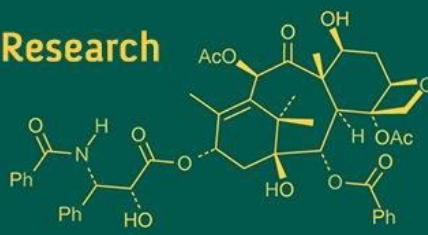


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Macrophytes as drivers of aquatic ecosystem resilience

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Abstract

Aquatic macrophytes, though comprising a small fraction of global plant diversity, play disproportionately large roles in shaping freshwater and coastal ecosystem dynamics. Their structural complexity enhances fish habitat by providing shelter, spawning grounds, and trophic support, while their biogeochemical functions regulate nutrient cycling, sediment stability, and water clarity. This review synthesizes current knowledge on the ecological functions of submerged, emergent, floating-leaved, and free-floating macrophytes, emphasizing their dual role in habitat enhancement and water quality improvement. Allelopathic interactions with cyanobacteria highlighted their potential in suppressing harmful algal blooms, offering sustainable alternatives to chemical controls. However, challenges such as invasive species proliferation, hypoxia from dense biomass, and management trade-offs underscored the need for adaptive, site-specific strategies. Restoration efforts ranging from constructed wetlands to integrated lake rehabilitation demonstrated promising outcomes when guided by appropriate species selection, hydrological alignment, and ecological monitoring. The review identified key research gaps, including climate-driven species responses, long-term restoration monitoring, and fish-macrophyte interactions in tropical systems. Strengthening the role of macrophytes in ecosystem-based management will require integrated approaches that align ecological science, policy, and stakeholder participation for resilient aquatic landscapes.

Keywords: Macrophytes; Fish habitat; Water quality

1. Introduction

Aquatic macrophytes large, photosynthetic plants inhabiting freshwater and coastal-marine ecosystems play a foundational role in shaping aquatic biodiversity and water chemistry. Though they represent less than 1% of vascular plant diversity, their ecological influence is disproportionately high, especially in shallow lakes, rivers, estuaries, and coastal lagoons where they often dominate (Cook, 1996; El-Sheekh *et al.*, 2017; Duarte, 1991) [7, 12, 11].

These macrophytes span a wide functional and taxonomic range including submerged species like Hydrilla and Elodea, emergent forms such as Typha and Phragmites, floating-leaved plants like Nymphaea, and free-floating genera such as Eichhornia and Lemna. Their morphological traits such as buoyant stems, flexible leaves, and aerenchyma tissue allow them to thrive in dynamic aquatic environments with fluctuating hydrology and nutrient levels (Brix, 1994; Cronk & Fennessy, 2001) [8].

In aquatic food webs, macrophytes serve as habitat architects. Their structural complexity creates microhabitats that offer spawning grounds, nursery shelter, and predator refuge for fish and invertebrates (Miranda & Hodges, 2000; Gasith & Gafny, 1998) [31, 16]. Periphyton and benthic fauna that colonize macrophyte surfaces become essential food resources, thereby supporting higher trophic levels and fisheries productivity (Chambers *et al.*, 2008; Santos *et al.*, 2020) [41, 5].

Beyond habitat provisioning, macrophytes are powerful agents of water purification. They absorb excess nitrogen and phosphorus, stabilize sediments, and facilitate oxygen transport to anaerobic zones all of which contribute to reducing eutrophication and improving water clarity (Vymazal, 2007; Mitsch & Gosselink, 2015) [52, 32]. These attributes have made them key components of constructed wetlands and nature-based solutions for water management (Zhang *et al.*, 2014) [54].

Yet, their ecological benefits are increasingly compromised by anthropogenic pressures. Eutrophication, invasive species, hydrological alteration, and unmanaged harvesting often

lead to degraded macrophyte communities or conversely, harmful overgrowth (Villamagna & Murphy, 2010; Srivastava *et al.*, 2020) ^[51, 47]. Such duality complicates management efforts, especially in systems where ecological goals intersect with navigation, fisheries, and livelihood needs.

Amid global calls for ecosystem-based aquatic management, macrophytes have emerged as both indicators and enablers of ecological integrity. Their multifaceted roles in habitat enhancement and water quality regulation extend across freshwater and coastal systems, making them central to integrated aquatic ecosystem planning. This review synthesized current knowledge on macrophyte ecology, focusing on their role in fish habitat improvement and water quality management, while also examining challenges, restoration strategies, and future research directions.

2. Classification and ecology of aquatic macrophytes

Aquatic macrophytes, or hydrophytes, comprise a taxonomically and functionally diverse group of plants adapted to life in aquatic settings ranging from freshwater to brackish and coastal marine environments (Cook, 1996; Cronk & Fennessy, 2001) ^[7, 8]. This group includes vascular angiosperms, bryophytes, and large macroalgae, all of which exhibit specialized adaptations that allow them to thrive under fully or partially submerged conditions (Bornette & Puijalon, 2011) ^[3]. Their ecological roles are manifold: from structuring habitat and facilitating nutrient fluxes to supporting aquatic biodiversity and stabilizing sediments (Vymazal, 2007; Chambers & Kalff, 1985) ^[52, 4].

2.1 Growth Forms of Aquatic Macrophytes

Based on their structural position in the water column, macrophytes are generally classified into four main growth forms: emergent, submerged, floating-leaved, and free-floating species (Cook, 1996) ^[7].

- **Emergent macrophytes**, such as *Typha spp.* and *Phragmites australis*, are rooted in sediments with aerial shoots that facilitate gas exchange and photosynthesis common in marshes, floodplains, and riparian zones (Cronk & Fennessy, 2001) ^[8].
- **Floating-leaved forms**: including *Nymphaea* and *Potamogeton*, are rooted but deploy leaves on the water surface to optimize light interception and flowering (Chambers & Kalff, 1985) ^[4].
- **Submerged species**: like *Elodea*, *Myriophyllum*, and *Chara*, remain entirely underwater, forming dense beds that enhance habitat heterogeneity for fish and invertebrates (Bornette & Puijalon, 2011) ^[3].
- **Free-floating macrophytes**: Such as *Eichhornia*, *Salvinia*, and *Lemna*, drift on the surface without anchoring and absorb nutrients directly from the water column playing a key role in nutrient uptake in eutrophic conditions (Villamagna & Murphy, 2010; Vymazal, 2007) ^[51, 52].

2.2 Functional Roles and Habitat Contributions

Macrophytes introduce structural complexity to aquatic environments, creating essential microhabitats for fish, amphibians, invertebrates, and birds. Submerged and emergent vegetation supports breeding and refuge zones for juveniles, while canopy and root zones offer foraging niches and physical protection from predators and currents (Cronk & Fennessy, 2001; Miranda & Hodges, 2000) ^[8, 31]. These

plants are known to enhance biodiversity by increasing habitat heterogeneity and stabilizing ecosystem processes across both still and flowing systems (Bornette & Puijalon, 2011) ^[3].

They also act as powerful modulators of nutrient dynamics. By assimilating nitrogen and phosphorus from both water and sediment, macrophytes reduce eutrophication and improve water clarity (Vymazal, 2007; Cook, 1996) ^[7, 52]. Their root systems bind substrates, limit turbidity, and, through internal air channels, transport oxygen to otherwise anoxic sediments processes especially vital in constructed wetland systems (Mitsch & Gosselink, 2015) ^[32].

In estuarine and marine fringe ecosystems, salt-tolerant macrophytes such as *Zostera*, *Halophila*, and *Thalassia* provide shoreline protection, buffer against wave erosion, and enhance fish productivity (Duarte, 1991; Hemminga & Duarte, 2000) ^[11, 19]. These seagrass beds serve as vital nurseries for juvenile fish and crustaceans, linking coastal vegetation to commercial fisheries and marine biodiversity (Hemminga & Duarte, 2000) ^[19].

2.3 Adaptations and Distribution Patterns

The success of macrophytes across diverse aquatic settings is largely due to their morphological and physiological plasticity. Traits such as internal air-filled tissues (aerenchyma), flexible stems, reduced cuticles, and variable root structures allow these plants to adapt to fluctuating water levels, turbidity, and temperature (Cook, 1996; Bornette & Puijalon, 2011) ^[7, 3]. Many propagate vegetatively through stolons, rhizomes, or fragmentation strategies that support rapid colonization and resilience in disturbed or temporary water bodies (Cronk & Fennessy, 2001) ^[8]. Meanwhile, sexual reproduction via hydrochorous seed dispersal facilitates gene flow and recolonization across fragmented habitats (Villamagna & Murphy, 2010) ^[51].

Light availability remains the primary constraint on vertical distribution, limiting most species to the photic zone (0-4 m), although taxa like *Chara* or aquatic mosses persist in deeper, clear lakes (Chambers & Kalff, 1985) ^[4]. Altitude, water temperature, and salinity also shape community composition. For instance, high-elevation systems favour bryophytes, while coastal lagoons host salt-tolerant genera such as *Ruppia* and *Halodule* (Duarte, 1991; Hemminga & Duarte, 2000) ^[19].

2.4 Environmental Drivers and Constraints

Aquatic macrophyte assemblages respond sensitively to both abiotic and biotic drivers. Key environmental factors include light penetration, water chemistry (e.g., pH, salinity, conductivity), sediment composition, temperature regimes, and flow dynamics (Vymazal, 2007; Bornette & Puijalon, 2011) ^[52, 3]. While moderate flow can facilitate oxygenation and nutrient exchange, excessive turbulence can uproot plants or damage delicate tissues (Cook, 1996) ^[7]. High turbidity and nutrient enrichment often favor surface floaters over submerged forms, thereby shifting community balance (Chambers & Kalff, 1985) ^[4].

Biotic interactions also exert strong influence. Herbivory, competition, and colonization by invasive macrophytes especially *Eichhornia crassipes* can drastically alter native community structures and ecosystem function (Villamagna & Murphy, 2010) ^[51]. These pressures underscore the importance of context-specific vegetation management

strategies that incorporate both ecological thresholds and anthropogenic stressors.

In restoration and management contexts, understanding these environmental gradients and species-specific traits is critical. Only through such integrative approaches can macrophytes be effectively used to restore degraded water bodies, improve fishery habitats, and support broader aquatic conservation goals (Cronk & Fennessy, 2001; Mitsch & Gosselink, 2015)^[8, 32].

3. Role of Aquatic Macrophytes in Fish Habitat Enhancement

Aquatic macrophytes are key architects of fish habitats, shaping ecological dynamics across freshwater and estuarine ecosystems. Their structural complexity, trophic contributions, and influence on water conditions create favourable environments for diverse fish communities and underpin many traditional and small-scale fisheries (Ferreira *et al.*, 2019; Pelicice *et al.*, 2021)^[15, 36].

3.1 Structural Complexity and Shelter

Macrophyte stands have a complex three-dimensional structure. Their canopy height, stem density, and leaf arrangement offer shelter from predators. They reduce water flow stress and help stabilize microhabitat temperatures. In India, submerged vegetation in Loktak and Vembanad Lakes supported up to 40-60% higher fish species richness compared to adjacent un-vegetated zones (Kumar *et al.*, 2020; Lalthanzara *et al.*, 2022)^[25, 27]. In the floodplains of the Yamuna, dense macrophyte zones harboured higher densities of juvenile carps and catfish, suggesting their critical role in shelter provisioning during early life stages (Sharma *et al.*, 2021)^[43].

3.2 Spawning and Nursery Functions

Vegetated habitats serve as secure spawning grounds and nurseries for numerous fish species. The foliage traps and stabilizes fish eggs, dampens velocity during floods, and buffers daily thermal variation, all of which increase egg viability and larval survival (Miranda & Hodges, 2000; Thomaz *et al.*, 2008)^[31]. Field studies in the wetlands of Assam and Bihar revealed that native species like *Channa punctata* and *Anabas testudineus* preferentially spawn within submerged macrophyte patches, with over 70% of observed egg clusters located among aquatic vegetation during the monsoon season (Singh *et al.*, 2019; Das *et al.*, 2021)^[45, 9].

3.3 Trophic Support and Prey Availability

The surfaces of aquatic plants support periphyton, filamentous algae, and a rich assemblage of invertebrates forming critical prey resources for detritivores and omnivorous fish (Santos *et al.*, 2020)^[41]. In ecosystems such as Chilika Lagoon and Kolleru Lake, vegetated zones sustain higher benthic macrofaunal biomass by up to 45% compared to bare sediment areas (Patnaik & Panigrahi, 2021; Reddy *et al.*, 2022)^[35]. This trophic enhancement not only supports fish growth and condition but also stabilizes fishery yields in seasonally fluctuating wetlands.

3.4 Water Conditions Shaping Fish Habitats

By anchoring sediments and absorbing nutrients, macrophytes contribute to clearer, oxygen-rich waters that indirectly support fish health and development (Jeppesen *et*

al., 2012)^[22]. Species such as *Vallisneria spiralis* and *Hydrilla verticillata* enhance oxygen levels in root zones through active gas exchange, which is particularly important for embryo development in hypoxic systems. However, invasive species like *Eichhornia crassipes* may form dense canopies that lower dissolved oxygen at night, leading to fish stress or mortality. Targeted removal of such mats has improved habitat quality and fish catch rates in impacted reservoirs (Chaudhary *et al.*, 2023; Bhowmick & Nath, 2020)^[6, 1].

3.5 Species-Specific and Contextual Dynamics

The ecological value of macrophytes is not uniform. Effects vary depending on species identity, growth density, and seasonal biomass turnover. Moderate vegetation often supports the highest fish diversity, whereas excessive growth may impair fish mobility, hinder oxygen exchange, and degrade foraging efficiency (Srivastava *et al.*, 2020)^[47]. In parts of the Gangetic basin, aggressive spread of *Pistia stratiotes* and *Ipomoea aquatica* has altered water chemistry and blocked access to spawning sites, leading to shifts in fish composition and reduced native species abundance by up to 30% in heavily infested wetlands.

These outcomes emphasize the need for adaptive management of macrophyte cover balancing vegetation benefits against the risks of overgrowth or invasion. Properly maintained, macrophyte-dominated habitats can enhance resilience in fisheries and support ecosystem-based management goals.

4. Role of Aquatic Macrophytes in Water Quality Management

Aquatic macrophytes play a fundamental role in regulating water quality by mediating nutrient dynamics, stabilizing sediments, modulating oxygen levels, and removing pollutants. These services are vital not only in natural water bodies but also in engineered systems such as constructed wetlands used for wastewater treatment and ecological restoration (Vymazal, 2007; Saha & Paul, 2019)^[52, 40]. Their presence often enhances the overall ecological integrity of aquatic ecosystems, particularly under eutrophic or degraded conditions.

4.1 Nutrient Uptake and Eutrophication Control

One of the most widely recognized functions of aquatic macrophytes is their capacity to absorb excess nutrients, particularly nitrogen (N) and phosphorus (P), which are the primary drivers of eutrophication. Nutrient uptake occurs through both roots (from sediments) and leaves (from the water column), with significant portions stored in aboveground biomass or directed toward rhizospheric microbial transformations (Vymazal, 2007; Saha & Paul, 2019)^[52, 40]. Indian wetlands such as the East Kolkata Wetlands and Bhitarkanika estuary have demonstrated high nutrient removal efficiency by native species like *Ipomoea aquatica* and *Phragmites karka*, making them effective biofilters in nutrient-enriched environments.

4.2 Sediment Stabilization and Turbidity Reduction

Rooted macrophytes enhance water clarity by binding sediments and reducing re-suspension caused by currents or wind-driven waves. Their mechanical resistance to flow limits turbidity and promotes light penetration, which in turn facilitates the growth of submerged vegetation and

associated primary producers (Engelhardt & Ritchie, 2001)^[13]. Case studies from Loktak Lake and Kolleru Lake indicate that dense macrophyte cover correlates with improved Secchi depth and increased benthic light availability, which support aquatic productivity and biodiversity (Kumar *et al.*, 2020; Patnaik & Panigrahi, 2021)^[25, 35].

4.3 Oxygen Regulation and pH Moderation

Through photosynthesis, macrophytes contribute to dissolve oxygen (DO) production in the water column, especially during daylight hours. Submerged and floating-leaved species also transport atmospheric oxygen to sediments via aerenchyma, enhancing aerobic microbial processes such as nitrification and reducing sediment anoxia (Zhang *et al.*, 2017). Additionally, their photosynthetic uptake of carbon dioxide (CO₂) during the day can raise local pH levels- often increasing from 6.5 to above 8.0 in productive shallow waters, thereby creating more favourable chemical conditions for aquatic life (Mandal *et al.*, 2020)^[30]. These dual fluctuations in pH and DO contribute to improved aquatic health but require careful monitoring to avoid night - time oxygen depletion in dense macrophyte zones

4.4 Pollutant Absorption and Detoxification

Aquatic macrophytes also exhibit strong phytoremediation potential by sequestering heavy metals and degrading organic pollutants. Species such as *Eichhornia crassipes*, *Hydrilla verticillata*, and *Lemna minor* have been widely studied for their capacity to accumulate lead (Pb), cadmium (Cd), chromium (Cr), and petroleum-derived compounds in polluted urban and peri-urban water bodies (Saha & Paul, 2019; Tripathi *et al.*, 2021)^[40, 50]. These bio-accumulative and detoxifying properties make them integral components of low-cost, decentralized wastewater treatment strategies, especially in rural or resource-constrained settings. Their effectiveness, however, depends on species selection, hydrological retention time, and pollutant load, necessitating system-specific design and management.

5. Allelopathic Interactions with Cyanobacteria

In aquatic ecosystems, submerged macrophytes often compete with phytoplankton not by outpacing them in nutrient uptake, but by chemically limiting their growth. This strategy known as allelopathy involves the release of bioactive compounds that disrupt key cellular processes in cyanobacteria, making it a promising biological tool for managing harmful algal blooms (Seto *et al.*, 2013; Donk & van de Bund, 2002)^[42, 10].

Unlike phytoplanktons which extract nutrients directly from the water column, most submerged macrophytes draw nutrients from sediments. This decoupling of resource competition allows them to suppress phytoplankton not through direct nutrient limitation but through the production of secondary metabolites with inhibitory effects. Species such as *Myriophyllum spicatum*, *Hydrilla verticillata*, *Ceratophyllum demersum*, and *Vallisneria spiralis* have been shown to exude polyphenols, organic acids, and sulfurous compounds that impair cyanobacterial physiology (Nakai *et al.*, 2012; Liu *et al.*, 2007)^[28].

These allelochemicals function like silent saboteurs interfering with photosynthesis by targeting photosystem II, disrupting protein synthesis, and triggering oxidative stress. In controlled studies, pyrogallol and gallic acids from *M. spicatum* notably inhibited *Microcystis aeruginosa* by

dismantling its cellular defense systems and damaging its photosynthetic machinery (Zhu *et al.*, 2010; Wu *et al.*, 2013a)^[56]. Other cyanobacteria, including *Anabaena*, showed similar vulnerability, with exposure resulting in membrane disruption and lipid peroxidation (Zhang *et al.*, 2011; Hong *et al.*, 2008)^[21].

Field-based observations from Indian freshwater systems reinforce this biochemical evidence. In reservoirs across Tamil Nadu and Odisha, native macrophytes like *H. verticillata* and *V. spiralis* have been associated with visibly reduced *Microcystis* blooms and improved water clarity, demonstrating their ecological utility beyond laboratory conditions (Bharathi *et al.*, 2018; Pradhan *et al.*, 2021)^[2, 37]. Notably, mixed-species stands appear to offer synergistic effects, with overlapping chemical profiles enhancing the inhibitory potential on cyanobacteria (Rojo *et al.*, 2013)^[39]. Allelopathy may also operate through indirect mechanisms. By limiting phosphorus availability or inhibiting enzymes such as alkaline phosphatase in cyanobacteria, macrophytes can constrain nutrient uptake under low-nutrient conditions. *V. spiralis*, for instance, has been shown to restrict phosphorus acquisition by *M. aeruginosa*, adding another layer to its suppressive capacity (Singh & Ghosh, 2020)^[46]. Despite these advantages, allelopathic outcomes are not universally predictable. Some cyanobacterial strains have evolved tolerance to macrophyte exudates or even thrive in their presence, possibly due to facilitative interactions with epiphytes or microflora that neutralize chemical stressors (Hilt, 2006; Mohamed & Al-Shehri, 2010)^[33]. Epiphytic communities can further complicate interactions by altering light availability or intensifying localized nutrient fluxes around macrophyte surfaces.

Nevertheless, with proper integration, native and mixed submerged macrophytes offer a natural and low-impact method to suppress harmful algal blooms. Their inclusion in lake restoration, aquaculture management, and water quality enhancement programs presents an ecologically sound alternative to chemical controls, with added benefits for habitat quality and fish health.

6. Challenges and Limitations in Macrophyte Management

While aquatic macrophytes offer vital ecological services, their unchecked proliferation or mismanagement can generate unintended ecological, economic, and social consequences. Balancing their ecosystem functions with human use demands site-specific management approaches that acknowledge both ecological complexity and socioeconomic constraints. According to Kawade *et al.* 2025^[24] Oil spill, climate change also leads to the damage to local macrophytes which are present along the shore line.

6.1 Invasive Species Proliferation

The spread of invasive macrophytes, most notably *Eichhornia crassipes* and *Hydrilla verticillata* has emerged as a major challenge across Indian freshwater systems. These fast-growing species displace native vegetation, reduce habitat heterogeneity, and alter trophic linkages, often leading to simplified and less resilient ecosystems (Villamagna & Murphy, 2010)^[51]. In Kerala's backwaters, seasonal infestations of *E. crassipes* have been linked to reduced fish access to spawning grounds and limited boat navigation, particularly during peak monsoon seasons (Kurup *et al.*, 2022)^[26].

6.2 Hypoxia from Dense Biomass

Excessive macrophyte growth can lead to significant oxygen fluctuations. While dense mats produce oxygen during the day via photosynthesis, night - time respiration and subsequent biomass decomposition often drive systems into hypoxia or anoxia (Strayer *et al.*, 2006) ^[48]. Such conditions are particularly detrimental to fish, benthic fauna, and aerobic microbial communities. In shallow eutrophic systems, these oxygen deficits may even trigger fish kills during warm seasons.

6.3 Nutrient Release during Senescence

Macrophytes serve as temporary nutrient sinks during active growth phases; however, their senescence releases stored nitrogen and phosphorus back into the water. This nutrient pulse, particularly during late monsoon or winter dieback, can fuel harmful algal blooms and degrade water quality (Mandal *et al.*, 2020; Sharma & Singh, 2021) ^[30, 43]. In unmanaged systems, this seasonal recycling of nutrients undermines long-term water quality improvements achieved through vegetative uptake.

6.4 Obstruction to Navigation and Livelihoods

Macrophyte overgrowth also presents practical challenges to inland navigation, fishing operations, and livelihood access. Floating mats of *E. crassipes* have been reported to entangle gillnets, hinder fish migration pathways, and significantly reduce fishing efficiency in major reservoirs such as Hirakud (Pradhan *et al.*, 2021) ^[37]. For artisanal fishers, these blockages often lead to increased labour, fuel costs, and reduced catch per unit effort.

6.5 Management Trade-offs and Ecological Impacts

Controlling macrophyte biomass involves trade-offs. Mechanical removal reduces surface cover but may disturb sediments, uproot beneficial plants, and damage fish nursery habitats. Chemical treatments risk leaving toxic residues or triggering secondary eutrophication. Biological control using species like grass carp (*Ctenopharyngodon idella*) can lead to selective grazing on native flora, altering ecosystem composition (Tripathi & Pandey, 2023; FAO, 2000; Bonar *et al.*, 2002) ^[49].

Emerging technologies such as low-impact harvesters and solar-powered shredders have shown promise for localized control in Indian wetlands and reservoirs. Pilot projects in Assam combine manual removal with biomass utilization (e.g., composting or biogas), improving ecological and economic outcomes (ICRISAT, 2023; IIT Guwahati, 2022). However, these methods require upscaling, long-term funding, and ecological safeguards to ensure sustainability. These challenges underscore the need for integrated, adaptive vegetation management guided by ecological monitoring and participatory governance to maintain the multifunctional benefits of aquatic macrophytes.

7. Restoration and Management Strategies

Aquatic macrophytes are increasingly recognized as pivotal tools in ecological restoration, particularly in degraded wetlands, lakes, and riverine ecosystems. Their ability to cycle nutrients, structure habitats, and remove pollutants has made them central to bioremediation and habitat rehabilitation initiatives. Yet, realizing their full potential requires context-specific planning, appropriate species selection, and adaptive long-term management.

7.1 Constructed Wetlands and Bioremediation

Constructed wetlands designed with macrophytes such as *Typha*, *Phragmites*, and *Eichhornia* have proven effective in removing excess nutrients, organic matter, and toxic metals from municipal and industrial effluents (Zhang *et al.*, 2014; Mitsch & Gosselink, 2015) ^[32]. Beyond improving water quality, these systems mimic natural wetland functions by enhancing biodiversity and ecological stability. While emergent plants dominate many designs, there is growing interest in incorporating floating and submerged species particularly in tropical and subtropical regions where hydrological variability demands flexible, functionally diverse vegetation (Rodrigo, 2021) ^[38].

7.2 Integrated Lake Restoration

Restoration of lakes and rivers increasingly integrates hydrological and vegetative components, combining sediment dredging, shoreline reshaping, and the reintroduction of native macrophytes aimed to restore ecological balance. Meta-analyses suggest that such interventions can significantly improve aquatic vegetation and support associated fauna, though gains often diminish without sustained maintenance (Kail *et al.*, 2015) ^[23]. The experience of Lake Manzala in Egypt illustrates these dynamics: while localized revegetation improved water quality and ecosystem services, uncontrolled growth in other areas worsened eutrophication highlighting the need for spatially targeted strategies supported by ecological modeling and monitoring (Haroon, 2022) ^[17].

7.3 Revegetation Challenges and Strategies

Revegetation efforts face both biological and environmental constraints. Herbivory, allelopathic effects from algal blooms, and unsuitable sediment or water chemistry frequently hinder success. Effective strategies must align plant traits with site-specific conditions, emphasizing native species, disturbance tolerance, and reproductive flexibility. Techniques such as direct seeding, clonal propagation, rhizome transplantation, and use of sediment seed banks are increasingly used, yet often underutilize submerged and floating species. Expanding restoration approaches beyond emergent vegetation could improve outcomes, particularly in nutrient-rich or ephemeral systems (Rodrigo, 2021) ^[38].

7.4 Governance and Policy Integration

Despite clear ecological potential, macrophyte-based restoration is rarely embedded into policy and institutional frameworks. Many programs lack provisions for post-restoration monitoring, climate adaptation, or stakeholder engagement. Adaptive management cycles featuring feedback loops, performance metrics, and cross-sectoral collaboration are essential for sustained success (Kail *et al.*, 2015) ^[23]. The variable outcomes from large-scale efforts like Lake Manzala reflected a broader challenge: ensuring institutional continuity and reconciling ecological goals with social and economic realities (Haroon, 2022) ^[17].

Growing global usage confirmed that hydrophyte integration offers an effective, scalable, and nature-based solution for aquatic ecosystem restoration when guided by robust science, governance, and community alignment.

8. Future Directions and Research Gaps

Despite growing recognition of their ecological and bioremediation value, aquatic macrophytes remain

underutilized in large-scale restoration and sustainable water management. Unlocking their full potential requires deeper understanding of species-specific traits, interactive ecosystem functions, and responses to changing environmental pressures. Future research should also leverage digital tools such as remote sensing, eDNA, and sensor-based monitoring, which offer scalable, non-invasive means to track macrophyte health and restoration outcomes over time.

8.1 Genomic Tools and Adaptive Breeding

Advances in genomics can accelerate the identification and propagation of macrophyte species with superior tolerance to eutrophication, salinity, and pollutants. Selective breeding informed by transcriptomic and gene expression analyses can enhance resilience and phytoremediation capacity in constructed wetlands and stressed aquatic systems (Chambers *et al.*, 2008; Bornette & Puijalon, 2011)^[5, 3]. Genomic profiling may also aid in discovering traits linked to phenotypic plasticity, allowing macrophytes to adapt under fluctuating abiotic conditions.

8.2 Climate Change and Ecosystem Function

Climate change poses serious but insufficiently understood risks to macrophyte-mediated ecosystem services. Rising temperatures, altered rainfall patterns, and nutrient flux disruptions may reduce their ability to sequester carbon, oxygenate sediments, and regulate nutrients (Chambers *et al.*, 2008)^[4]. There is an urgent need to integrate macrophyte functional traits into long-term climate forecasting models to develop site-specific, adaptive restoration frameworks that can withstand future climatic variability (Bornette & Puijalon, 2011)^[3]. Emerging evidence suggested species-specific responses: for instance, *Vallisneria* and *Potamogeton* exhibited declining growth under warming scenarios, while certain free-floating species may proliferate under eutrophic, high-temperature conditions (Zhou *et al.*, 2022; Mallick *et al.*, 2023)^[55, 29]. Invasive species may also gain competitive advantage under climate stress, potentially shifting ecosystem composition in unpredictable ways (Singh & Das, 2023).

8.3 Fish-Macrophyte Interactions in Altered Landscapes

The ecological interdependence between fish and macrophytes remains poorly studied in anthropogenically altered and tropical ecosystems. While it is well established that macrophytes influence fish spawning, shelter, and trophic dynamics, much of the existing evidence is derived from temperate zones. Expanding research into tropical and subtropical systems, especially in Asia and Africa, is crucial for informing locally grounded fishery and habitat management strategies (Chambers *et al.*, 2008)^[5].

8.4 Longevity and Monitoring of Restoration Projects

Many macrophyte-based interventions suffer from short monitoring horizons, making it difficult to assess long-term success or failure. Restoration trajectories can be non-linear sometimes reversing due to invasive encroachment, succession, or inadequate follow-up management. Incorporating adaptive monitoring systems and trait-based ecological models can improve predictive accuracy and help align restoration outcomes with environmental goals over time (Bornette & Puijalon, 2011)^[3].

Closing these knowledge gaps will strengthen the role of aquatic macrophytes in ecosystem-based management and help position them as climate-resilient, cost-effective solutions for degraded aquatic landscapes.

9. Conclusion

Aquatic macrophytes constitute foundational components of habitat structure and water quality regulation across freshwater and coastal ecosystems. Their contributions span multiple ecological functions - enhancing habitat complexity, providing spawning and nursery grounds, supporting food webs, and improving water quality through nutrient uptake, sediment stabilization, and pollutant removal. Their allelopathic properties further highlight their potential in mitigating harmful algal blooms and promoting ecological resilience. However, the benefits of macrophytes are context-dependent. Uncontrolled growth, invasive species expansion, or inappropriate management can degrade water quality, disrupt fishery dynamics, and compromise ecosystem services. Site-specific, adaptive strategies are therefore essential to balance ecological function with human use. Restoration efforts, particularly in wetlands, lakes, and estuarine lagoons, demonstrated promising results when guided by appropriate species selection, hydrological alignment, and long-term ecological monitoring. Yet, critical knowledge gaps persist- especially regarding species-specific dynamics under climate stress and in data-deficient tropical regions. To fully realize the ecological potential of macrophytes, future efforts must embrace a holistic, ecosystem-based framework. This requires integration of ecological science, governance mechanisms, and community engagement to ensure sustainable aquatic resource management under accelerating environmental change.

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