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Role of Submerged Macrophytes in Restoring Eutrophic Lakes

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***Abstract*— *Eutrophication remains one of the most pressing challenges for freshwater ecosystems, leading to harmful algal blooms, oxygen depletion, and biodiversity loss. Submerged macrophytes, or submerged aquatic plants, play a central role in counteracting eutrophication by functioning as ecosystem engineers. They regulate nutrient dynamics, suppress algal growth, stabilize sediments, and enhance oxygen conditions, thereby facilitating the transition of lakes from turbid, phytoplankton-dominated states to clear-water conditions. This article reviews the ecological roles of submerged macrophytes in restoring eutrophic lakes, highlighting their contributions to nutrient uptake, algae control, oxygen production, habitat provision, sediment stabilization, and allelopathic interactions. A better understanding of these functions underscores the importance of submerged plants as a natural, sustainable, and cost-effective approach to freshwater restoration.*

Keywords*— Eutrophication, submerged macrophytes, submerged aquatic plants, ecological restoration, freshwater ecosystems, eutrophic lake restoration

I. INTRODUCTION

Freshwater ecosystems are among the most productive yet vulnerable environments on Earth, supporting biodiversity, providing ecosystem services, and sustaining human needs such as drinking water, fisheries, and recreation. However, these systems are increasingly threatened by eutrophication, a process driven by excessive nutrient enrichment, primarily nitrogen (N) and phosphorus (P), originating from agricultural runoff, wastewater discharge, and industrial effluents (Smith et al., 1999; Schindler et al., 2006; Liu et al., 2022). Eutrophication triggers a cascade of ecological problems, including harmful algal blooms, oxygen depletion, fish kills, biodiversity loss, and the collapse of aquatic food webs (Dodds et al., 2009).

Traditional approaches to lake restoration—such as chemical treatments, sediment dredging, and artificial oxygenation—can provide temporary relief but are often costly, energy-intensive, and ecologically disruptive (Cooke et al., 2005). In contrast, biological approaches that harness natural ecosystem processes are increasingly recognized as sustainable alternatives. Among these, submerged macrophytes, or submerged aquatic plants, function as ecosystem engineers that can profoundly influence nutrient dynamics, water clarity, oxygen balance, and aquatic community structure (Carpenter & Lodge, 1986; Jeppesen et al., 2005) (Fig. 1).

Submerged macrophytes provide multiple ecological functions that help counteract the drivers and symptoms of eutrophication. They absorb nutrients directly from the water column and sediments, reducing nutrient availability for phytoplankton (Hilt et al., 2006). Their photosynthetic activity releases oxygen into the water, which supports aerobic microbial processes and aquatic fauna. Structurally, macrophyte beds offer habitat complexity that enhances biodiversity and stabilizes trophic interactions. Moreover, by anchoring sediments and releasing allelopathic compounds, submerged macrophytes suppress phytoplankton dominance and reinforce water clarity (van Donk & van de Bund, 2002; Hilt & Gross, 2008).

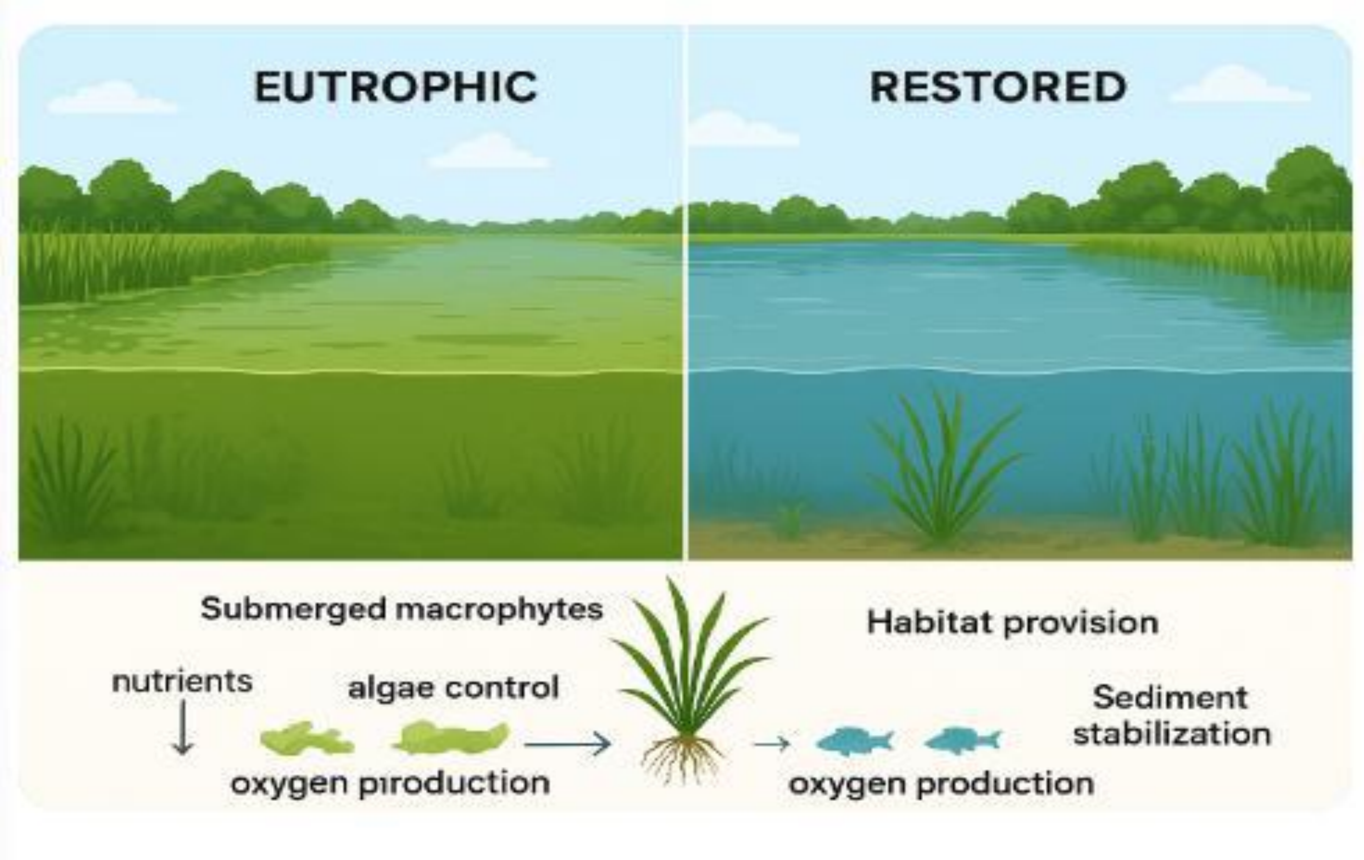

Fig. 1: Submerged macrophytes restore eutrophic lake

This paper focuses on the role of submerged macrophytes in restoring eutrophic lakes, with an emphasis on their ecological functions and feedback mechanisms. By synthesizing evidence from empirical studies, long-term monitoring projects, and theoretical frameworks, we highlight how submerged macrophytes contribute to nutrient cycling, algal control, oxygenation, habitat provision, sediment stabilization, and allelopathy. The goal is to provide a mechanistic understanding of their role in ecological resilience and regime shifts from turbid, algae-dominated states to clear-water, macrophyte-dominated systems.

II. HOW SUBMERGED MACROPHYTES HELP RESTORE EUTROPHIC LAKES

Submerged macrophytes play a pivotal role in reversing and stabilizing eutrophic conditions in freshwater ecosystems. Acting as both nutrient sinks and ecological engineers, these plants contribute to the transition of lakes from a turbid, phytoplankton-dominated state to a clear-water, macrophyte-dominated state (Scheffer et al., 1993; Jeppesen et al., 1998; Yang et al., 2025). Their presence initiates a cascade of positive feedback mechanisms that simultaneously reduce nutrient availability, suppress algal dominance, and enhance habitat quality for diverse aquatic organisms.

At the ecosystem level, submerged macrophytes influence nutrient cycling by directly absorbing nitrogen and phosphorus from both the water column and sediments, thereby limiting the resources available for phytoplankton blooms (Hilt et al., 2006). This reduction in nutrient concentrations improves water clarity, which further supports macrophyte growth by increasing light penetration. The establishment of macrophyte beds also stabilizes sediments, preventing nutrient resuspension and turbidity (Horppila & Nurminen, 2003). In addition, many submerged macrophytes excrete allelopathic compounds that inhibit the growth of cyanobacteria and other algae, adding a chemical layer of control (Hilt & Gross, 2008).

These plants also contribute to oxygen balance by releasing oxygen through photosynthesis, particularly during daylight hours. This enhances aerobic conditions in the water column and upper sediments, which promotes nitrification and other microbial processes essential for nutrient removal (Ferreira et al., 2018). Beyond water chemistry, submerged macrophytes provide physical habitat complexity, offering refuge for zooplankton that graze on phytoplankton and for fish species that depend on structured vegetation for spawning and feeding (Warfe & Barmuta, 2004). By supporting these trophic interactions, submerged macrophytes indirectly regulate algal populations and reinforce ecosystem stability.

The cumulative effect of these functions creates a reinforcing cycle that strengthens lake resilience. Once established, submerged macrophyte dominance can buffer lakes against external nutrient inputs, thereby stabilizing the clear-water state. However, the persistence of this state depends on factors such as species composition, nutrient load reductions, and management interventions (Scheffer & van Nes, 2007). This section will explore the specific mechanisms through which submerged macrophytes restore eutrophic lakes, focusing on nutrient uptake, algae control, oxygenation, habitat provision, sediment stabilization, and allelopathy.

2.1 Nutrient Uptake

Submerged macrophytes function as effective nutrient sinks by assimilating both nitrogen (N) and phosphorus (P), the two key drivers of eutrophication, from multiple sources within aquatic ecosystems. These plants are capable of absorbing nutrients directly from the water column through their leaves and shoots as well as from sediments via their root systems, thereby linking benthic and pelagic nutrient cycles (Denny, 1972; Barko & Smart, 1981). This dual nutrient acquisition strategy enables submerged macrophytes to effectively reduce the concentrations of dissolved inorganic nitrogen (DIN) and soluble reactive phosphorus (SRP), limiting the resource availability that typically sustains algal blooms (Hilt et al., 2006) (Fig. 2).

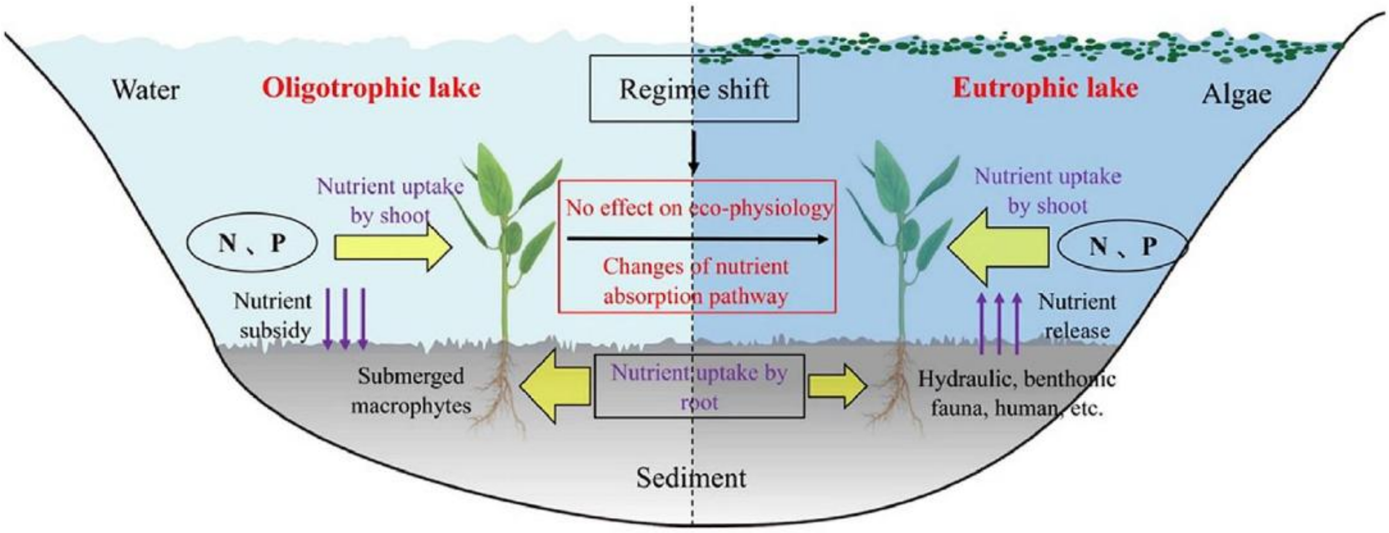

Fig. 2: Nutrient update by Submerged macrophytes (Xu et al. 2019)

The ability of submerged macrophytes to draw nutrients from sediments is particularly important in shallow eutrophic lakes, where internal loading often contributes more to eutrophication than external nutrient inputs (Søndergaard et al., 2003; Mi et al., 2008). By intercepting and immobilizing nutrients in their tissues, submerged macrophytes reduce nutrient recycling between sediments and the water column. Over time, this process contributes to sediment nutrient sequestration, especially when plant biomass is buried or decomposes in situ (Carignan & Kalff, 1980; Yang et al., 2007).

In addition to direct uptake, macrophytes enhance nutrient retention through indirect mechanisms. Their dense canopies slow down water movement, which promotes particle settling and reduces the resuspension of nutrient-rich sediments (van Donk & van de Bund, 2002). Moreover, oxygen released from plant roots into the rhizosphere enhances nitrification and the subsequent denitrification processes carried out by associated microbial communities, thereby facilitating permanent nitrogen removal from aquatic systems (Reddy et al., 1989; Li et al., 2020; He et al., 2010).

Nutrient uptake efficiency varies among species, with fast-growing plants such as Ceratophyllum demersum and Elodea canadensis showing particularly high assimilation capacities (Hussner et al., 2017). Seasonal dynamics also play a role: nutrient uptake is generally highest during the growing season when photosynthetic rates and biomass accumulation peak (Chambers et al., 2008; Yang, 2011). Restoration efforts can therefore strategically employ nutrient-efficient macrophyte species to accelerate the shift from turbid, algae-dominated states to clear-water, macrophyte-dominated regimes.

Overall, submerged macrophytes reduce nutrient availability through direct assimilation, sediment stabilization, and microbial facilitation, thereby serving as key biotic agents in reversing eutrophication processes.

2.2 Algae Control

Submerged macrophytes exert strong regulatory effects on algal growth, acting through both direct and indirect mechanisms. By competing with phytoplankton for essential nutrients such as nitrogen (N) and phosphorus (P), macrophytes reduce the resource pool available for algal proliferation, thereby limiting the intensity and duration of algal blooms (Jeppesen et al., 2007; Hilt et al., 2006). This competition is particularly effective in shallow lakes, where macrophytes can intercept nutrient fluxes from both sediments and the overlying water column.

In addition to nutrient competition, submerged plants improve light conditions that indirectly suppress algae. By stabilizing sediments and reducing turbidity, macrophytes increase water clarity and light penetration, which further promotes their own growth and reinforces conditions unfavorable for phytoplankton dominance (Scheffer, 2004). This feedback loop helps maintain a clear-water state, which is typically characterized by reduced phytoplankton biomass and higher ecological stability.

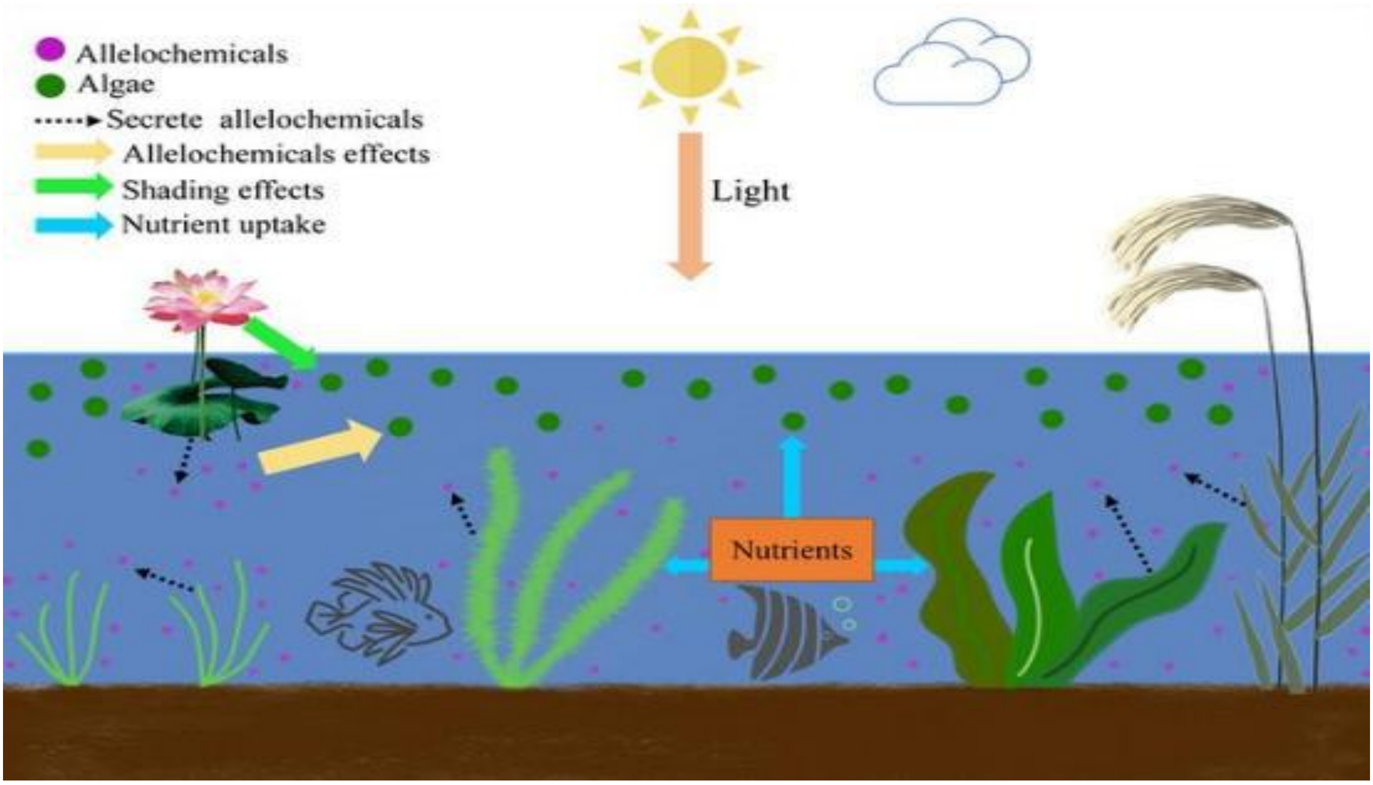

Fig. 3: Algae control by Submerged macrophytes (Wang & Liu, 2023)

Another critical pathway of algal control involves allelopathy, whereby certain macrophyte species release chemical compounds that inhibit the growth and photosynthetic activity of phytoplankton and cyanobacteria (Hilt & Gross, 2008; Gross et al., 2003). These allelochemicals include phenolic compounds and fatty acids that reduce algal cell division or disrupt metabolic processes, directly suppressing harmful algal blooms. For example, Ceratophyllum demersum has been shown to excrete allelochemicals capable of reducing cyanobacterial biomass under experimental conditions (Gross et al., 2003).

Submerged macrophytes also contribute to algal suppression through their role in structuring aquatic food webs. Dense plant stands provide refuge for zooplankton, particularly cladocerans such as Daphnia, which are efficient grazers of phytoplankton (Timms & Moss, 1984; van Donk & van de Bund, 2002). By offering protection from planktivorous fish, macrophytes indirectly enhance grazing pressure on algae, creating a trophic cascade that further limits algal biomass.

The combined effects of nutrient competition, sediment stabilization, allelopathy, and zooplankton-mediated grazing establish submerged macrophytes as key biological controls of algal populations. Their presence is therefore critical for maintaining ecological balance in eutrophic lakes and for restoring ecosystems that have shifted to turbid, algae-dominated states (Fig. 3).

2.3 Oxygen Production

Submerged macrophytes significantly influence the oxygen dynamics of eutrophic lakes. Through photosynthesis, they release oxygen directly into the surrounding water, counteracting the hypoxic or anoxic conditions that commonly develop in nutrient-enriched systems. This oxygenation effect is most pronounced during daylight hours when photosynthetic activity peaks, providing localized zones of elevated dissolved oxygen that benefit aquatic organisms (Carpenter & Lodge, 1986; Sand-Jensen et al., 1982).

The enhancement of oxygen concentrations by submerged macrophytes contributes to several important ecological processes. First, higher oxygen availability supports aerobic microbial decomposition of organic matter in the water column and sediment, reducing the accumulation of harmful metabolites such as hydrogen sulfide and methane (Barko & James, 1998). Second, oxygen penetration into surface sediments fosters nitrification and coupled denitrification processes, which play a vital role in removing bioavailable nitrogen from aquatic ecosystems (Klapper, 1991). These biogeochemical processes help regulate nutrient cycling and improve overall lake health.

In addition to biochemical benefits, oxygen production enhances the survival and growth of fish and invertebrate communities that are sensitive to oxygen depletion. In eutrophic lakes where oxygen demand is high due to algal decomposition, submerged macrophyte beds can act as refugia, offering zones of improved water quality that sustain higher trophic levels (Jeppesen et al., 2007). Furthermore, oxygen supersaturation in plant stands during daylight may suppress the release of phosphorus from sediments, thereby limiting internal nutrient loading (Körner & Nicklisch, 2002; Yang et al., 2025).

The diurnal fluctuations of oxygen caused by submerged plant activity underscore the need for careful monitoring in restoration projects. While daytime oxygen levels may be elevated, respiration at night can lead to reductions in dissolved oxygen, particularly in dense plant stands. Nevertheless, when managed appropriately, the net contribution of submerged macrophytes to oxygen enrichment is strongly positive, reinforcing their role as ecosystem engineers in restoring eutrophic lakes.

2.4 Habitat Provision

One of the most critical ecological roles of submerged macrophytes is the creation of structural habitat complexity that supports diverse aquatic communities. The three-dimensional architecture of macrophyte beds provides shelter, feeding grounds, and breeding areas for a wide array of organisms, ranging from microorganisms to higher trophic levels such as fish (Diehl & Kornijów, 1998; Thomaz & Cunha, 2010). This structural heterogeneity increases habitat availability and fosters higher biodiversity compared to unvegetated lakebeds.

For invertebrates, macrophytes serve both as physical refugia and as surfaces for periphyton colonization, which constitutes an important food resource (Cheruvelil et al., 2000). Aquatic insects, mollusks, and crustaceans utilize submerged vegetation for protection from predation and as oviposition sites. Zooplankton communities also benefit, as dense macrophyte stands reduce fish predation pressure, thereby supporting larger-bodied grazers such as Daphnia that help regulate phytoplankton biomass (Timms & Moss, 1984).

Fish communities are particularly influenced by macrophyte presence. Submerged vegetation provides spawning substrates for many species, nursery habitats for juvenile fish, and ambush sites for piscivores (Stahra et al., 2012). For example, studies have shown that lakes with extensive macrophyte coverage often sustain higher fish biomass and species diversity compared to lakes where vegetation is absent or sparse (Engel, 1990) (Fig. 4).

Beyond individual species benefits, the habitat provisioning role of submerged macrophytes enhances the stability and resilience of lake ecosystems. By supporting multiple trophic levels, they contribute to more complex and interconnected food webs that can buffer against environmental fluctuations and anthropogenic disturbances (Philippov et al., 2022). This is particularly relevant in eutrophic systems, where biodiversity tends to decline due to algal dominance and oxygen depletion. Restoring macrophyte beds thus reintroduces essential habitat complexity that promotes ecological balance.

The extent and quality of habitat provision in aquatic ecosystems depend strongly on plant species composition, density, and spatial distribution. Species with finely divided leaves, such as Myriophyllum spicatum, generally provide more surface area and refugia for invertebrates and small fish compared to broad-leaved species like Vallisneria (Kilgore et al, 1990; Gettys et al, 2023). Restoration strategies should therefore consider both functional diversity and structural complexity when selecting macrophytes for reintroduction.

Fig. 4: Native Potamogeton plants as fish habitat provision in Lake Ototoa, New Zealand

2.5 Sediment Stabilization

Submerged macrophytes play a crucial role in stabilizing sediments, which is fundamental for improving water clarity and reducing internal nutrient loading in eutrophic lakes. Their root and rhizome systems anchor sediments to the lakebed, thereby reducing resuspension caused by wind-induced turbulence, waves, or bioturbation from benthic organisms such as carp (Zhang et al., 20022; van Donk & van de Bund, 2002). This stabilization decreases turbidity and helps prevent the release of nutrients—particularly phosphorus—back into the water column.

The importance of sediment stabilization extends beyond physical processes to include significant chemical interactions. By reducing sediment disturbance, macrophytes limit the diffusion of soluble reactive phosphorus and ammonium from anoxic sediments (Horppila & Nurminen, 2003; Yang, 2011). Additionally, oxygen released from macrophyte roots can oxidize the sediment-water interface, promoting the formation of iron and manganese oxides that bind phosphorus and decrease its mobility (Barko & James, 1998; Sand-Jensen et al., 1982). These processes collectively reduce the risk of internal loading, which often sustains eutrophication even when external nutrient inputs have been reduced.

Sediment stabilization also creates positive feedback for macrophyte growth. Reduced turbidity increases light penetration, enhancing photosynthesis and allowing macrophyte populations to expand further into deeper zones (Scheffer, 2004). This expansion, in turn, leads to greater stabilization effects, reinforcing a clear-water state.

Field studies have demonstrated that lakes with healthy macrophyte stands experience markedly lower sediment resuspension rates compared to lakes dominated by phytoplankton or devoid of vegetation (Hilt et al., 2006).

For example, restoration projects in shallow European lakes have shown that reintroduction of macrophytes such as Vallisneria and Potamogeton significantly improved water clarity by reducing resuspended particulate matter and internal phosphorus cycling (Amador et al., 2024).

However, the efficiency of sediment stabilization varies depending on plant morphology, density, and distribution. Species with extensive root and rhizome systems, such as Vallisneria and Potamogeton, tend to be more effective in stabilizing sediments compared to rootless species like Ceratophyllum demersum. Therefore, species selection should carefully consider sediment stabilization as a functional trait when planning lake restoration projects.

2.6 Allelopathic Effects

Beyond nutrient uptake, oxygenation, and sediment stabilization, submerged macrophytes can influence eutrophic lake dynamics through allelopathic interactions. Allelopathy refers to the release of biochemically active compounds by plants that inhibit the growth or reproduction of other organisms, such as phytoplankton and cyanobacteria (Gross, 2003). This mechanism adds another layer of control against harmful algal blooms, making submerged macrophytes effective biotic regulators in lake ecosystems.

Research has shown that various macrophyte species, including Ceratophyllum demersum, Myriophyllum spicatum, and Elodea canadensis, release secondary metabolites such as phenolic compounds, fatty acids, and terpenoids into the water (Hilt & Gross, 2008; Gross et al., 2003; Yang et al., 2025). These substances can disrupt algal cellular processes, including photosynthesis, enzyme activity, and cell division, leading to reduced algal biomass and altered community structure. For example, Myriophyllum spicatum has been demonstrated to inhibit cyanobacteria through the release of hydrolysable tannins and polyphenolic compounds (Gross et al., 1996).

Allelopathic effects are particularly valuable in eutrophic systems where nutrient concentrations remain high, as they can directly suppress algal growth even when nutrient competition alone is insufficient. In controlled mesocosm experiments, macrophyte exudates have been observed to significantly reduce the dominance of cyanobacteria, thereby improving water clarity and enabling macrophyte reestablishment (Gross et al., 2003). This creates a positive feedback loop that favors the persistence of a clear-water state.

The strength of allelopathic effects, however, can vary depending on plant species, biomass density, environmental conditions, and the sensitivity of algal taxa present. Light, temperature, and microbial degradation of allelochemicals can also influence their efficacy (Hilt & Gross, 2008). Consequently, while allelopathy represents a promising mechanism for phytoplankton control, its practical application in restoration projects requires further investigation and adaptive management.

In summary, allelopathy adds a unique biological mechanism to the suite of ecological functions provided by submerged macrophytes. By directly suppressing algal growth, allelopathic plants strengthen the stability of restored systems and may reduce reliance on chemical or mechanical algal control methods.

III. CONCLUSION

Submerged macrophytes play indispensable roles in restoring and maintaining the ecological balance of eutrophic lakes. Through nutrient uptake, algae control, oxygen production, habitat provision, sediment stabilization, and allelopathic interactions, these plants function as ecosystem engineers that reinforce the transition from turbid, phytoplankton-dominated states to clear-water conditions. Their capacity to regulate nutrient cycling, enhance biodiversity, and promote ecosystem resilience underscores their significance as a natural solution for eutrophication management.

Although challenges remain—such as species-specific responses to environmental change, vulnerability to external nutrient loading, and ecological thresholds that limit macrophyte recovery—their ecological functions provide a strong foundation for sustainable restoration strategies. Understanding these mechanisms not only advances theoretical ecology but also informs applied management practices, bridging the gap between fundamental science and practical restoration.

Future research should continue to refine knowledge of species-specific functional traits, feedback dynamics, and climate resilience, while integrating submerged macrophytes into broader ecosystem models. In doing so, the role of these plants can be fully realized as a cornerstone in safeguarding freshwater ecosystems against the persistent threat of eutrophication.

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