

MACROPHYTES AS ECOSYSTEM ENGINEERS: IMPLICATIONS FOR BIODIVERSITY, WATER QUALITY, AND AGRICULTURAL SUSTAINABILITY

Emilia RADU, Constantin-Ciprian BÎRSAN, Ioan PĂCEȘILĂ

Institute of Biology Bucharest, 296 Splaiul Independentei Street, District 6, Bucharest, Romania

Corresponding author email: emilia.radu@ibiol.ro

Abstract

Macrophytes are recognized as ecosystem engineers that strongly influence freshwater and wetland ecosystems by shaping habitat structure, regulating nutrient cycling, and supporting key ecosystem services. Through their structural and functional diversity, macrophyte communities sustain high biodiversity, stabilize sediments, and enhance the resilience of aquatic food webs. Macrophytes play a central role in water quality regulation by retaining excess nutrients, reducing turbidity, and supporting biogeochemical processes that mitigate pollution. At the interface between aquatic ecosystems and agricultural landscapes, they contribute to sustainable agriculture by buffering nutrient runoff, improving water availability, and offering potential for nature-based solutions such as phytoremediation and nutrient recovery. Despite these benefits, macrophyte communities are increasingly threatened by eutrophication, habitat alteration, invasive species, and climate change. This paper emphasizes the need to integrate macrophyte conservation and management into water and agricultural policies to enhance biodiversity, maintain water quality, and support long-term agricultural sustainability.

Key words: macrophytes, ecosystem engineering, biodiversity, water quality, agricultural sustainability.

INTRODUCTION

Freshwater ecosystems are increasingly recognized as some of the most vulnerable environments on the planet, undergoing an accelerated process of degradation largely caused by anthropogenic pressures associated with agricultural intensification (Majeed et al., 2025). The expansion of agricultural land has substantially modified riparian vegetation and channel morphology, affecting the structural integrity of aquatic habitats and thus contributing to biodiversity loss (Fares et al., 2020). A determining factor in this decline is the excessive loading of nitrogen (N) and phosphorus (P) from agricultural runoff, which accelerates the eutrophication process and triggers ecological chain effects, such as harmful algal blooms and hypoxia (Yang et al., 2025).

Within these disturbed ecosystems, aquatic macrophytes play a central ecological role that goes beyond the mere presence of vegetation. They function as true ecosystem engineers, with the ability to modify both the physical structure and the chemical conditions of aquatic

environments (Gopal, 2016; Lesiv et al., 2020; Thomaz, 2021). By influencing hydrodynamics, sedimentation processes, and nutrient cycling, macrophytes contribute significantly to the regulation and resilience of freshwater ecosystems (Swe et al., 2021; Poveda, 2022). These ecological engineering effects manifest themselves through complementary mechanisms, both physical and biogeochemical. Structurally, dense macrophyte populations attenuate wave energy and reduce water flow velocity, facilitating the settling of suspended particles and limiting sediment resuspension, an essential process for maintaining water clarity (Yang et al., 2025). At the sediment-water interface, rooted macrophytes further modify environmental conditions through radial oxygen loss (ROL), a mechanism by which oxygen is transported to the rhizosphere and released into otherwise anoxic sediments (Rejmánková, 2011). The resulting aerobic microzones stimulate microbial processes, including nitrification and degradation of organic pollutants (Majeed et al., 2025). In addition, macrophytes act as active regulators of nutrient dynamics, assimilating nitrogen and

phosphorus from both sediments and the water column, thereby reducing the availability of these elements for phytoplankton proliferation (Poveda, 2022; Yang et al., 2025).

Despite these well-documented ecological functions, a significant conceptual and practical gap remains at the intersection of aquatic ecology and agricultural management. Research on macrophytes has largely developed along separate disciplinary lines: ecological studies focus on ecosystem functioning and species interactions, while agricultural perspectives often view aquatic vegetation as a management nuisance or a biomass removal problem (Quilliam et al., 2015). As a result, current management approaches rarely integrate the phytoremediation capacity of macrophytes into nutrient management strategies in agricultural landscapes (Poveda, 2022). Furthermore, limited attention has been paid to developing frameworks that recognize nutrient-enriched macrophyte biomass as a potential resource, capable of recovering nutrients lost from agricultural systems and supporting circular bioeconomy initiatives (Quilliam et al., 2015; Majeed et al., 2025).

To fill this gap, a more integrated perspective is needed, one that connects ecosystem processes with agricultural sustainability. In this context, the present study proposes a conceptual framework that positions macrophytes as key mediators between freshwater ecosystem functioning and agricultural resource management. The central hypothesis is that integrating macrophyte-based processes into hydrological and agricultural management strategies can enhance socio-ecological resilience, simultaneously promoting ecosystem restoration and resource recovery (Quilliam et al., 2015). Accordingly, the objectives of this study are to: (1) examine the role of macrophytes in sustaining biodiversity through habitat structuring; (2) evaluate their contribution to water quality regulation and eutrophication mitigation via nutrient cycling and sediment stabilization; (3) explore their potential applications in sustainable agriculture through nutrient recovery and phytoremediation; and (4) discuss implications for integrated water resources management policies.

MATERIALS AND METHODS

This study is based on a structured literature review, conducted with the aim of synthesizing current knowledge on the ecological and agricultural functions of aquatic macrophytes. Scientific papers were identified in the main academic databases - Web of Science, Scopus and Google Scholar - thus ensuring extensive coverage of peer-reviewed sources.

The selection focused primarily on peer-reviewed journal articles, relevant book chapters, and policy documents published primarily between 2015 and 2025, but some previously relevant studies were also considered. Fundamental ecological studies were included to substantiate the theoretical basis of the concepts related to ecosystem engineering by macrophytes. The search strategy involved combining key terms such as "aquatic macrophytes", "ecosystem engineers", "phytoremediation", "nature-based solutions", and "agricultural sustainability".

The collected literature was screened and subsequently organized through thematic synthesis. Four principal analytical themes were identified: (1) physical and biogeochemical mechanisms through which macrophytes act as ecological engineers; (2) their role in supporting biodiversity and regulating water quality; (3) applications at the agriculture-freshwater interface, particularly nutrient buffering and nutrient recovery processes; and (4) the integration of these ecological functions into environmental governance and policy frameworks.

In addition, information on species-specific functional traits was extracted from the selected literature, in order to assess the practical relevance of different macrophyte taxa for sustainable agricultural systems and nutrient management strategies.

RESULTS AND DISCUSSIONS

MACROPHYTES AS ECOSYSTEM ENGINEERS

Structural Engineering

Aquatic macrophytes function as true ecosystem engineers, physically shaping aquatic habitats and increasing the structural

complexity of these environments. This complexity, often described in terms of fractal dimensions, amplifies habitat heterogeneity and is strongly correlated with higher biodiversity of epiphytic algae and macroinvertebrates (Celewicz-Goldyn & Kuczyńska-Kippen, 2017; Filho et al., 2021; Thomaz, 2021). In addition to providing substrate for numerous organisms, dense macrophyte populations also influence local hydrodynamic conditions, attenuating wave energy and reducing water flow velocity. As a result, suspended particles settle more easily, bank erosion is minimized, and overall turbidity decreases. These processes contribute, at the same time, to changes in sediment distribution and riverbed morphology (Barko & James, 1998; Madsen et al., 2001; Horppila & Nurminen, 2003; Catianis et al., 2022).

Nutrient Cycling and Biogeochemical Regulation

Macrophytes also contribute to the regulation of biogeochemical cycles through interactions between their root systems and the surrounding sediment matrix. One of the key mechanisms involved is radial oxygen loss (ROL), by which rooted species, such as *Phragmites australis*, transport atmospheric oxygen to the rhizosphere, generating localized aerobic microzones within anoxic bulk sediments (Brix, 1994). This localized oxygenation stimulates microbial activity and promotes the coupled nitrification-denitrification pathways, essential for nitrogen removal and the degradation of various pollutants (Brix, 1997; Vymazal, 2013; Kochi et al., 2020; Paul et al., 2022; Ijoma et al., 2024).

In terms of nutrient dynamics, macrophytes have the capacity to store considerable amounts of nitrogen and phosphorus during the active growing season (Preiner et al., 2020). However, this ecological function varies over time. As macrophyte populations enter the senescence phase, they can transform from nutrient reservoirs to potential nutrient sources, releasing previously stored elements into the water column. Consequently, appropriate timing vegetation management becomes an important aspect in preventing internal nutrient loading of aquatic ecosystems (Lu et al., 2017).

Regime Shifts

Submerged macrophytes are a central component in the stabilization of the clear water state of shallow lakes, acting mainly through positive ecological feedback mechanisms. By directly competing with phytoplankton for light and nutrients, and in some cases by releasing allelopathic compounds that inhibit algal growth, they limit the proliferation of phytoplankton. In addition, macrophyte populations reduce sediment resuspension, thereby enhancing water transparency (Scheffer et al., 1993; Hilt & Gross, 2008; Vanderstukken et al., 2011; Bakker et al., 2016).

When macrophyte cover decreases as a result of eutrophication, these stabilization mechanisms can collapse. This phenomenon often leads to a nonlinear transition to a phytoplankton-dominated turbidity state. Once established, this alternative ecological state can become extremely resilient and difficult to reverse without substantial restoration interventions (Jeppesen et al., 2012; Phillips et al., 2016; Zeng et al., 2017; Yang et al., 2025).

BIODIVERSITY AND WATER QUALITY REGULATION

Functional Diversity

Macrophyte assemblages show a clear functional complementarity that is correlated with their growth forms, thus generating heterogeneous “mosaic communities” that enhance ecosystem stability (Wang et al., 2009). Submerged species, such as *Potamogeton* spp. and *Hydrilla* spp., play an essential role in coupling benthic and pelagic processes and contribute to oxygenation of the water column. In contrast, species with floating leaves influence the thermal regime and regulate light penetration in aquatic systems (Rawat & Singh, 2025; Yang et al., 2025). Emergent macrophytes, located at the interface between land and water, contribute to shoreline stabilization and favor sediment oxidation through specialized tissues such as aerenchyma, which also facilitate microbial degradation of pollutants (Rejmánková, 2011).

Higher functional diversity within macrophyte communities has been consistently correlated with increased ecosystem multifunctionality. Such diverse communities support a wider range of invertebrate trophic groups and improve nutrient retention compared to monospecific populations (Thomaz, 2021; Yofukuji et al., 2021; Moi et al., 2021).

Refuge and Trophic Cascades

The structural complexity generated by macrophyte vegetation plays a central role in regulating biodiversity and water quality through trophic cascade mechanisms. Dense populations, especially those formed by macrophytes with complex leaf architectures, such as *Myriophyllum* spp., provide essential diurnal shelter for large zooplankters (e.g., *Daphnia* spp.), protecting them from fish predation (Warfe & Barmuta, 2006). This refuge function allows zooplankton populations to maintain strong grazing pressure on phytoplankton, which contributes to the suppression of algal blooms and supports the persistence of clear water conditions (Burks et al., 2006; Celewicz-Goldyn & Kuczyńska-Kippen, 2017).

Beyond their importance for invertebrate communities, the habitats created by macrophytes also play a key role in fish reproduction. Their structural complexity provides spawning substrates and rearing habitats for phytophilic fish species, such as *Cyprinus carpio* and *Micropterus salmoides*, where the juvenile fish benefit from protection both against predators and against hydrodynamic disturbances (Mandal & Bera, 2025).

Indicator Role

Because macrophytes are sessile organisms whose distribution reflects long-term environmental conditions, they are widely used as biological quality elements in ecological assessments carried out under the European Union Water Framework Directive (Stelzer et al., 2005). The composition of macrophyte communities therefore serves as an integrative indicator of ecological status. For example, the presence of sensitive charophyte species generally indicates good water quality, while the dominance of more tolerant taxa, such as

Potamogeton pectinatus or *Ceratophyllum demersum*, usually signals the onset of eutrophication and ecological degradation (Schneider, 2007; Schneider-Binder, 2018; Costică et al., 2018; Robbe et al., 2024).

To quantify these ecological changes, numerous assessment tools have been developed, including the Reference Index (RI) and the Macrophyte Biological Index for Rivers (MBRI). These metrics assess deviations from reference conditions specific to different types of water bodies (Stelzer et al., 2005; Kozak & Goldyn, 2016).

INTERFACE WITH AGRICULTURAL SUSTAINABILITY

Nutrient Buffering and Nature-Based Solutions

Macrophytes form important vegetated buffer zones, also known as ecotones, at the interface between terrestrial and aquatic ecosystems. Certain emergent species are particularly valued for their functional traits, including high nutrient retention capacity and sediment stabilization (Table 1). For example, *Phragmites australis* and species of the genus *Typha* are highly effective in intercepting agricultural runoff due to their extensive rhizome networks, which attenuate water movement and promote denitrification processes (Kurniawan et al., 2021; Poveda, 2022).

These characteristics make macrophytes essential components of nature-based solutions (NBS) designed to improve water quality in agricultural landscapes. Their application also extends to constructed wetlands (CWs), which have proven highly effective in reducing biochemical oxygen demand (BOD) and removing emerging pollutants from wastewater streams (Agaton, 2025).

Phytoremediation and Irrigation Enhancement

Beyond their passive filtering capacity, macrophytes can actively improve water quality through phytoremediation processes in agricultural reservoirs. Species such as *Lemna minor* and *Ceratophyllum demersum* are particularly effective in nutrient recovery systems due to their rapid uptake rates (Table

1). There is evidence that irrigation with water treated by these macrophytes, which effectively function as a liquid biofertilizer, can significantly increase crop productivity (Poveda, 2022; Patel & Kumar, 2025; Mignoni et al., 2025). In addition, certain macrophyte species act as hyperaccumulators (Table 1), having the ability to remove heavy metals from contaminated waters, thus increasing the safety of water used in agricultural production systems (Ansari et al., 2020; Opitz et al., 2021; Rawat & Singh, 2025).

Socio-Ecological Feedback

Ensuring long-term sustainability requires management strategies capable of generating a positive socio-ecological feedback loop, in which ecosystem functioning and economic

benefits are mutually reinforcing (Figure 1). From this perspective, management should go beyond the traditional approach of simply removing biomass and focus on valorizing aquatic vegetation, thus contributing to closing nutrient cycles. Harvesting macrophyte biomass before senescence sets in is particularly important, as it prevents the re-release of nutrients into the water column and reduces the risk of internal nutrient loading. At the same time, the collected biomass can serve as a valuable resource for the production of compost or biochar, transforming what was previously considered waste into a useful input for sustainable agricultural systems (Quilliam et al., 2015; Gusain & Suthar, 2020; Yatoo et al., 2025).

Table 1. Functional traits of representative macrophyte species relevant for biodiversity, water quality regulation, and agricultural sustainability (based on synthesis of Cook, 1996; Brix, 1997; Cronk & Fennessy, 2001; Cotton et al., 2006; Kadlec & Wallace, 2009; Vymazal, 2013; Ali et al., 2013; Rezanian et al., 2015; Kurniawan et al., 2021; Poveda, 2022)

Species	Growth form	N retention	P retention	Phytoremediation potential	Sediment stabilization	Agricultural application
<i>Phragmites australis</i>	Emergent	High	High	Heavy metals, organic pollutants	Very High	Buffer strips, CWs
<i>Typha latifolia</i>	Emergent	High	Moderate-High	Nutrients, metals	High	Nutrient interception zones
<i>Ceratophyllum demersum</i>	Submerged	Moderate	High	Nutrient pulses	Low-Moderate	Irrigation ponds
<i>Potamogeton pectinatus</i>	Submerged	Moderate	Moderate	Nutrient stabilization	Moderate	Shallow agricultural reservoirs
<i>Myriophyllum spicatum</i>	Submerged	Moderate	High	Nutrient uptake	Moderate	Water quality enhancement
<i>Lemna minor</i>	Free-floating	High	Moderate	Wastewater nutrient removal	Low	Nutrient recovery systems
<i>Elodea canadensis</i>	Submerged	Moderate	Moderate	Nutrient buffering	Moderate	Secondary irrigation canals

POLICY AND MANAGEMENT IMPLICATIONS INTEGRATION INTO WATER AND AGRICULTURAL POLICY

Integration into Water and Agricultural Policy

Contemporary governance frameworks need to evolve to more effectively integrate macrophyte management into large-scale agricultural and water policy strategies. Historically, environmental interventions in vulnerable regions such as the Lower Danube

have focused mainly on damming and drainage aimed at expanding intensive agriculture, often to the detriment of natural capital (Vădineanu et al., 2003). In contrast, recent agricultural policy directions, within the Common Agricultural Policy (CAP), increasingly promote the implementation of nature-based solutions (NBS) as a means of reconciling agricultural productivity with ecosystem conservation (David & Hulea, 2001; Vădineanu et al., 2003; Szoszkiewicz et al., 2025). In this framework, the restoration and reconstruction of wetlands

are encouraged as natural nutrient buffers, capable of reducing agricultural runoff, while contributing to the achievement of the nutrient

reduction objectives set by the European Union Water Framework Directive (WFD) (Vădineanu et al., 2003; Robbe et al., 2024).

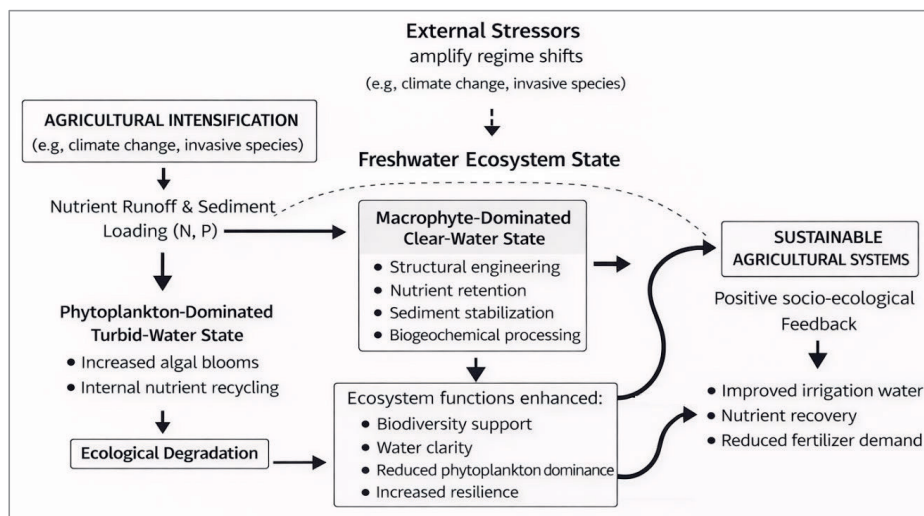


Figure 1. Macrophytes as ecosystem engineers linking agriculture and freshwater resilience (based on Jeppesen et al., 1998; Scheffer et al., 2001)

Conflict and Synergy in Monitoring

Although the WFD mandates the use of macrophytes as biological quality elements for assessing ecological status – using indicators such as the Reference Index (RI) – a gap often remains between ecological monitoring systems and practical agricultural management (Stelzer et al., 2005; Caffrey et al., 2006). Strengthening governance therefore requires identifying practical synergies through which monitoring data can directly inform agricultural decision-making. For example, changes in community composition in favour of tolerant species, such as *Potamogeton pectinatus*, can function as early warning signals for nutrient enrichment associated with agricultural runoff (Schneider-Binder, 2018). Integrating such ecological indicators into land management strategies would allow for a more proactive response to emerging environmental pressures (Schneider, 2007).

Long-term Resilience and Adaptive Management

Achieving sustainable ecosystem resilience requires adaptive management strategies that can address the hysteresis frequently observed in shallow lake systems, where simply reducing

external nutrient inputs may not be sufficient to restore submerged macrophyte communities (Hilt et al., 2018; Troia, 2023). Effective restoration therefore requires more comprehensive approaches that combine multiple interventions, including biomanipulation and water level management, with the aim of restoring structurally diverse “mosaic communities” capable of stabilizing clear water conditions (Kozak & Goldyn, 2016; Wang et al., 2009). In addition, conservation strategies should prioritize the protection of key habitats and rare aquatic plant species, such as *Trapa natans*, in both urban and rural wetlands. Protecting these ecological components is essential for maintaining biodiversity, while balancing the increasing pressures associated with human activities (Sârbu et al., 2006; Strat, 2016; Manea et al., 2016).

CONCLUSIONS

Aquatic macrophytes represent a key socio-ecological component within freshwater systems, connecting water quality regulation, biodiversity conservation, and the sustainability of agricultural landscapes. Through their capacity to engineer habitats, these plants

contribute to sediment stabilization, enhance structural complexity, and support diverse trophic interactions, functioning as one of the main biological mechanisms that maintain clear-water conditions in many freshwater ecosystems.

Despite these ecological functions, the potential of macrophytes remains insufficiently integrated into agricultural management. In many landscapes, they could simultaneously mitigate diffuse nutrient pollution and enable nutrient recovery through the harvesting of aquatic biomass. Reframing aquatic vegetation not as a nuisance but as a valuable biological resource is therefore essential for developing circular bioeconomy strategies, where harvested biomass may be converted into biofertilizers or bioenergy products.

Future management approaches should overcome traditional disciplinary boundaries by encouraging collaboration among ecologists, agronomists, and policymakers. Such interdisciplinary cooperation is necessary to implement integrated catchment-scale strategies that fully recognize and utilize the ecosystem services provided by macrophyte communities.

Ultimately, the conservation and restoration of aquatic macrophytes should be viewed not only as a biodiversity objective but also as a fundamental requirement for maintaining long-term water security and strengthening the resilience of agricultural systems under accelerating global environmental change.

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USE OF GENERATIVE ARTIFICIAL INTELLIGENCE (GenAI)

The authors declare the use of Generative Artificial Intelligence (GenAI) tools in the preparation of this manuscript. GenAI was used exclusively for drafting assistance, language editing, and text refinement. All scientific content, original data, and interpretations presented in this paper were developed and verified solely by the authors.

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