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Research on The Application of Microorganisms in The Ecological Health of Water Bodies

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Abstract

Microorganisms play a crucial role in aquatic ecosystems, contributing to ecological balance, water purification, and element cycling. Understanding the various types and functions of microorganisms is vital for ecosystem management. This paper delves into the diverse applications of microorganisms in promoting ecological health in water bodies, covering water quality assessment, ecological restoration, and sustainable aquaculture practices. Through the utilization of high-throughput sequencing technology and other advanced methodologies, researchers have successfully acquired a deeper understanding of the composition and activities of microbial communities. This has led to the development of innovative evaluation frameworks like the Microbial Integrity Index. The article further explores the practical implementation of microbial technology in environmental cleanup efforts and the maintenance of ecological balance in aquaculture. It highlights the crucial roles played by microorganisms in bioremediation and feed processing, offering valuable insights and suggestions for establishing a harmonious ecological framework in water ecosystems and fostering sustainable socio-economic growth at a regional level.

Keywords: Microorganisms; Ecological health; Water quality indicators; Ecological restoration; Water bodies ecosystems

Introduction

Microorganisms play a crucial role in aquatic ecosystems by maintaining ecological balance, purifying water, and recycling elements [1]. Understanding the various types and functions of microorganisms in these ecosystems is vital for comprehensively grasping how they operate and for informing conservation and management strategies [2]. Thorough research into the ecological functions and interactions of microorganisms in water bodies offers a scientific foundation and technical assistance for the preservation and restoration of aquatic ecosystems [3]. Enhancing research on microorganisms in water is essential for safeguarding water resources, preserving ecological equilibrium, and enhancing the well-being of aquatic ecosystems [4]. Recent focus and extensive study on the aquatic ecosystem have delved into the utilization of microorganisms to promote ecological health in water bodies. This discussion aims to improve the management of aquatic resources and uphold the stability and vitality of aquatic ecosystems through scientific approaches [5].

Microorganisms, including bacteria, fungi, viruses, and protozoa, are vital to aquatic ecosystems, playing a central role in the decomposition and recycling of organic matter [6]. These organisms efficiently break down dead matter, plant residues, and waste, transforming them into carbon dioxide, water, and inorganic salts. This process is crucial for the recycling of organic substances and ensures the stability of aquatic ecosystems [7]. Moreover, microorganisms facilitate nutrient cycling, particularly of nitrogen and phosphorus. They convert organic nitrogen into inorganic forms and reduce inorganic nitrogen to gaseous nitrogen, enhancing nitrogen utilization and playing a significant role in the phosphorus cycle [8]. Microorganisms also purify water by degrading organic wastes and pollutants, thus improving environmental quality. In photosynthesis, certain aquatic microorganisms release oxygen, supporting aquatic life and maintaining ecosystem balance [9]. They form part of food chains that build the broader food web and ecological network, influencing the distribution and abundance of various organisms and stabilizing the ecosystem. Microorganisms also serve as vital indicators for environmental monitoring; the presence and population density of specific types can reflect pollution levels and ecosystem health [10].

Although there are many studies on the application of microorganisms in water bodies ecological health, there is still a lack of systematic generalization and analysis [11]. In this paper, by studying the application of microorganisms in water bodies ecosystems, we can better recognize and utilize the functions of microorganisms, provide some basis for protecting water bodies ecosystems, and achieve the goal of water bodies ecological health and sustainable development [12]. Microorganisms have diverse functions in aquatic ecosystems and play an indispensable role in maintaining the ecological balance of aquatic ecosystems, purifying water quality, and recycling elements [13]. Therefore, the study and protection of microorganisms in aquatic ecosystems is of great significance and helps to maintain the stability and health of aquatic ecosystems [14].

Application of microorganisms in water quality evaluation

Microorganisms play a crucial role in assessing water quality, as their presence and abundance serve as indicators of pollution levels and ecosystem health. Due to their short life cycles and high metabolic rates, microorganisms are highly sensitive to environmental changes making them valuable early indicators of ecological shifts in water bodies [15]. Moreover, the composition and function of microbial communities can offer insights into the trophic status, pollution levels, and overall stability of aquatic ecosystems [16]. By providing essential information for water quality assessment, monitoring water health, and informing water resource management and protection, microorganisms play a vital role in safeguarding our water resources [17].

Index of Biological Integrity

Karr first introduced the concept of the Index of Biological Integrity (IBI) for assessing the health of stream ecosystems and later expanded its application to other types of water bodies in subsequent studies [18]. The IBI has emerged as a crucial tool for evaluating, restoring, and safeguarding aquatic ecosystems, and has been extensively utilized in freshwater ecosystems for assessing and managing the risks posed by human activities [19]. While there are alternative indices available for assessing the health of aquatic ecosystems, the IBI is widely regarded as the most effective approach due to its scientific rigor, practicality, and capacity to provide a quantitative assessment of ecosystem conditions [20]. However, the conventional IBI primarily relies on macro-organisms like benthic animals and fish as indicators which may present limitations in degraded or impaired ecosystems [21].

Research is increasingly focusing on the potential of aquatic microorganisms as indicators of ecological health due to their shorter life cycles and higher metabolic rates, making them more sensitive to environmental changes and essential in aquatic ecological processes [22]. Studies have shown that microbial communities respond differently to environmental changes compared to macrofaunal communities, suggesting that microbial communities could serve as a novel indicator for assessing lake ecosystem health [23]. With advancements in high-throughput sequencing technology, researchers have gained a deeper understanding of microbial community structure and function leading to the development of new microbial indicators such as the Microbial Index of Biotic Integrity (M-IBI) [24]. Similar to the traditional IBI, the M-IBI aims to evaluate water body health by analyzing the structure and function of the microbial community within it. The development of the M-IBI is rooted in recognizing the significance of microorganisms in water body ecosystems and addressing the limitations of traditional bioindicators [25].

The development of M-IBI typically involves sampling and analyzing microbial communities in water bodies to assess ecological health. This process includes determining microbial diversity, abundance, composition [26], and functional characteristics to calculate a comprehensive index (Figure 1).

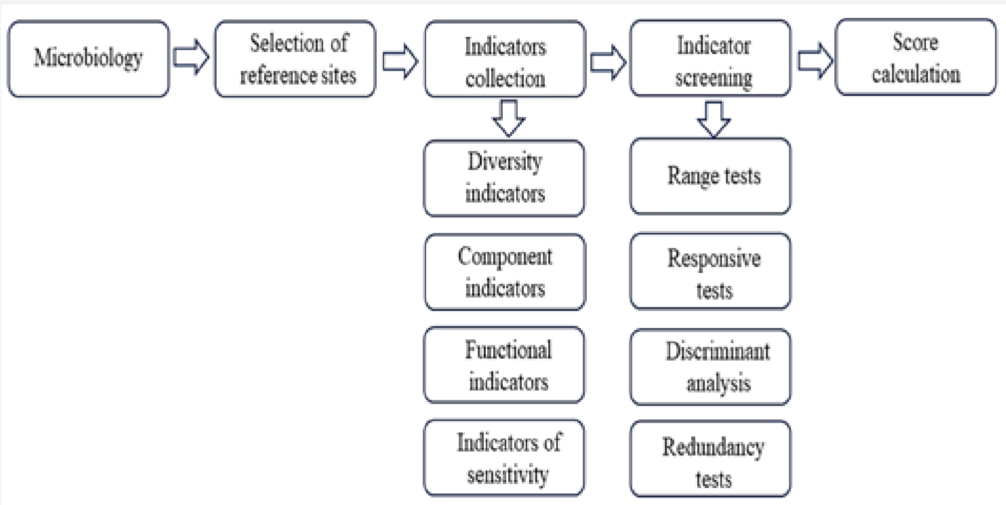

Figure 1: Schematic overview of the steps required to develop the M-IBI.

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Key indicators may include bacterial count, diversity index, and abundance of specific functional bacteria [27]. While M-IBI introduces new possibilities for water body health assessment, it also presents challenges. Environmental factors influence the structure and function of microbial communities, necessitating the establishment of tailored evaluation systems for different water bodies and environmental conditions [28]. Furthermore, continuous improvement of techniques for sampling and analyzing microbial communities is essential to enhance the accuracy and reliability of M-IBI assessments [29]. In summary, M-IBI, as a novel bioindicator system, holds promise for ecological health assessment of water bodies, but further research and refinement of methodology are crucial for its effective application [30].

Contamination indicator microorganisms

Pollution-indicating microorganisms are a distinct category of microorganisms that can serve as indicators of specific types of pollution in a body of water [31]. These microorganisms are highly sensitive to particular substances in the environment, making their presence or abundance a valuable tool in assessing water quality pollution levels [32]. For instance, certain bacteria possess the unique capability to break down organic pollutants, making their presence and activity crucial for evaluating pollution levels in water bodies. The presence, quantity, or specific physiological condition of these microorganisms can offer insights into the extent of environmental pollution [33]. They play a significant role in environmental monitoring and pollution management.

The Bacterial Eutrophication Index (BEI) has proven to be a valuable tool for assessing water quality in eutrophic lakes [34]. Research indicates that certain bacteria in lakes play a key role in breaking down organic and inorganic compounds, facilitating nutrient cycling, and ultimately influencing the trophic status of lakes [35]. Understanding the variations in microbial community structures among lakes with different trophic states is essential. However, previous studies have primarily focused on the diversity of microbial communities in natural ecosystems, rather than their response to aquatic ecosystem degradation [36]. There are significant spatial, seasonal, and interannual variations in the composition of microbial communities in lake sediments across different trophic states [37]. Jiao et al. (2021) highlighted that the distribution of microorganisms in sediments, as well as seasonal variations, contribute to distinct patterns of microbial community diversity and assembly processes along the trophic gradient in freshwater lakes [38]. BEI was first proposed to quantitatively characterize the quality of freshwater ecosystems using the ratio of the abundance of cyanobacteria in water to the abundance of the ratio of abundance of actinomycetes in water. This was the first time that biological factors were used as indicators to assess the trophic status of lakes; it compensated for the lack of use of physical and chemical indicators to characterize the interim trophic status of lakes [39].

Fecal flora, a group of microorganisms used as indicators of pollution in water quality assessment, are commonly associated with feces [40]. Their presence in a water body can signal contamination with feces. E. coli, an enteric bacterium typically found in the intestinal tracts of humans and animals, is a widely used indicator of fecal pollution [41]. In water quality assessment, E. coli is utilized to detect organic waste inputs like domestic sewage or animal feces. Detection of E. coli is commonly carried out through molecular biology techniques (e.g., PCR), culture methods, or other microbiological approaches [42]. The assessment of water body contamination levels can be determined by the presence and quantity of E. coli, enabling appropriate measures to be implemented for safeguarding water quality and public health [43]. Alongside E. coli, other bacteria like Enterococcus spp. can serve as indicators of fecal contamination. These microorganisms are closely linked to fecal contamination levels in water bodies, making them valuable tools in water quality assessment and monitoring [44]. Given that feces can harbor pathogenic microorganisms like E. coli and Salmonella, the presence of fecal flora in a water body indicates potential health hazards, including the transmission of infectious diseases. Monitoring fecal flora is crucial for informing water resource managers on how to effectively manage and reduce fecal pollution in water bodies [45]. This could involve enhancing wastewater treatment facilities, implementing better agricultural non-point source pollution control measures, and establishing protected areas.

Microorganisms for Ecological Restoration

Microorganisms play a crucial role in the restoration of water ecosystems, particularly in wetlands [46]. Wetlands act as important ecological filters in water ecosystems, effectively purifying water quality and enhancing the overall ecological environment of water bodies. Microorganisms are key players in processes such as organic matter degradation, nitrogen and phosphorus removal, and other essential functions within wetlands, ultimately enhancing the self-purification capacity of these ecosystems [47]. Moreover, microorganisms have the ability to degrade pollutants like oil and heavy metals in water, transforming them into harmless substances. By introducing suitable microbial communities or altering the ecosystem of microorganisms in water bodies [48], the restoration and reconstruction of these ecosystems can be facilitated, leading to improved ecological health and sustainable development of water bodies (Figure 2).

Microbial Agent Delivery Method

The principle of the microbial agent placement method is rooted in the environmental remediation capabilities of microorganisms. These microorganisms possess the ability to degrade pollutants, adsorb pollutants, and transform toxic substances. By introducing

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specialized microbial agents, the process of degrading and transforming harmful substances in the environment can be accelerated, ultimately leading to environmental restoration and ecological recovery [49]. Through the selection of high-efficiency strains, optimization of bacterial group composition, and expansion of culture and release, the purification of river water quality can be achieved. Specifically cultivated microorganisms have shown great effectiveness in degrading organic matter that is resistant to biodegradation [50]. Microbial agent delivery methods encompass directional delivery, diffuse delivery, point source delivery, carrier material delivery, composite delivery, and more. Selection of the appropriate method is crucial, as it should align with the specific characteristics of the target environment and remediation requirements to effectively leverage microorganisms for environmental remediation purposes [51].

Figure 2: Microbial remediation technology framework diagram.

The microbial agent delivery method holds significant promise in environmental remediation by enhancing efficiency, lowering costs, and minimizing secondary pollution. Nonetheless, challenges persist in selecting microbial agents, determining release amounts, and ensuring survival environments, necessitating further research and practical solutions. Through extensive exploration of microbial ecology and environmental microbiology, the microbial agent delivery method can offer additional options and opportunities for environmental restoration, leading to a cleaner and healthier living environment for humans [52].

Inter Gravel Contact Oxidation

Microbial inter gravel contact oxidation is a wastewater treatment technology that employs bio gravel as a carrier for the indirect contact of organic matter in wastewater. This is achieved through the attachment and growth of microorganisms on the surface of the gravel, leading to organic matter degradation and wastewater purification [53]. Bio-gravel typically consists of porous materials with a significant surface area, which can be either man-made or natural, such as ceramic grains, river pebbles, or plastic particles. These materials are known for their numerous pores and extensive surface area [54]. The bio gravel has a high number of pores and surface area, facilitating microbial attachment and growth. It also offers ample oxygen transfer channels to support the breakdown of organic matter in wastewater. Microorganisms in the biofilm on the bio gravel surface metabolize organic matter in wastewater into harmless compounds like carbon dioxide and water [55]. Additionally, the bio gravel not only fosters microbial growth but also shields them from external environmental changes.

Indirect contact between microorganisms and wastewater occurs through the pores and surface area of bio gravel during contact. This indirect contact maximizes the biodegradation capabilities of microorganisms, while minimizing the exposure to harmful substances and harsh environments present in the wastewater [56]. Future advancements in the microbial gravel indirect contact oxidation method will focus on enhancing and optimizing filler materials to improve adhesion, biocompatibility, and pollution resistance. Additionally, there will be emphasis on enhancing the stability of biofilm and the diversity of microbial communities to enhance the reliability of wastewater treatment

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[57]. Integration of this technology with other wastewater treatment methods will create a comprehensive treatment approach with multiple benefits, offering various options for environmental protection and water resource management.

Artificial fill Technology

Microbial artificial filler technology utilizes specific materials as carriers to provide microorganisms with a surface for growth and attachment [58], facilitating biofilm formation, wastewater treatment, and environmental remediation. The surface of the filler is characterized by numerous tiny pores and micro-convexities, creating an optimal environment for microbial growth and attachment, thus accelerating biofilm formation. This biofilm effectively adsorbs and degrades organic matter, ammonia nitrogen, and other pollutants in wastewater, leading to water purification [59]. Commonly used microbial artificial filler materials include plastic, ceramic, glass, and synthetic fiber, each with unique physical structures and chemical properties that offer an ideal attachment surface and growth environment for microorganisms [60], ultimately enhancing the efficiency of wastewater treatment.

Microbial artificial packing technology is extensively utilized in various applications such as wastewater treatment, biological oxidation, water purification, and environmental remediation. In the context of wastewater treatment, filler reactors are commonly configured as biological contact oxidation tanks, biofilters, aeration tanks, etc., to eliminate organic matter, ammonia nitrogen, and other pollutants from wastewater [61]. In ecological restoration efforts, fillers are employed in artificial wetlands, aquatic plant areas, and similar settings to facilitate the restoration and enhancement of water ecosystems. This technology offers several advantages including ease of operation, low energy consumption, small footprint, and high treatment efficiency [62]. It is particularly well-suited for small to medium-sized wastewater treatment plants and urban water quality purification projects. The challenges faced by microbial artificial filler technology include filler clogging, biofilm aging, and microbial community imbalance, all of which must be addressed through strategic design and management. Moving forward, the focus of microbial artificial filler technology will be on enhancing and optimizing filler materials to improve adhesion [63], biocompatibility, and pollution resistance.

Furthermore, efforts will be made to enhance the stability of biofilms and promote diversity within microbial communities to enhance the overall stability and reliability of wastewater treatment processes. Additionally, the integration of microbial artificial filler technology with other bioremediation approaches will lead to the development of comprehensive treatment strategies that offer multiple remediation options [64], thereby expanding the possibilities for environmental protection and ecological restoration.

Microorganisms for Healthy Breeding

The utilization of chemicals in aquatic environments can result in significant ecological and health concerns [65]. The issues surrounding antibiotic misuse and environmental contamination within the aquaculture sector have garnered considerable attention from both national authorities and industry stakeholders. Overuse of antibiotics not only leads to elevated levels of antibiotic residues in farmed animals, but also has the potential to spur the development of bacterial resistance, thereby posing a threat to both human health and the environment. Additionally, the use of chemical substances contributes to pollution of the breeding environment, impacting water quality, ecological equilibrium [66], and the sustainable development of the aquaculture industry. In light of these challenges, functional microorganisms emerge as a sustainable and environmentally friendly alternative with the capacity to replace chemical substances effectively [67]. These microorganisms can break down waste, aid in the treatment of aquaculture wastewater, and bolster the immunity and growth rates of farmed animals, offering a promising solution for promoting ecologically sound farming practices.

Application of Microorganisms in Bio Feed Processing

A microbial feed is a type of feed primarily composed of microorganisms, commonly utilized in animal feeding and farming (Figure 3). These microorganisms may consist of unicellular fungi, bacteria, yeasts, or multicellular algae [68]. Microbial feeds can serve as the primary feed source for animals or as additives to enrich the nutrient composition of the feed, thereby enhancing the growth performance and health of the animals. The production process of microbial feed typically involves microbial culture, fermentation, and drying steps [69]. First, appropriate microbial strains are carefully selected, and a suitable culture medium along with optimal growth conditions are provided to facilitate the growth and reproduction of microorganisms. Subsequently, during the fermentation process, these microorganisms synthesize the necessary nutrients and bioactive substances, thereby enhancing the nutritional quality and functional properties of the feed [70]. The fermented microorganisms are then processed into powder or granules, followed by drying treatment to create microbial feed. Microbial feed is distinguished by its high nutritional content, ease of digestion and absorption, presence of functional ingredients, and eco-friendly nature. The abundance of nutrients in microbial feed fulfills the requirements for animal growth and development, promoting easy digestion and absorption, while also delivering specific bioactive substances that contribute to animal health and growth [71]. Moreover, the production process of microbial feed is environmentally sustainable, reducing reliance on traditional feed ingredients, minimizing resource wastage and environmental pollution, and offering innovative solutions for the sustainable advancement of the aquaculture sector.

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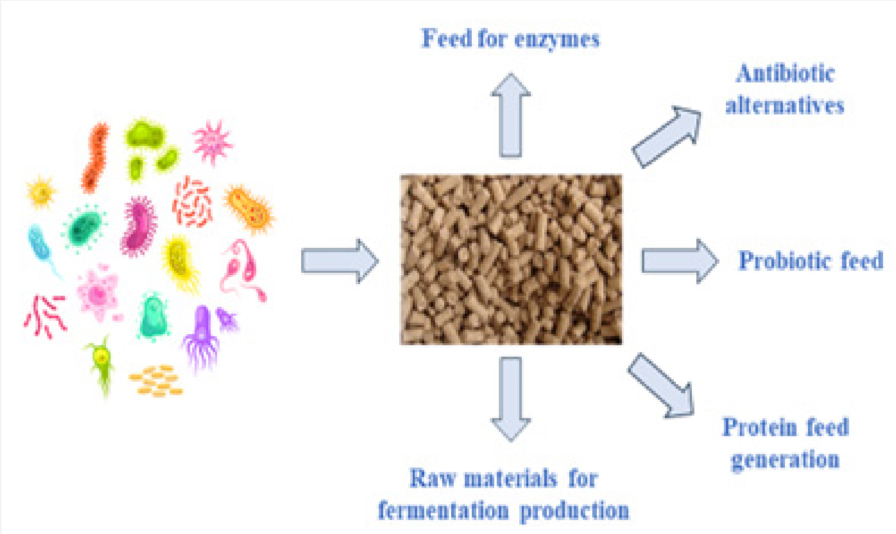

Figure 3: Uses of microorganisms in feed production.

Microorganisms play a crucial role in bio feed processing by enhancing feed quality and nutritional value, as well as improving animal health and growth performance. Enzymes from microorganisms are commonly used to break down complex organic matter in feed, such as starch, cellulose, and protein, into simpler substances that are more easily digested and absorbed by animals [72]. The addition of appropriate amounts of amylase, cellulase, and other enzyme preparations can increase the energy value and utilization rate of feed, decrease the presence of anti-nutritional factors, and support animal growth and development. The fermentation technology of microorganisms also has important applications in biological feed processing, which can change the chemical composition and organizational structure of feed, increase the content of vitamins [73], amino acids and other nutrients in feed, and improve the nutritional value and bioavailability of feed. Organic acids and growth factors produced in the fermentation process and other active substances can promote animal digestion and absorption and immune function, improve animal disease resistance and growth performance. The additives of microorganisms also play an important role in biological feed, such as probiotics can regulate the structure of animal intestinal flora, inhibit the growth of harmful flora [74], promote the reproduction of beneficial flora, and improve the digestion and absorption function and health of animals. In addition, some microbial proteins and cell wall components are also widely added to biological feeds for enhancing the nutritional value and functionality of feeds.

Application of Microorganisms in Improving the Aquaculture environment

In the aquaculture water environment, certain microorganisms have the ability to inhibit the growth and proliferation of pathogenic microorganisms [75]. Initially, probiotics and beneficial microorganisms engage in competition with pathogenic microorganisms for nutrients and living space, effectively reducing the population of pathogenic microorganisms. Additionally, some microorganisms are capable of producing inhibitory substances like antibiotics and antimicrobial peptides, which directly hinder the growth and reproduction of pathogenic microorganisms. Furthermore, microorganisms alter the environmental conditions of aquaculture water by regulating pH levels, oxygen content, etc., creating an unfavorable environment for the survival of pathogenic microorganisms [76]. These microorganisms also modulate the immune system of farm animals, enhancing their resistance to pathogenic microorganisms. Lastly, certain microorganisms can serve as biological control agents by directly attacking and eliminating pathogenic microorganisms [77]. Through various mechanisms, microorganisms play a crucial role in inhibiting pathogenic microorganisms in the aquaculture water environment, thereby safeguarding the health of farm animals, reducing disease incidence, and supporting the sustainable development of the aquaculture industry [78].

Microorganisms are essential in controlling aquaculture odor [79], which typically arises from the breakdown of organic wastes leading to the production of hydrogen sulfide and ammonia, among other compounds, as well as the decomposition of organic matter in water. These microorganisms help mitigate odor concerns by breaking down these compounds through various pathways [80]. Certain sulfur bacteria and ammonia oxidizing bacteria utilize hydrogen sulfide and ammonia as electron acceptors to catalyze oxidation reactions, converting them into harmless sulfate and nitrate. Through these oxidation reactions, microorganisms play a vital role in reducing hydrogen sulfide and ammonia levels

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in water bodies [81], effectively addressing odor problems. Anaerobic ammonia oxidizing bacteria and nitrifying bacteria utilize sulfate and nitrate as electron acceptors for denitrification and anti-sulfate reduction reactions, converting them into nitrogen and hydrogen [82]. This process helps to further decrease nitrogen levels in water bodies, contributing to odor reduction. Additionally, acid-producing bacteria and heterotrophic bacteria utilize organic waste as a carbon source to facilitate acidification reactions and anaerobic fermentation, producing organic acids and gases that promote the degradation of organic substances in water bodies. In this way, microorganisms can reduce the content of organic substances in the water body and reduce the occurrence of spoilage reactions [83], thus alleviating the odor problem of the water body. Through oxidation reaction, reduction reaction and anaerobic fermentation, microorganisms can effectively degrade the odor substances in the water body and alleviate the odor problem of the water body, providing a green and environmentally friendly odor control method for the aquaculture industry.

Conclusion

Microorganisms have diversified functions in water bodies ecosystems and play an important role in maintaining the ecological balance of water bodies, purifying water quality and cycling elements. Through in-depth research on the types and functions of microorganisms, it can provide some basis and technical support for the protection of water bodies ecosystems. Strengthening the research and protection of microorganisms in water bodies ecosystems can help maintain the stability and health status of water bodies ecosystems and promote the sustainable utilization and management of water bodies resources. With the development of science and technology, especially in the era of rapid progress of molecular technology, the application of microorganisms shows great potential in the field of environmental monitoring and ecological restoration. Future studies need to further explore the response mechanisms of microbial communities to environmental changes and optimize the application strategies of microorganisms in water health assessment and environmental restoration, in order to better utilize this natural resource and promote the health and stability of water bodies ecosystems.

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