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A Review on Eutrophication as an Environmental Challenge in Aquaculture: Mechanisms, Ecological Impacts, and Sustainable Management Strategies

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ABSTRACT

This article reviewed mitigation strategies for eutrophication in aquaculture, aiming to provide an integrated understanding of its causes, impacts, and management approaches. The global expansion of aquaculture, driven by increasing demand for animal protein and its contribution to local economies, has also generated significant environmental challenges, particularly eutrophication. This condition, caused by excessive nutrient loading—primarily nitrogen and phosphorus—from uneaten feed, feces, and organic waste, leads to uncontrolled algal growth, harmful algal blooms (HABs), reduced water quality, and adverse effects on cultured species. Using a narrative literature review approach, publications from major databases (Scopus, ScienceDirect, SpringerLink, and ResearchGate) were synthesized to identify research gaps and potential strategies. Effective mitigation measures include improving feed efficiency, implementing Integrated Multi-Trophic Aquaculture (IMTA) systems, applying biofloc technology to recycle waste into nutrients, and developing wastewater treatment systems with sedimentation, aeration, and equalization stages. Beyond technical solutions, education of aquaculture practitioners and enforcement of environmental regulations are also essential. A synergistic application of these strategies is recommended to support sustainable aquaculture development while preserving aquatic ecosystems.

INTRODUCTION

Eutrophication is the condition in which a water body contains excessive concentrations of nutrients, particularly nitrogen and phosphorus, leading to explosive algal growth (algal blooms) and a subsequent decline in water quality **(Bali & Gueddari, 2019)**. It is a process that may occur naturally or be accelerated by human activities **(Sonarghare *et al.*, 2020)**. Naturally, eutrophication takes place over millions of years as part of the ecological succession of a water body, during which nutrient levels gradually increase, shifting the system toward a eutrophic state **(Rathore *et al.*, 2016)**. In contrast, human-induced eutrophication, referred to as cultural eutrophication, occurs much more rapidly **(Malone & Newton, 2020)**. Pollution from agricultural runoff, aquaculture waste, and domestic or industrial discharges rich in nitrogen and phosphorus can drastically accelerate this process **(Zhang *et al.*, 2023)**. Eutrophication is typically characterized by the excessive growth of aquatic plants, macroalgae, or phytoplankton **(O'Hare *et al.*, 2018)**, which results from the increased availability of photosynthetic inputs such as sunlight, carbon dioxide (CO_2), the key nutrients nitrogen (N) and phosphorus (P) **(Ahmed *et al.*, 2024)**. Such nutrient enrichment drives the transition of water bodies from oligotrophic (nutrient-poor) to eutrophic (nutrient-rich), and in severe cases, to hypertrophic (extremely nutrient-rich) states **(Khan & Mohammad, 2014)**. Excessive phytoplankton growth reduces oxygen availability, decreases light penetration, alters ecosystem community structures, and ultimately leads to biodiversity loss **(Messyasz *et al.*, 2015; Costa *et al.*, 2018)**.

In aquaculture systems, nutrient accumulation largely originates from uneaten feed, metabolic excretions, and decomposed organic matter **(Dauda *et al.*, 2019)**. This accumulation degrades water quality, lowers dissolved oxygen levels, and disrupts ecosystem balance **(Rathore *et al.*, 2016)**. The problem is particularly severe in open aquaculture systems, such as ponds, floating net cages, and traditional enclosures, where nutrient-rich effluents are directly released into surrounding waters. Over time, eutrophication threatens not only aquaculture sustainability but also the biodiversity and ecological functioning of natural aquatic environments **(Wurtsbaugh *et al.*, 2019)**.

Aquaculture has been one of the fastest-growing food production sectors in recent decades, contributing significantly to global food security, protein supply, and economic development. According to the **FAO (2024)**, aquaculture production has exceeded capture fisheries yields for several years, particularly in major aquaculture-producing countries. In 2022, 45 countries reported higher production of farmed aquatic animals than capture fisheries. While this rapid expansion underscores aquaculture's critical role in global food systems, it also poses major ecological risks linked to eutrophication. Intensification practices—such as high stocking densities and excessive feed inputs—promote nutrient accumulation (N and P) in water bodies **(Dauda *et al.*, 2019)**, potentially triggering uncontrolled algal blooms, oxygen depletion, and long-term declines in both aquaculture productivity and surrounding ecosystem health **(Lan *et al.*, 2024)**.

Given these challenges, sustainable environmental management in aquaculture has become increasingly urgent to balance productivity with aquatic ecosystem conservation. Accordingly, this review synthesizes current knowledge on the mechanisms, ecological impacts, and mitigation strategies of eutrophication in aquaculture, with a focus on sustainable management practices and research gaps requiring future attention.

METHODS

This study adopted a narrative literature review approach to synthesize existing research on the causes, ecological impacts, and mitigation strategies of eutrophication in aquaculture systems. This method was chosen since it allows the integration of findings from diverse studies into a comprehensive narrative, thereby facilitating the identification of knowledge gaps and the formulation of future research directions **(Nahdiyin, 2023)**.

Relevant articles were retrieved from academic databases including Google Scholar, ScienceDirect, SpringerLink, and ResearchGate. The literature search employed combinations of keywords such as *eutrophication*, *nutrient pollution*, *aquaculture*, *nitrogen*, *phosphorus*, *phytoplankton bloom*, and *water quality*, with Boolean operators (AND/OR) used to refine results. Articles that met the inclusion criteria were subjected to a detailed review of their abstracts, methods, and results sections, from which data were extracted regarding eutrophication drivers, ecological consequences, and management strategies within aquaculture systems.

RESULTS AND DISCUSSION

1. Basic concepts of eutrophication

Eutrophication is the process of nutrient enrichment in water bodies, leading to a nutrient-rich, or eutrophic, state. The term deriven from the Greek words *eu* (“well”) and *trophe* (“nourishment”), originally describes lakes and estuaries with high levels of plant nutrients **(Akinnawo, 2023)**. According to **Lan *et al.* (2024)**, eutrophication is characterized by excessive microalgal growth, which disrupts food chain balance and accelerates ecological succession in aquatic ecosystems. While microalgal production is essential as the base of the aquatic food web, uncontrolled growth under eutrophic conditions significantly degrades water quality. The first step in the eutrophication process is the introduction of nutrients into the aquatic system, which are rapidly assimilated by microalgae **(Riza *et al.*, 2023)**.

Nitrogen (N) and phosphorus (P) are the two key elements responsible for nutrient enrichment and the excessive growth of aquatic plants **(Boeykens *et al.*, 2017)**. Accelerated eutrophication occurs when large amounts of N and P enter aquatic systems **(Tang *et al.*, 2020)**. When their concentrations exceed the assimilation capacity of the ecosystem, these nutrients become environmentally harmful **(Olsen *et al.*, 2008)**. Nitrogen naturally enters water from the atmosphere via rainfall and from microbial decomposition of organic matter in soils and sediments **(Kumar *et al.*, 2020)**. However, anthropogenic sources—including agricultural runoff, aquaculture effluents, and organic waste discharges—are the primary contributors to nitrogen loading in water bodies **(Suo *et al.*, 2012)**. Phosphorus also occurs naturally, but human activities play a major role in its accumulation in aquatic environments **(Cakmak *et al.*, 2022)**. Naturally, phosphorus originates from soil leaching, decomposition of organic matter, and microbial breakdown

(Witek-Krowiak *et al.*, 2022), while anthropogenic inputs include domestic and industrial wastewater, detergents, animal manure, and fertilizers.

Nitrogen is an essential macronutrient for microalgal growth, as it supports the synthesis of proteins, lipids, and carbohydrates **(Yakoob *et al.*, 2021)**. Microalgae can assimilate nitrogen in both inorganic forms (ammonium, nitrite, nitrate) and organic forms (e.g., urea) **(Chen & Wang, 2020)**. Ammonium (NH_4^+) and nitrate (NO_3^-) are the primary nitrogen sources assimilated in aquatic systems **(Goncu *et al.*, 2025)**. Ammonium uptake is generally faster and preferred over nitrate uptake because it requires less energy for assimilation **(Ramli *et al.*, 2020; Salbitani & Carfagna, 2021; Carletti *et al.*, 2024)**. Ammonium can be directly incorporated into amino acids in microalgal cells via glutamine synthetase, while nitrate and nitrite must first be reduced to ammonium through nitrate reductase and nitrite reductase activity (Fig. 1). Thus, ammonium is considered the most energy-efficient nitrogen source for microalgae.

Nitrate assimilation, however, remains a critical process for phytoplankton, as it supports nitrogen acquisition when ammonium is limited **(Sanz-Luque *et al.*, 2015)**. Nitrogen plays essential roles in the synthesis of amino acids, proteins, nucleic acids, coenzymes, and chlorophyll **(Coban *et al.*, 2021)**. Nitrate availability influences protein and lipid accumulation during microalgal growth and regulates chlorophyll production, thereby modulating phytoplankton biomass productivity **(Toumi & Politaeva, 2021)**.

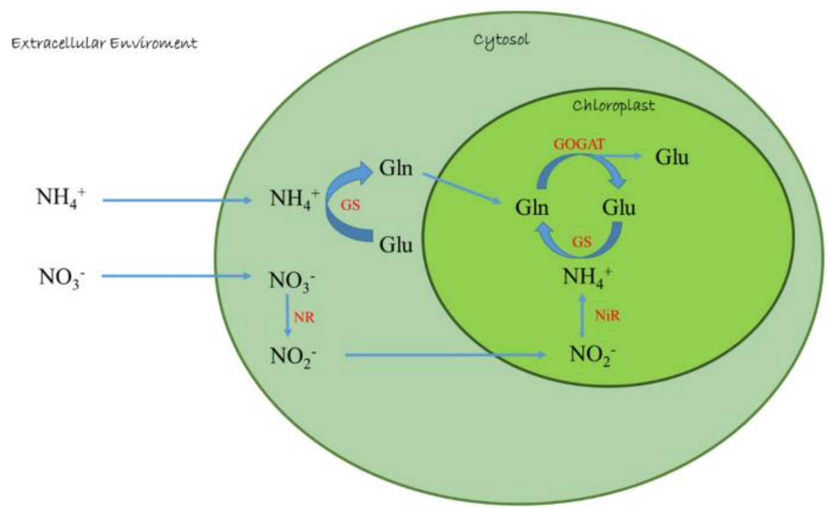

Fig. 1. Ammonium and nitrate assimilation in microalgae (**Salbitani & Carfagna, 2021**)
Caption: NR: Nitrate reductase; NiR: Nitrite reductase; GS: Glutamine synthetase; GOGAT: Glutamate synthase; Glu: Glutamic acid; Gln: Glutamine

Sanz-Luque *et al.* (2015) demonstrated that nitrate is absorbed by phytoplankton through nitrate transporter proteins located in the cell membrane. The activity of these transporters depends on both the external nitrate concentration and the nitrogen requirements of the cell. As illustrated in Fig. (1), once inside the cell, nitrate (NO_3^-) is reduced to nitrite (NO_2^-) by the enzyme nitrate reductase. This reaction occurs in the cytosol and requires NADPH as an electron donor. Nitrite is subsequently reduced to ammonium (NH_4^+) by nitrite reductase, a process that typically occurs in the chloroplasts of phytoplankton and utilizes ferredoxin as an electron donor. The resulting ammonium is assimilated through the glutamine–glutamate cycle to synthesize amino acids, the fundamental building blocks of proteins. This assimilation pathway is catalyzed by glutamine synthetase and glutamate synthase (the GS–GOGAT pathway).

Phosphorus assimilation in microalgae

Phosphorus, another key nutrient driving eutrophication, exists in both organic and inorganic forms. Among these, inorganic phosphates such as PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^-$ are the preferred forms for microalgal uptake **(Su, 2021)**. The primary form assimilated in aquatic environments is orthophosphate (PO_4^{3-}) **(Bossa *et al.*, 2024)**, which phytoplankton rapidly absorb for metabolic functions including the synthesis of DNA, RNA, ATP, and phospholipids **(Diaz *et al.*, 2018)**. Orthophosphate is transported across the cell membrane via active transport mediated by inorganic phosphorus transporters. Once inside the cell, it is directly incorporated into nucleic acids, phospholipids, and ATP through phosphorylation **(Whitton *et al.*, 2015)**.

In addition, under light conditions, phosphate can be converted into acid-soluble polyphosphate in a reaction catalyzed by polyphosphate kinase, subsequently contributing to the synthesis of DNA and proteins **(Su, 2021)**. According to **Lovio-Fragoso *et al.* (2021)**, phosphate plays critical roles in ATP production, nucleic acid formation, and phospholipid biosynthesis, which are essential for cell membrane integrity. Moreover, phosphate is vital for photosynthesis, cellular respiration, growth, and cell division. The pathway for phosphorus uptake and transformation in microalgae is illustrated in Fig. (2).

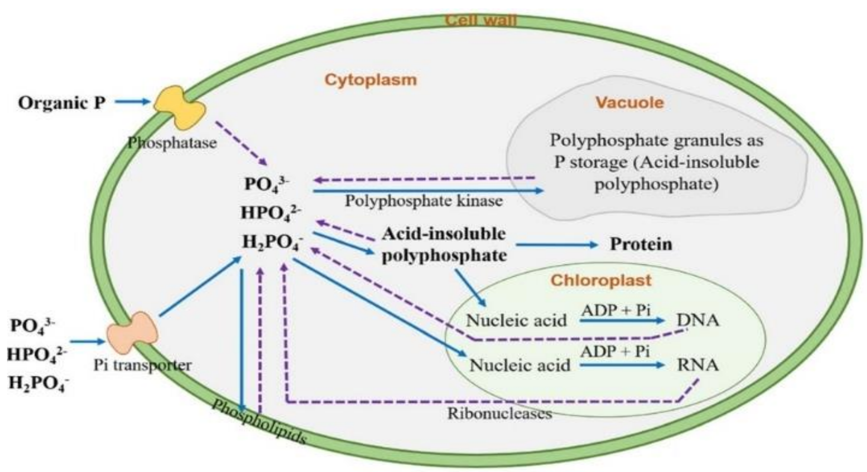

Fig. 2. Schematic diagram of phosphorus uptake and transformation pathways in microalgae **(Liu & Hong, 2021)**. Caption: solid lines indicate sufficient phosphorus conditions; dashed lines indicate phosphorus-deficient conditions.

Based on Fig. (2), phosphorus can be absorbed by microalgae in the form of inorganic phosphate (PO_4^{3-}, HPO_4^{2-}, and $H_2PO_4^{-}$) through phosphate transporters (Pi transporters) located on the cell membrane. Additionally, organic phosphorus from the aquatic environment is converted into inorganic phosphate by phosphatase enzymes before entering the cell. Inorganic phosphate inside the microalgal cell undergoes various transformations. Some phosphate is used to form nucleic acids (DNA and RNA) through nucleotide synthesis in the chloroplast, which also involves reactions with ADP and Pi. Phosphate is also required in the synthesis of proteins and phospholipids, and as a structural and functional component of the cell. In response to phosphorus availability, microalgae have adaptive mechanisms. When phosphorus levels are sufficient, the cell stores phosphate as acid-insoluble polyphosphate in the vacuole as a long-term phosphorus reserve. This storage process is catalyzed by the enzyme polyphosphate kinase. During phosphorus deficiency, the pathway for releasing phosphorus from polyphosphate stores is activated, and the degradation of RNA by ribonucleases is enhanced to recycle internal phosphate.

The input of nitrogen and phosphorus into water bodies can, to a certain extent, alter the nutrient structure of the water and its biological communities **(Chaffin *et al.*, 2014)**. The relationship between nitrogen and phosphorus can affect the trophic web and biogeochemical cycles of aquatic ecosystems **(Yan *et al.*, 2016)**. The nitrogen-to-phosphorus ratio (N/P ratio) plays a significant role in aquatic ecosystems and is a critical component in the study of changes in trophic structure, biodiversity, and biochemical cycles, exerting a strong influence on biological structure and function **(Zhang *et al.*, 2018)**. The N/P ratio is one of the factors that affects aquatic eutrophication **(Huang *et al.*, 2022)**. Research by **Peng *et al.* (2016)** has explained the close relationship between harmful algal blooms (HABs) and the N/P ratio. When eutrophication increases and the N/P ratio is low, cyanobacteria generally become dominant **(Isles *et al.*, 2017; Sondergaard *et al.*, 2017)**. **Zhang *et al.* (2018)** revealed that the N/P ratio can also influence the severity of algal blooms. A lower N/P ratio, especially with high P levels, can lead to more intense microalgal blooms. Microalgal blooms, or algal blooming, result from an increased intake of nitrogen and phosphorus into a water body, causing the dominance of certain species. This is illustrated in Fig. (3).

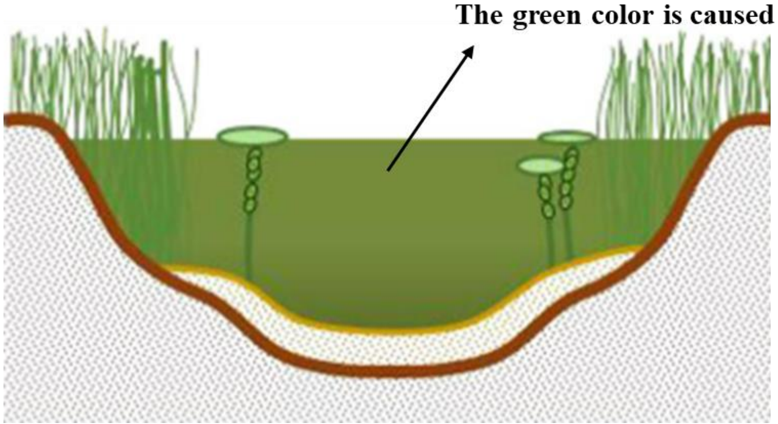

Fig. 3. Illustration of eutrophication in a water body **(O'Hare *et al.*, 2018)**

Based on the illustration in Fig. (3), the dominance of microalgae is visible as a green coloration throughout the water body. The process of eutrophication has serious environmental impacts. Dead zones are one of the consequences of this process, caused by algal blooms and low-oxygen (hypoxic) conditions. The overgrowth of aquatic vegetation, phytoplankton, or algae can disrupt the functioning of aquatic ecosystems and cause various problems, such as a shortage of the oxygen that fish need to survive **(Devlin & Brodie, 2023)**.

2. Mechanisms of nutrient enrichment from aquaculture activities

Aquaculture is the practice of cultivating aquatic organisms to meet the growing human demand for animal protein **(Ahmad, 2021)**. Like other production systems, aquaculture requires inputs in the form of feed, which enables cultured fish to reach market size **(Verdegem *et al.*, 2023)**. However, in addition to fish production, aquaculture inevitably generates waste, either as unused feed inputs or as metabolic by-products **(Dauda *et al.*, 2019)**.

Intensification of aquaculture—through higher stocking densities and greater use of protein-rich artificial feed—has been the main strategy to increase production **(Emerenciano *et al.*, 2022; Prasetiyono *et al.*, 2023)**. Yet, this also results in higher waste outputs. Only a fraction of the nitrogen and phosphorus contained in feed is assimilated into fish biomass. For example, the proportion incorporated into fish tissue is about 21–24% for nitrogen and 10–13% for phosphorus **(Chaikaew *et al.*, 2019)**. Similarly, cultured fish typically retain only 20–25% of ingested protein, with the remainder released as ammonium or organic nitrogen into the water column **(Patil *et al.*, 2021)**.

Fish feed is therefore the primary source of organic and inorganic waste in aquaculture **(Dauda *et al.*, 2019)**. Waste can be classified into solid and dissolved fractions. Solid waste includes uneaten feed, feces, and carcasses of dead organisms **(Akinwole *et al.*, 2016)**. Dissolved wastes, particularly nitrogen (N) and phosphorus (P), are metabolic by-products or arise from the decomposition of uneaten feed **(Zhang *et al.*, 2023)**. In intensive systems, nutrient accumulation increases proportionally with feed use, leading to significant nutrient discharges into the environment **(Bai *et al.*, 2023)**. Solid waste typically originates from uneaten feed, metabolic residues, and dead microbial biomass, while dissolved waste consists of ammonia, urea, and other nitrogen- and phosphorus-rich compounds released through feed decomposition **(Jasmin *et al.*, 2020; Iber & Kasan, 2021)**. When settled, solid organic matter acts as a nutrient reservoir at the pond bottom **(Syah *et al.*, 2017)**.

The principal nitrogen source in culture systems is ionized ammonia (NH_4^+), a product of protein metabolism. Ammonia is excreted through fish gills or released via the decomposition of feces, uneaten feed, and dead organic matter **(Setyastuti *et al.*, 2020; Ott *et al.*, 2024)**. Ammonium may be directly assimilated by phytoplankton **(Hastuti, 2011)**, or undergo nitrification: first oxidized to nitrite by nitrifying bacteria (*Nitrosomonas, Nitrosococcus, Nitrosospira, Nitrosolobus, Nitrosovibrio*), and subsequently to nitrate by *Nitrobacter, Nitrococcus, Nitrospira,* and *Nitrospina* **(Bayer *et al.*, 2021)**. Elevated ammonium, nitrite, and nitrate concentrations are indicators of organic pollution and correlate with increased phytoplankton abundance **(Wijaya & Elfiansyah, 2022; Musa *et al.*, 2023)**.

Phosphorus in aquaculture ponds primarily originates from uneaten feed and undigested fractions excreted in feces **(Nathanailides *et al.*, 2023)**. Its accumulation depends on the culture system, species, and feed formulation. The phosphorus requirement of cultured organisms is determined by tissue growth rates and digestive physiology, which affect absorption efficiency **(Herath & Satoh, 2015)**. Unutilized phosphorus is excreted as particulate phosphorus in feces **(Milian-Sorribes *et al.*, 2021)**. While some particulate phosphorus can be removed in sedimentation ponds, dissolved phosphorus remains in the water and is ultimately released into natural environments **(Sugiura, 2018)**.

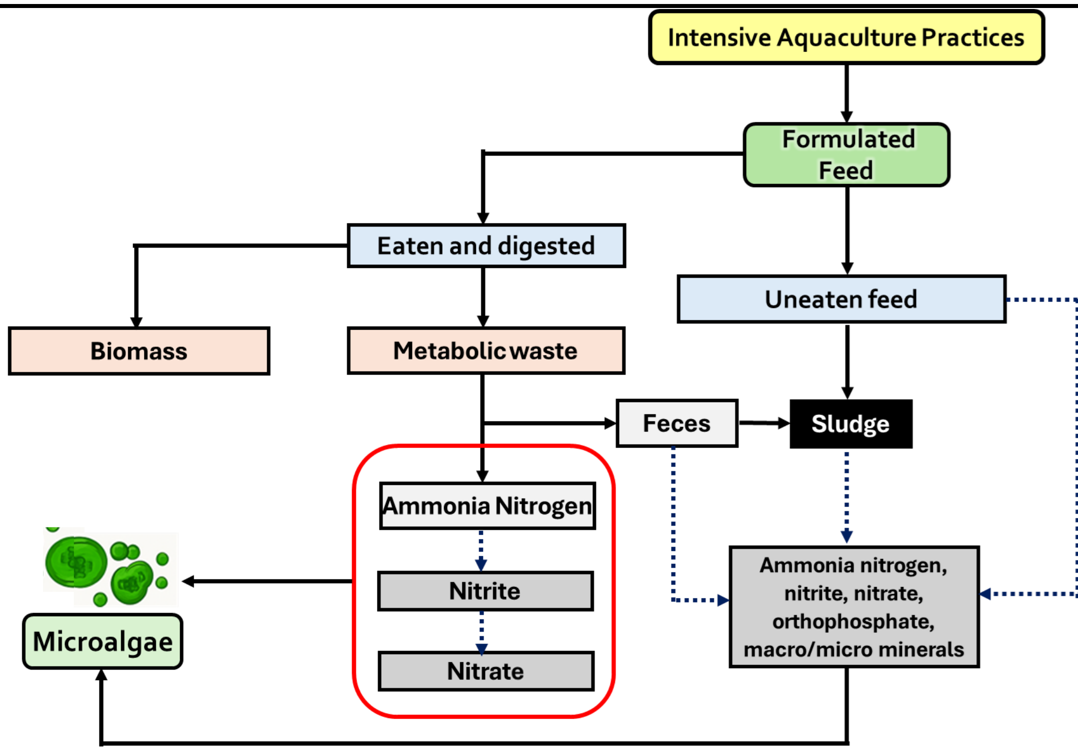

Fig. 4. Mechanism of nutrient enrichment from aquaculture activities leading to increased microalgal growth in aquatic environments (modified from **Prasetiyono *et al.*, 2023**)

Wastewater discharge from aquaculture activities can significantly alter environmental quality. The decomposition of organic matter releases inorganic compounds, leading to elevated concentrations of nutrients such as ammonium (NH_4^+), nitrate (NO_3^-), and orthophosphate (PO_4^{3-}) **(Prasetiyono *et al.*, 2023)**. Total nitrogen and phosphorus in aquaculture wastewater can account for 10–30% and 30–80%, respectively, of the organic matter released into surrounding waters **(Dauda *et al.*, 2019)**. Elevated nutrient concentrations stimulate excessive phytoplankton growth, potentially disrupting aquatic ecosystem balance **(Cui *et al.*, 2021)**. Furthermore, macro- and micro-minerals in aquaculture waste undergo demineralization, contributing to phytoplankton abundance **(Ramos *et al.*, 2017; Chiquito-Contreras *et al.*, 2022)**. The general mechanism of nutrient enrichment leading to algal growth in aquaculture systems is illustrated in Fig. (4).

As shown in Fig. (4), intensive aquaculture practices characterized by high stocking densities require large amounts of artificial feed. While a portion of feed is consumed and partially converted into fish biomass, only about 20–25% of dietary protein is assimilated; the remainder is excreted as total ammonia nitrogen and organic nitrogen **(Patil *et al.*, 2021)**. Ammonia is further oxidized by nitrifying bacteria into nitrite and nitrate, while uneaten feed and feces decompose into dissolved nutrients, including ammonia nitrogen, nitrite, nitrate, orthophosphate, and minerals. These compounds fuel microalgal growth, and the nutrient-rich effluents from intensive systems promote eutrophication and algal blooms.

3. Impacts of eutrophication from aquaculture systems on aquatic ecosystems

Eutrophication from aquaculture can have both positive and negative ecological effects. In controlled conditions, nutrient enrichment may stimulate phytoplankton growth, supporting higher trophic levels and benefiting species such as shellfish, which can reduce nutrient loads through filter-feeding **(Cubillo *et al.*, 2023)**. However, when nutrient inputs are excessive, the consequences are detrimental both within culture systems and in connected external ecosystems. Excessive nutrients can trigger uncontrolled algal blooms, deteriorate water quality, and in some cases directly harm fish due to toxic nitrogen compounds **(Banderol, 2024)**.

High levels of organic matter increase ammonia production, the main metabolic waste product of protein catabolism **(Xu *et al.*, 2021)**. Ammonia is toxic to fish: elevated concentrations impair ammonia excretion, raise blood ammonia levels, reduce oxygen transport, and disrupt metabolism **(Romano & Zeng, 2013; Uddin *et al.*, 2024)**. Ammonia easily diffuses across cell membranes, damaging vital organs such as gills, and causing respiratory distress, oxidative stress, reduced feeding, and stunted growth **(Kim *et al.*, 2020)**.

Nitrite, an intermediate in ammonia oxidation, is also toxic. It interferes with chloride uptake, disrupting osmoregulation, ionic balance, and metabolism in fish **(Deane *et al.*, 2007)**. Although unstable and quickly oxidized to nitrate, nitrite can cause acute toxicity. Nitrate, by contrast, is generally non-toxic even at concentrations up to 200mg/L **(Dauda & Akinwole, 2015)**.

Orthophosphate, unlike ammonia and nitrite, is not directly toxic to fish, even at high concentrations. Instead, it functions as a nutrient for phytoplankton and aquatic plants, fueling photosynthesis and primary production **(Barbosa *et al.*, 2021; Akinnawo, 2023)**. However, excessive orthophosphate inputs act as a major driver of eutrophication.

The buildup of nutrients and algal biomass causes dissolved oxygen (DO) to decline, particularly at night when photosynthesis ceases while respiration continues in algae, bacteria, and fish **(Abdel-Raouf *et al.*, 2012; Dauda *et al.*, 2019)**. Decomposition of dead algae further depletes oxygen, creating hypoxic or anoxic conditions that can lead to fish kills and biodiversity loss **(Zhang *et al.*, 2023)**. Eutrophication also alters biological community structure, reducing diversity and favoring opportunistic algal species and pathogenic microorganisms **(Romano & Zeng, 2013)**.

Algal blooms form when nutrient enrichment stimulates excessive phytoplankton growth. These blooms block sunlight penetration, reduce oxygen availability, and create dead zones **(Sonarghare *et al.*, 2020)**. Certain blooms, dominated by cyanobacteria, produce harmful algal blooms (HABs) that release cyanotoxins (e.g., microcystins, cylindrospermopsin, anatoxin-a, saxitoxins) with severe ecological consequences **(Paul *et al.*, 2021)**. HABs suffocate fish by triggering excess mucus secretion in gills, clog filtration structures in fish and shellfish, and release allelopathic compounds that inhibit competing algae **(Glibert *et al.*, 2010; Huang *et al.*, 2022)**. HAB dominance also suppresses zooplankton grazing, exacerbating ecosystem imbalance. In eutrophic systems, cyanobacteria often dominate, creating toxic dead zones **(Rathore *et al.*, 2016; Hwang, 2020)**.

Empirical studies confirm these impacts. Shrimp farms in Ha Long Bay, Vietnam, significantly increased nutrient loads (TAN, NO_2-N, NO_3-N, TP, PO_4-P), organic matter (BOD, COD), chlorophyll-a, and suspended solids, exceeding safe ecological limits and causing eutrophication across broader coastal waters **(Bui *et al.*, 2012)**. In Lake Batur, Bali, floating net cage farming surpassed carrying capacity, with each liter of water receiving 7.29 mg organic waste annually (2.18 mg N, 0.53 mg P). This led to lower water clarity, higher chlorophyll-a, reduced DO, fish kills, and biodiversity loss, demonstrating ecosystem-wide eutrophication **(Garno *et al.*, 2024)**.

4. Management and mitigation strategies for eutrophication in aquaculture

Eutrophication caused by aquaculture presents a major challenge for water quality and ecosystem sustainability. Mitigation strategies must target root causes, particularly feed inputs and nutrient accumulation, and should combine technical, ecological, and management approaches. Technologies must be practical, cost-effective, efficient, and address the problem at its source **(Prasetiyono & Efendi, 2022)**.

Improving feed efficiency is a primary strategy. Feed should be supplied in accordance with the physiological needs of cultured species, both in quantity and frequency **(Eriegha *et al.*, 2017)**. High-quality feed with a low feed conversion ratio (FCR) reduces waste and nutrient loading **(Hasan & Soto, 2017)**. Feed additives such as probiotics can further enhance nutrient absorption. For example, incorporating *Saccharomyces cerevisiae* and *Bacillus subtilis* into tilapia feed reduced FCR by improving digestion, gut health, and immunity, resulting in more efficient feed-to-biomass conversion **(Opiyo *et al.*, 2019)**.

Another key approach is Integrated Multi-Trophic Aquaculture (IMTA), which co-cultures species from different trophic levels to recycle waste and mimic natural ecosystems. In IMTA systems, waste from one species serves as input for another, reducing nutrient discharge and enhancing system productivity **(Hossain *et al.*, 2022; Nissar *et al.*, 2023)**. This ecological approach, illustrated in Fig. (5), offers both environmental and economic benefits.

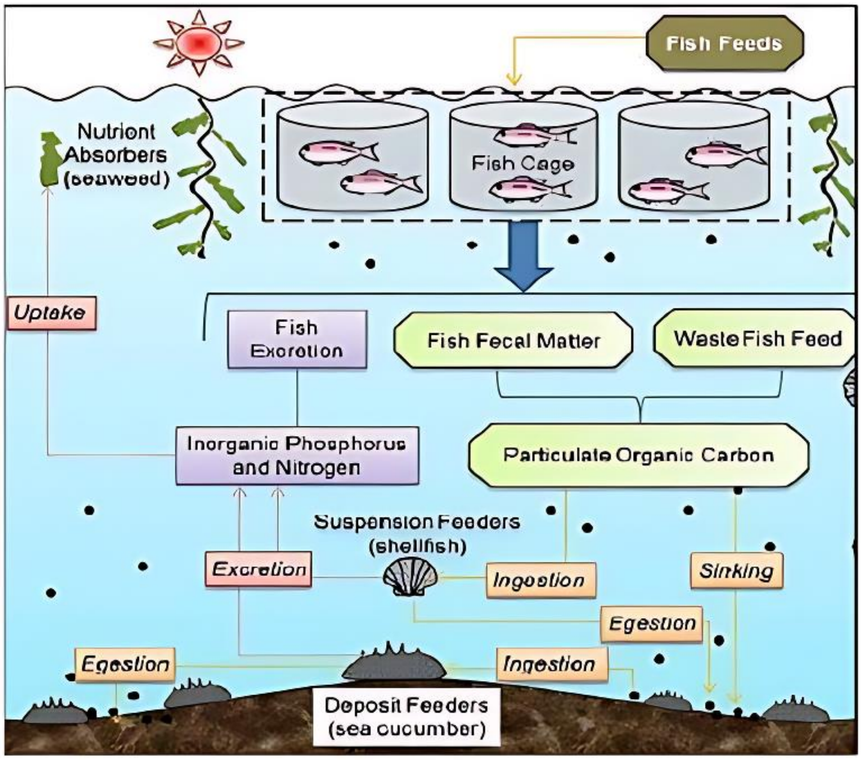

Fig. 5. Illustration of the IMTA system in aquaculture activities (**Kamleshbhai *et al.*, 2023**)

Cultivation with the IMTA system refers to the explicit combination of species from different trophic positions or nutritional needs within a single culture system **(Kamleshbhai *et al.*, 2023)**. In an IMTA system, the by-products (waste) of one species are recycled as inputs for another. Aquaculture species (e.g., fish or shrimp) are combined in appropriate proportions with organic extractive aquaculture species (e.g., suspension feeders or deposit feeders) and inorganic extractive aquaculture species (e.g., seaweed) for a balanced ecosystem management approach **(Yang *et al.*, 2025)**. Cultivation using the IMTA system allows the waste load generated from the culture process, in the form of organic matter or organic and inorganic compounds, to be utilized by other aquatic species at different trophic levels within the same area **(Sickander & Filgueira, 2022)**. This significantly reduces the impact of waste, thus supporting sustainable aquaculture. The more intensive the cultivation, the greater the waste load produced.

The next technology that can be used to address eutrophication in aquaculture is biofloc. Biofloc technology is a technique for maintaining water quality in aquaculture by balancing the carbon and nitrogen content in the system **(Crab *et al.*, 2012)**. This is done by retaining waste within the system and converting it into biofloc, which is a natural food source for fish or shrimp **(Avnimelech, 2009)**. An illustration of the biofloc system is shown in Fig. (6).

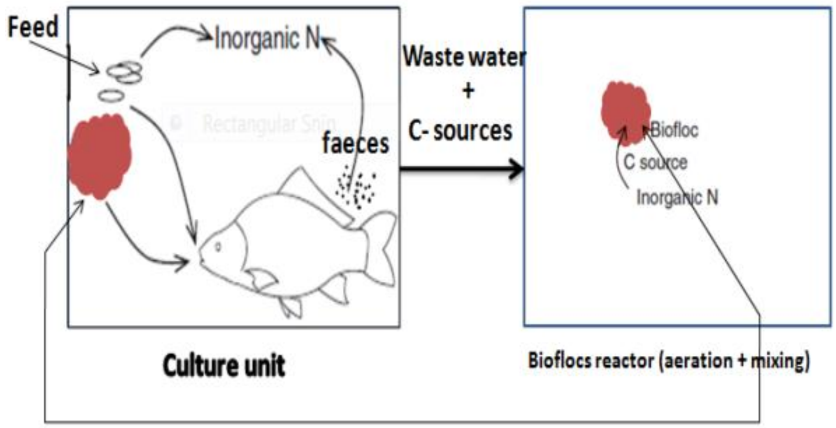

Fig. 6. Schematic diagram of biofloc-based aquaculture system **(Jena *et al.*, 2017)**

Biofloc consists of small clumps of algae, bacteria, protozoa, and other organic particles such as feces and uneaten feed, bound together by bacterial mucus. In this system, carbohydrates are added to ponds to stimulate heterotrophic bacterial growth. These bacteria assimilate nitrogen by forming microbial protein **(Jena *et al.*, 2017)**. The resulting bioflocs can be re-consumed by cultured fish or shrimp as supplementary feed **(Nayak *et al.*, 2023)**. When the carbon-to-nitrogen (C/N) ratio is balanced, nitrogenous wastes such as ammonium are absorbed by bacteria and converted into bacterial biomass. This is achieved either by supplying external carbon sources or by using feeds with high carbon content. The rapid proliferation of heterotrophic bacteria enables ammonium removal more efficiently than conventional nitrification **(Luo *et al.*, 2023)**.

Biofloc technology thus recycles organic waste into microbial biomass, creating a zero-waste system where nutrients are reused within the culture environment **(Ogello *et al.*, 2021)**. Its fundamental principle is maintaining a high C/N ratio (10–20), which stimulates heterotrophic bacteria to assimilate ammonia nitrogen and produce cellular protein **(Xu *et al.*, 2016; Abakari *et al.*, 2021)**. This microbial protein, available as feed for cultured organisms, consists of diverse microbial communities including floc-forming and filamentous bacteria, organic polymers, colloids, cations, dead cells, and suspended particles **(Cu & Lee, 2004)**. For shrimp and fish, these suspended protein-rich particles serve as an additional food source, reducing dependency on external feed.

Wastewater treatment plants (WWTPs)

Another strategic approach for mitigating eutrophication in aquaculture is the use of wastewater treatment plants (WWTPs) or dedicated waste stabilization ponds to minimize nutrient discharge before effluents reach natural waters. Organic matter from aquaculture—primarily uneaten feed and fecal waste—contains high nitrogen and phosphorus concentrations that must be treated. A typical WWTP in aquaculture consists of three main units: a sedimentation pond, an aeration pond, and an equalization pond **(Syah *et al.*, 2017)**.

- **Sedimentation pond (settling pond):** This unit removes suspended solids through gravitational settling. Baffles are installed to slow water flow and extend retention time, enhancing particle settling **(Kurnia & Purwanti, 2023)**.
- **Aeration pond:** Equipped with aerators, this pond increases dissolved oxygen (DO), reduces biochemical oxygen demand (BOD), raises pH, and strips dissolved gases such as CO_2 and H_2S. Aerobic bacteria degrade organic matter, while nitrifying bacteria oxidize nitrogen compounds **(Syah *et al.*, 2017; Putri *et al.*, 2022)**.
- **Equalization pond:** This final stage collects treated wastewater, serving as both a holding pond and a biological polishing unit. Here, macroalgae absorb nutrients and convert them into harvestable biomass, while plankton populations provide food for filter-feeding organisms such as blood clams, green mussels, and tilapia, which also act as bioindicators of water quality **(Prasetiyono *et al.*, 2023)**.

Together, biofloc technology and WWTP systems represent complementary strategies for closing nutrient loops in aquaculture, reducing eutrophication risks, and promoting environmentally sustainable production.

CONCLUSION

Eutrophication represents a major challenge in the environmental management of modern aquaculture. It arises from the accumulation of nutrients, primarily nitrogen and phosphorus, generated by excessive feeding, organic waste buildup, and inadequate waste management. This process has far-reaching consequences, including declining water quality, harmful algal blooms (HABs), impaired growth and health of cultured organisms, and associated economic and social losses.

Addressing eutrophication requires strategies that target both its root causes and impacts. Key approaches include improving feed efficiency and utilization, adopting Integrated Multi-Trophic Aquaculture (IMTA) systems, applying biofloc technology to recycle nutrients, and utilizing wastewater treatment plants (WWTPs) incorporating sedimentation, aeration, and equalization processes. Beyond technical measures, practitioner education and the enforcement of environmental regulations are essential to ensuring effective prevention and long-term mitigation.

Together, these integrated strategies provide a pathway toward sustainable aquaculture production while preserving aquatic ecosystem health.

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