriculture Organization. (2024b). *The state of world fisheries and aquaculture 2024*. Retrieved from https://surl.li/ndqlre.

[11] Godzieba, M., Hliwa, P., & Ciesielski, S. (2025). Network of nitrifying bacteria in aquarium biofilters: An unfaltering cooperation between comammox *Nitrospira* and ammonia-oxidizing archaea. *Water,* 17(1), article number 52. doi: 10.3390/w17010052.

[12] Gupta, S., *et al.* (2024). Recent developments in recirculating aquaculture systems: A review. *Aquaculture Research,* 2024(1), article number 6096671. doi: 10.1155/are/6096671.

[13] Hashmi, Z., Metali, F., Amin, M., Abu Bakar, M.S., Wibisono, Y., Nugroho, W.A., & Bilad, M.R. (2025). Recirculating aquaculture systems: Advances, impacts, and integrated pathways for sustainable growth. *Bioresource Technology Reports,* 32, article number 102340. doi: 10.1016/j.biteb.2025.102340.

[14] Hu, C., Lin, M., Hu, T., Zeng, Y., Zeng, R., & Wang, C. (2026). Linking bacterial r/k ecological shifts to spatiotemporal nitrogen removal dynamics in recirculating aquaculture systems. *Microbial Ecology,* 89, article number 91. doi: 10.1007/s00248-026-02742-1.

[15] Jafari, L., Montjouridès, M.A., Hosfeld, A.-C., Attramadal, K.J., Fivelstad, S., & Dahle, H. (2024). Biofilter and degasser performance at different alkalinity levels in a brackish water pilot scale recirculating aquaculture system (RAS) for post-smolt Atlantic salmon. *Aquacultural Engineering, 106*, article number 102407. doi: 10.1016/j.aquaeng.2024.102407.

[16] Li, H., Cui, Z., Cui, H., Bai, Y., Yin, Z., & Qu, K. (2023). A review of influencing factors on a recirculating aquaculture system: Environmental conditions, feeding strategies, and disinfection methods. *Journal of the World Aquaculture Society,* 54(3), 566-602. doi: 10.1111/jwas.12976.

[17] Liu, W., Yang, Y., Li, X., & Fan, X. (2024). Enhanced biofiltration coupled with ultrafiltration process in marine recirculating aquaculture system: Fast start-up of nitrification and long-term performance. *Journal of Water Process Engineering,* 58, article number 104901. doi: 10.1016/j.jwpe.2024.104901.

[18] Lu, Z., Lin, W., Li, Q., Wu, Q., Ren, Z., Mu, C., Wang, C., Shi, C., & Ye, Y. (2024). Recirculating aquaculture system as microbial community and water quality management strategy in the larviculture of Scylla paramamosain. *Water Research*, 252, article number 121218. doi: 10.1016/j.watres.2024.121218.

[19] Malandrakis, E.E. (2025). Design and implementation of a cost-effective IoT-based monitoring and alerting system for recirculating aquaculture systems (RAS). *Sensors,* 25*(*21), article number 6692. doi: 10.3390/s25216692.

[20] Moschos, S., Kormas, K.A., & Karayanni, H. (2022). Prokaryotic diversity in marine and freshwater recirculating aquaculture systems. *Reviews in Aquaculture,* 14(4), 1861-1886. doi: 10.1111/raq.12677.

[21] Nędzarek, A., Bonisławska, M., Tórz, A., Tański, A., & Formicki, K. (2022). Effect of filter medium on water quality during passive biofilter activation in a recirculating aquaculture system for *Oncorhynchus mykiss*. *Energies,* 15(19), article number 6890. doi: 10.3390/en15196890.
[22] Neissi, A., Rafiee, G., Rahimi, S., Farahmand, H., Pandit, S., & Mijakovic, I. (2022). Enriched microbial communities for ammonium and nitrite removal from recirculating aquaculture systems. *Chemosphere,* 295, article number 133811. doi: 10.1016/j.chemosphere.2022.133811.
[23] Preena, P.G., Rejish Kumar, V.J., & Singh, I.S. (2021). Nitrification and denitrification in recirculating aquaculture systems: The processes and players. *Reviews in Aquaculture,* 13(4), 2053-2075. doi: 10.1111/raq.12558.
[24] Ramli, N.M., Verreth, J.A., Yusoff, F.M., Nurulhuda, K., Nagao, N., & Verdegem, M.C. (2020). Integration of algae to improve nitrogenous waste management in recirculating aquaculture systems: A review. *Frontiers in Bioengineering and Biotechnology,* 8, article number 1004. doi: 10.3389/fbioe.2020.01004.
[25] Sarosh, S., Kulkarni, R.M., Varma, E., Sirivibha, S.P., & Ramaswami, S. (2024). Recirculating aquaculture system and nitrification: A review. *Journal of the Indian Institute of Science,* 104, 861-895. doi: 10.1007/s41745-024-00443-7.
[26] Shitu, A., Liu, G., Muhammad, A.I., Zhang, Y., Tadda, M.A., Qi, W., Liu, D., Ye, Z., & Zhu, S. (2022). Recent advances in application of moving bed bioreactors for wastewater treatment from recirculating aquaculture systems: A review. *Aquaculture and Fisheries,* 7(3), 244-258. doi: 10.1016/j.aaf.2021.04.006.
[27] Sun, J., Wang, H., Chen, Y., Huang, S., Bi, X., Cheng, L., Shi, X., Zhao, W., & Zhou, X. (2026). Performance of nitrogen removal and biofilm-associated microbial community in a compact marine shrimp recirculating aquaculture system with MBBR. *Microorganisms,* 14(4), article number 841. doi: 10.3390/microorganisms14040841.
[28] Villar-Navarro, E., Garrido-Pérez, C., & Perales, J.A. (2021). The potential of different marine microalgae species to recycle nutrients from recirculating aquaculture systems (RAS) fish farms and produce feed additives. *Algal Research,* 58, article number 102389. doi: 10.1016/j.algal.2021.102389.
[29] Xu, P., Ding, H., Si, M., Fan, Y., & Zhang, S. (2025). Research on nitrate removal from recirculating aquaculture systems using solid-phase denitrification process. *Polish Journal of Environmental Studies*. doi: 10.15244/pjoes/207489.
[30] Yang, X., Wu, Y., Shu, L., Gu, H., Liu, F., Ding, J., Zeng, J., Wang, C., He, Z., Xu, M., Liu, F., Zheng, X., & Wu, B. (2024). Unraveling the important role of comammox *Nitrospira* to nitrification in the coastal aquaculture system. *Frontiers in Microbiology,* 15, article number 1355859. doi: 10.3389/fmicb.2024.1355859.
[31] Zhang, B., Wen, C., Ke, Z., Yang, F., Cheng, J., Yi, X., Yang, S., & Huang, W. (2026). A pilot-scale sand moving bed biofilm reactor for nitrogen removal in a seawater recirculating aquaculture system: Rapid start-up, stable nitrification and high-density aquaculture. *Bioresource Technology Reports,* 34, article number 102689. doi: 10.1016/j.biteb.2026.102689.
[32] Zhou, X., Liu, H., Fan, X., Xu, X., Gao, Y., Bi, X., Cheng, L., Huang, S., Zhao, F., & Yang, T. (2024). Innovative inbuilt moving bed biofilm reactor for nitrogen removal applied in household aquarium. *Frontiers in Microbiology,* 15, article number 1373119. doi: 10.3389/fmicb.2024.1373119.

Оптимізація біофільтрації у замкнутих водних системах для сталого розвитку аквакультури: екологічні аспекти та технологічні інновації

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Анотація. Мета дослідження полягала в обґрунтуванні теоретичних і прикладних засад оптимізації біофільтрації у замкнутих водних системах аквакультури з урахуванням екологічних вимог, технологічних інновацій і стабільності функціонування біофільтра. Дослідження було виконано в межах теоретико-прикладного дизайну із застосуванням наукового аналізу, біохімічного узагальнення, порівняльно-технологічного зіставлення, екологічного узагальнення та систематизації сучасних даних про біологічне очищення води. Було встановлено, що біофільтрація забезпечувала перетворення амонійного азоту, нітритів і нітратів через послідовну дію бактеріальних та архейних угруповань, а її стабільність визначалася температурою, водневим показником, лужністю, розчиненим киснем, солоністю, органічним навантаженням і станом біоплівки. Було систематизовано шість основних груп забруднювачів водного середовища, дев'ять параметрів контролю біофільтра, сім технологічних варіантів біофільтрації, шість екологічних ефектів і шість інноваційних напрямів оптимізації. Узагальнення джерел показало, що вибір типу біофільтра має залежати від азотного навантаження, солоності, потреби в дегазації CO_2, рівня автоматизації та складності експлуатації. Реактори з рухомим шаром біоплівки доцільні для інтенсивних recirculating aquaculture system (RAS), денітрифікаційні модулі – для контролю накопичення нітратів, а комбіноване очищення – для комплексного управління якістю води. Конструкційні удосконалення, сенсорний контроль, автоматизоване регулювання та прогностичні моделі підвищують керованість азотного циклу й зменшують ризик накопичення токсичних сполук. Обґрунтовано, що біофільтрація сприяє зниженню потреби у водообміні, обмеженню забруднених скидів, зменшенню ризику евтрофікації та підвищенню ефективності використання водних біоресурсів. Практична значимість результатів полягає в тому, що їх можуть використати інженери аквакультурних підприємств, екологи, проєктувальники замкнутих водних систем і фахівці рибницьких господарств для вибору типу біофільтра, налаштування моніторингу якості води та зниження екологічного навантаження виробництва

Ключові слова: лужність; розчинений кисень; нітрати; денітрифікаційні модулі; токсичні сполуки