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A Comprehensive Review of Eutrophication in Water Resources: From Identifying Contributing Factors to Proposing Management Strategies

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Abstract

Eutrophication, which refers to the excessive enrichment of water bodies with nutrients, has emerged as a significant global environmental and economic crisis. This complex ecological process primarily results from extensive human activities, including the overuse of chemical fertilizers in agriculture, the discharge of untreated domestic and industrial wastewater, and intensive livestock and aquaculture systems. The influx of large amounts of nitrogen and phosphorus compounds into aquatic ecosystems disrupts natural nutrient cycles, leading to algal blooms and ultimately severe depletion of dissolved oxygen (hypoxia). The devastating consequences of this phenomenon include biodiversity loss, the creation of dead zones in coastal waters, threats to fisheries and aquaculture industries, and substantial increases in water treatment costs for drinking and industrial purposes. To address this multifaceted challenge, various solutions have been proposed, including chemical methods (such as coagulants), physical approaches (like artificial aeration), and biological techniques (using nutrient-absorbing plants and microorganisms). However, international experience demonstrates that only through integrated management strategies—combining smart policymaking, continuous water quality monitoring, and the development of clean technologies in agriculture and industry, and active local stakeholder engagement—can we effectively control this problem and safeguard water resources for future generations.

Keywords: Eutrophication, Harmful Algal Bloom (HAB), Water Quality Management, Nutrient Load.

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1. Introduction

Water stands as the fundamental building block of life, an irreplaceable resource that sustains all terrestrial ecosystems. This remarkable chemical substance – characterized by its transparency, neutral taste, and absence of color or odor – constitutes approximately 71% of Earth's surface. Its critical importance extends across biological, environmental, and socioeconomic domains, making responsible water management absolutely imperative. Contemporary water resources face unprecedented challenges, including severe scarcity, escalating pollution levels, and inefficient utilization patterns. Implementing robust conservation measures has therefore become essential to safeguard water security for current and future populations. This necessitates adopting sustainable management approaches, promoting water preservation initiatives, and enforcing stringent anti-pollution regulations (Islam et al., 2020).

As a finite yet indispensable resource, water demands meticulous stewardship to maintain its availability. Strategic water storage solutions coupled with rigorous quality control measures form the cornerstone of effective water governance (Elhaga et al., 2020) .The primary objectives of water storage encompass drought mitigation, reliable supply assurance, and climate resilience enhancement (Yousefi et al., 2019) .Subsequent water quality monitoring becomes equally vital, addressing critical considerations for public health protection, environmental conservation, and agricultural/industrial requirements (saboktakin et al., 2022). Water's extraordinary value manifests through its life-sustaining properties, ecosystem support functions, economic facilitation, and community enrichment capabilities. Proper recognition of water's centrality and implementation of science-based conservation frameworks constitute pivotal steps toward achieving planetary sustainability (Elhaga et al., 2020).

Both surface water bodies and groundwater aquifers serve as crucial reservoirs supporting human civilization and natural biodiversity (Ma et al., 2020) . Alarmingly, escalating pollution trends have recently compromised these resources, particularly affecting reservoirs and underground water tables. Contamination occurs through identifiable point sources and diffuse pathways, originating from either natural processes (geological leaching, watershed degradation) or human activities (municipal wastewater, agricultural runoff containing agrochemicals, livestock operations, industrial effluents, and mining byproducts). A comprehensive understanding of these pollution mechanisms proves essential for developing targeted remediation strategies (Khamidun, 2022) .Among various water quality threats, eutrophication emerges as particularly detrimental to reservoir ecosystems(Ayele & Atlabachew, 2021) .Eutrophication refers to a condition where nutrient concentrations (particularly phosphorus and nitrogen) gradually increase in water bodies, leading to excessive growth of aquatic plants and algae. This phenomenon represents one of the most serious challenges facing freshwater systems and has a long history in water resource management. Although eutrophication is a natural process occurring in aquatic ecosystems over centuries, human activities have significantly accelerated its pace and extent. The mechanism involves enhanced productivity of aquatic ecosystems due to the accumulation of organic matter that decomposes into simpler compounds. The most visible manifestation is phytoplankton blooms, which not only reduce water clarity but also severely degrade water quality. These blooms limit sunlight penetration, endangering coastal vegetation and disrupting ecological balance. Eutrophication-induced changes lead to biodiversity loss and dramatic declines in populations of larger aquatic fauna like fish and waterfowl. The primary source of excess nutrients is typically surface runoff carrying terrestrial ecosystem products into water bodies. While previously considered irreversible, recent successes in several lakes have demonstrated that proper nutrient input management can reverse eutrophication.

2. Factors Influencing Eutrophication

The phenomenon of eutrophication is considered one of the major challenges facing most lakes and dam reservoirs. It is associated with the growth of algae and other plankton, and a reduction in dissolved oxygen, which leads to the deterioration of water quality and mass fish mortality, along with the death of other aquatic organisms (Astuti et al., 2022).Eutrophication is one of the most significant indicators of water pollution and the process of ecosystem degradation and aging of water bodies (Song & Burgin, 2017) .The degree of a reservoir's vulnerability to eutrophication is determined by the concentration of nutrients and the biomass of aquatic vegetation in the water. Eutrophication is a biological process driven by the presence of nutrients such as nitrogen and phosphorus, which leads to the proliferation and growth of chlorophyll-containing organisms in the reservoir (Figure 1).

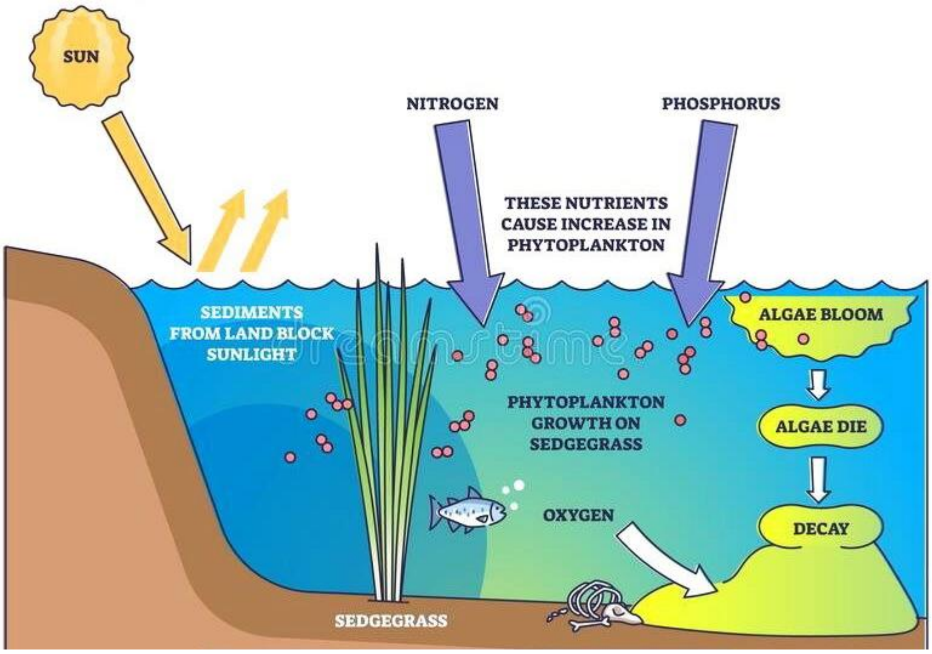

Figure 1. Factors Influencing the Eutrophication Phenomenon in the Reservoir

The concentration of nutrients and the biomass of aquatic vegetation in the water determine the degree to which a reservoir is affected by eutrophication. This classification is defined in three levels:

- Oligotrophic level refers to lakes that have low nutrient concentrations, low biomass of aquatic vegetation, and high water transparency.
- Eutrophic level includes lakes with high nutrient concentrations, high biomass of aquatic vegetation, and low water column transparency.
- Mesotrophic level represents an intermediate condition between the two aforementioned states(Tugrul et al., 2019).

Natural eutrophication is a process that occurs over centuries as part of the ecosystem's life cycle. However, human activities have accelerated this process, causing it to occur more rapidly and with immediate consequences. The main cause of eutrophication is the entry of large amounts of readily available nutrients into water bodies, leading to increased fertility and excessive growth of plants and algae(Wu et al., 2017). Some of the factors that intensify the eutrophication process by increasing the nutrient content of water sources include:

2.1. Discharge of Urban and Industrial Wastewater

The discharge of urban and industrial wastewater into water bodies is considered one of the main factors exacerbating eutrophication. These effluents contain significant amounts of nitrogen and phosphorus compounds, which are key nutrients for the growth of algae and aquatic plants. In many cities, outdated or inefficient wastewater treatment systems are unable to completely remove these nutrients, resulting in their direct discharge into rivers, lakes, and groundwater resources. The increased concentration of these substances in water leads to excessive algal growth and the formation of algal blooms, which have many negative consequences for aquatic ecosystems(Preisner et al., 2021).

2.2. Agricultural Activities

Modern agriculture, through the widespread use of chemical and organic fertilizers, significantly contributes to nutrient enrichment in water resources. These fertilizers are rich in nitrogen and phosphorus, essential for crop growth. However, a large portion of these substances, due to over-irrigation or heavy rainfall, is carried away through surface runoff into nearby water bodies. Their entry into surface and groundwater disrupts the natural balance of aquatic ecosystems and creates conditions conducive to the rapid growth of algae and aquatic plants—an issue especially evident in regions with dense agricultural activity(Mishra, 2023).

2.3. Livestock Wastewater

Livestock farming also plays a significant role in increasing nutrient loads in water resources. Animal waste contains high levels of organic and nutrient-rich matter, which, if not properly managed, can infiltrate water bodies. In many cases, these wastes are directly discharged into rivers or seep into groundwater, increasing nitrogen and phosphorus concentrations. This not only leads to eutrophication but also degrades water quality for human and agricultural use.

2.4. Discharge of Untreated Wastewater

In many parts of the world, especially in developing countries, human and industrial wastewater is directly discharged into water bodies without any treatment. These wastewaters contain high levels of nutrients, organic matter, and various pollutants, quickly increasing the nutrient load in water. This not only results in excessive algal growth but also reduces dissolved oxygen levels, causing fish kills and harming other aquatic life(Preisner, 2020).

2.5. Urban Development and Riparian Zone Degradation

Rapid urban development and construction within riparian zones and wetlands reduce the natural self-purification capacity of these ecosystems. The loss of natural vegetation around water bodies increases soil erosion and the entry of sediments and nutrients into the water. Additionally, unregulated construction can disrupt natural water flow, promoting nutrient accumulation and algal growth(Oliver et al., 2019).

2.6. Soil Erosion

Soil erosion, as a natural process, plays a major role in transporting nutrients to water bodies. When soil is eroded by heavy rainfall or human activities, large amounts of organic and mineral matter are carried into rivers and lakes via runoff. These materials include nitrogen, phosphorus, and other elements essential for plant growth, potentially intensifying eutrophication(Lin et al., 2016).

2.7. Decomposition of Organic Matter in Water

The decomposition of organic matter in water, such as fallen leaves or aquatic plant residues, is a natural process that gradually releases nutrients. Under normal conditions, this occurs slowly and maintains ecosystem balance. However, when the quantity of organic matter increases due to human activities, the decomposition process accelerates, rapidly raising nutrient concentrations in the water—resulting in algal blooms and deteriorated water quality(Deng et al., 2023).

2.8. Intense Rainfall

Heavy and torrential rains can wash large amounts of nutrients from watersheds into aquatic ecosystems. These include agricultural fertilizers, animal waste, and other pollutants that quickly enter rivers and lakes during storms. This phenomenon is especially common in areas with reduced vegetation cover or erosion-prone soils(H. Xu et al., 2019).

2.9. Rising Water Temperatures

Rising water temperatures due to climate change or human activity can accelerate the growth of algae and aquatic plants. Warmer water also holds less dissolved oxygen, favoring species that can tolerate low-oxygen conditions. These changes disrupt the natural balance of aquatic ecosystems and intensify eutrophication(Zhao et al., 2022).

2.10. Inefficient Treatment Systems

Outdated or poorly functioning wastewater treatment systems often fail to remove all nutrients from effluents. As a result, even treated wastewater may still contain significant levels of nitrogen and phosphorus, which are discharged into water bodies. This issue is especially problematic in densely populated or industrial areas where large volumes of wastewater are produced.

2.11. Poor Watershed Management

Improper watershed management practices—such as unsustainable agriculture or destruction of vegetative cover—can lead to increased pollution and nutrient runoff into water bodies. This not only worsens eutrophication but also reduces water quality and degrades aquatic ecosystems.

2.12. Encroachment on Water Body Buffer Zones

Construction and destruction of natural areas such as wetlands and coastal forests around water bodies reduce these ecosystems' ability to filter nutrients and pollutants. This leads to an increase in nutrient concentrations in the water and worsens eutrophication(Li et al., 2017).

2.13. Inadequate Water Quality Monitoring:

Insufficient water quality monitoring and failure to detect nutrient increases in a timely manner can exacerbate eutrophication. In many cases, control measures are only implemented once eutrophication has reached a critical stage(Kapsalis & Kalavrouziotis, 2021).

2.14. Decline in Filter-Feeding Species

Filter-feeding species like freshwater mussels play a vital role in controlling nutrient levels in water. Their decline due to pollution or overharvesting can increase nutrient concentrations and worsen eutrophication.

2.15. Changes in Microbial Communities

Shifts in the microbial communities within water bodies can affect the natural nutrient cycling processes. Some microorganisms are crucial for organic matter decomposition and nutrient recycling; changes in their populations can disrupt ecosystem balance(Han et al., 2020).

3. General Process of Eutrophication

3.1. Nutrient Accumulation

The initial stage of the eutrophication process involves the gradual accumulation of nutrients—primarily nitrogen and phosphorus—in various ecosystems. These nutrients can accumulate through both natural processes and anthropogenic activities. Natural mechanisms such as rainfall, soil erosion, landslides, and storms can transport nutrient-rich soil from surrounding lands into aquatic systems. In contrast, human activities such as the discharge of domestic and industrial wastewater and the expansion of agricultural and residential areas contribute directly or indirectly to the nutrient load in nearby water bodies. At the beginning of this process, aquatic ecosystems are typically oligotrophic, meaning they have low nutrient availability. As nutrient concentrations increase, microorganisms and aquatic plant species utilize them to boost their productivity.

3.2. Increased Productivity

Elevated nutrient concentrations in aquatic systems lead to a significant increase in the production of phytoplankton and aquatic plants. These ecosystems host a diverse community of microorganisms capable of utilizing a wide range of simple and complex nutrients. As a result, the biomass of both microorganisms and aquatic flora increases substantially. When these organisms die, their biomass accumulates in the system. This cycle continues as long as nutrients remain sufficiently available.

3.3. Algal Bloom Formation

Excessive algal growth leads to the formation of algal blooms on the surface of water bodies. These blooms not only produce oxygen through photosynthesis but also trigger a feedback loop, in which the decomposition of dead algae releases additional nutrients, further intensifying eutrophication. Algae near the surface receive ample sunlight, allowing them to photosynthesize and proliferate rapidly. As the blooms expand, sunlight penetration into deeper water layers diminishes, disrupting photosynthesis in other aquatic plants. Consequently, dissolved oxygen levels decline, leading to algal death. The decomposition of these dead organisms by bacteria further depletes the remaining oxygen. This sequence of events ultimately degrades water quality and threatens the health of aquatic life (Dorgham, 2014; Targamadzė, 2019; Vinçon-Leite & Casenave, 2019).

4. Effects/Problems of Eutrophication

Eutrophication is considered a form of water pollution, affecting approximately 30 to 40 percent of the world's water bodies. In addition to polluting water, it has various negative impacts on ecosystems and living organisms.

4.1. Increase in Phytoplankton Biomass

One of the most prominent consequences of eutrophication is the increased production of phytoplankton, especially in the form of algal blooms. These blooms may include toxic species such as cyanobacteria, which are harmful to both aquatic life and humans. They also reduce water clarity and overall water quality.

4.2. Oxygen Depletion

Algal blooms block sunlight from reaching underwater plants, reducing photosynthesis and leading to plant death. The decomposition of these plants by bacteria consumes the remaining oxygen, creating anoxic conditions that promote the production of toxic and foul-smelling gases.

4.3. Loss of Biodiversity

The dominance of algal species limits light and nutrient availability for other aquatic organisms, resulting in a significant decline in biodiversity.

4.4. Water Pollution

Algal blooms reduce water transparency, making the water unsafe for drinking and recreational use. They also diminish the aesthetic value of water bodies(Kotsiuba et al., 2022; Zhao et al., 2022).

5. Solutions for Eutrophication

Eutrophication can be addressed through a variety of chemical, physical, and environmental strategies, especially when preventive measures are insufficient.

5.1. Chemical Methods

When conventional treatments fail to adequately reduce nutrient concentrations, chemical agents can effectively control eutrophication. Chemical methods are typically more suitable for lakes with severe eutrophic conditions leading to blue-green algal blooms. Worldwide, substances such as copper sulfate ($CuSO_4$), herbicides, algaecides, ferrous sulfate, aluminum sulfate, calcium oxide, ferric chloride, magnesium sulfate, magnesium chloride, alum, and iron anode/aluminum cathode electrodes are used for chemical control of eutrophication (Akinnawo, 2023; Zhang et al., 2021).

5.2. Physical Methods

Physical methods are recognized as crucial engineering measures and the most important corrective actions for eutrophication in lakes, primarily targeting the reduction of internal nutrient loading.

5.2.1. Dilution and Flushing

Dilution and flushing involve introducing water from an external source or another lake with lower nutrient concentrations into the eutrophic lake. Ideally, the added water should have higher calcium (Ca^{2+}) and bicarbonate (HCO_3^-) content, directly reducing nutrient concentrations. Lakes with low nutrient content naturally limit algal growth and maintain good water clarity, making them suitable for dilution. Winter is recommended for this process due to slower algal growth and easier access to high-quality water. However, feasibility studies on sediment removal must be conducted before implementation. While dilution and flushing are simple and rapid techniques effective for small water bodies, their success heavily depends on a consistent supply of high-quality water. For medium to large water bodies, the high investment and extended drainage time make implementation challenging(Chen et al., 2024).

5.2.2. Deep Aeration

Aeration is a physical technique used to increase oxygen levels in water bodies, preventing stratification and reducing internal phosphorus cycling. Deep aeration serves two primary purposes: (1) increasing dissolved oxygen (DO) without altering the water column and (2) creating a more favorable environment for benthic organisms and enhancing food supply. It also helps reduce ammonia (NH_3), iron (Fe), manganese (Mn), and other ionic substances. Countries like the Netherlands and the UK have successfully applied deep aeration in small lakes and reservoirs with positive results. However, economic and technological constraints limit its effectiveness in large lakes, making it more suitable for smaller water bodies(Zhang et al., 2020).

5.2.3. Sediment Dredging

Sediment dredging is a vital tool for rapidly improving water quality in eutrophic lakes affected by internal phosphorus (P) loading from sediments. Dredging is a direct and effective restoration method, but it deepens the water body, altering nutrient concentrations and abiotic water column dynamics, thereby impacting ecological balance(Yang et al., 2024).

5.2.4. Other Physical Methods:

Artificial Mixing: Used to prevent eutrophication and cyanobacterial growth in lakes.

Mechanical Harvesting: Aquatic plants and algae absorb large amounts of nutrients. Harvesting them directly improves surface water ecology. Though simple and safe, this method is energy-intensive and increases disposal costs.

Sediment Capping: Techniques like sand, plastic films, or fly ash can reduce phosphorus release from sediments but may negatively affect submerged aquatic plant development.

5.3. Biological Methods

Ecological restoration of lakes is a key criterion for the reestablishment of natural ecosystem cycles and is considered the ultimate goal of eutrophication control. Ecological restoration is used to regulate lake stability and suppress the circulation rate of nutrients by reconstructing and rehabilitating relatively complex ecosystems, ultimately aiming to recreate a healthy ecosystem. Biological methods can enhance the interactions between microorganisms and aquatic organisms, as well as the water's self-purification capacity during pollution treatment. Bioremediation employs specific microorganisms, aquatic plants, and aquatic animals to degrade, absorb, and transform nutrients in lakes. Factors affecting bioremediation include nutrient levels, pH, temperature, and inhibitory substrates or metabolites (Paul et al., 2021).

Phosphorus is one of the key elements inducing eutrophication; therefore, its removal from various sources is essential. One natural tool for phosphorus removal is periphyton. These microbes contribute to phosphorus removal by absorbing, precipitating, and filtering it from the water. Various phytoremediation techniques have also been proposed to effectively reduce water toxicity (C. Xu et al., 2023) .Phytoremediation is an effective method for controlling, regulating, and mitigating eutrophic environments. Aquatic plants can efficiently absorb nutrients during their growth and are capable of removing, degrading, or isolating harmful substances from the environment. It has been shown that different plant species exhibit varying pollutant removal efficiencies in floating island systems. Aquatic plants can be classified as emergent, floating-leaved, free-floating, submerged, and wetland plants. They are usually selected based on effectiveness and cost-efficiency. Some of the most commonly used species include *Canna*, *Typha*, *Scirpus*, water hyacinth (*Eichhornia crassipes*), duckweed (*Lemna*), *Vetiveria zizanioides*, *Acorus calamus*, and *Cyperus alternifolius*. Reports indicate that, compared to other plants, *Canna* shows superior performance in terms of improving dissolved oxygen (DO) levels, hydraulic efficiency, and nutrient removal attributed to plant uptake.

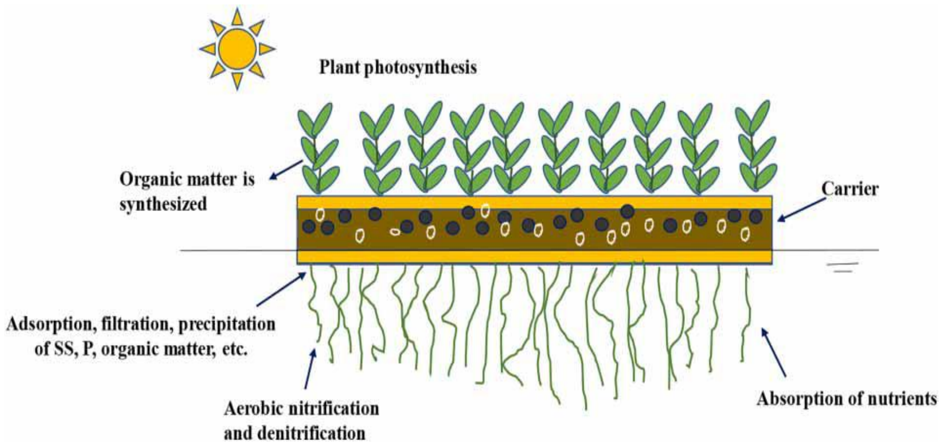

Figure 2. Lake Phytoremediation Using Floating Islands

Algae play a crucial role in controlling reservoir eutrophication through various mechanisms. Research has shown that increasing direct hydrodynamic effects—such as flow velocity and shear stress—can inhibit algal growth, while intensified indirect effects—such as nutrient redistribution—may promote algal blooms. Additionally, the use of ultrafine (micro/nano) bubbles has proven effective in controlling algal growth in water bodies, offering an environmentally friendly and chemical-free solution. Moreover, strategies such as biomanipulation—including the removal of zooplanktivorous fish and application of biological control agents—have shown promise in managing algal blooms and invasive aquatic weeds. These approaches underscore the importance of integrating biological control methods with nutrient load management to effectively combat eutrophication.

Table 1. Summary of advantages and disadvantages of reservoir eutrophication control methods

Method	Disadvantages	Advantages
Chemical	High cost Not suitable for long-term treatment Risk of secondary pollution	Direct and fast effectiveness Simple implementation
Physical	High operational and maintenance costs Temporary effect Potential harm to ecosystems	Simple and easy to implement Quick and visible effects in the short term
Biological	Long treatment time	Cost-effective Sustainable and comprehensive method Less secondary pollution Suitable for both small and large-scale systems Effectively reduces pollutant concentration

6. Conclusion

This comprehensive review has identified eutrophication as one of the most critical threats to the quality and sustainability of aquatic resources. In the section on influencing factors, it was demonstrated that nutrient inputs—particularly nitrogen and phosphorus—can enter aquatic ecosystems through chemical fertilizers, domestic and industrial wastewater, concentrated animal feeding operations, and natural processes. These inputs create favorable conditions that significantly accelerate the eutrophication process. Identifying and managing these nutrient sources is a fundamental starting point for any sustainable control strategy. An analysis of the types and processes of eutrophication revealed that while natural eutrophication occurs over centuries, cultural eutrophication—driven by human activities—can result in serious environmental and economic consequences within much shorter timeframes. The impacts of eutrophication, including toxic algal blooms, decreased dissolved oxygen levels, and loss of biodiversity, serve as warning signals for local communities, aquaculture industries, and water consumers. Ultimately, the proposed solutions highlight that no single method can effectively resolve eutrophication on its own. A combination of chemical (e.g., phosphorus coagulants), physical (e.g., dilution, aeration, sediment dredging), and biological (e.g., bioremediation, ecological restoration) methods—applied through an integrated, nutrient load-based management approach—offers the greatest likelihood of success. Furthermore, continuous water quality monitoring and the application of advanced technologies for rapid detection of key ecological parameters are essential for ensuring the long-term effectiveness of these interventions. In conclusion, tackling eutrophication and ensuring the sustainability of water resources requires a coordinated effort among policymakers, environmental experts, water project implementers, and local communities. Through the adoption of preventive and corrective strategies, it is possible to steer development toward the effective protection of this invaluable resource.

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