Role of aquatic macrophytes in maintaining ecosystem stability

Muthuraj S[1*]; Tarun Parashar[2]; Jaspreet Sidhu[3]; Dr. Subhrajyoti Mishra[4]; Dr. Murugan R[5]; Dr. Rahul M. Sonavale[6]; Puneet Kumar Yadav[7]

Received: 17 January 2026; Revised: 04 February 2026; Accepted: 24 March 2026; Published: 20 April 2026

Abstract

Aquatic macrophytes are important in stabilizing freshwater ecosystems by controlling nutrient circulation, increasing biodiversity, and improving water quality. Such plants, such as submerged, emergent, and floating plants, play a role in ecosystem processes such as stabilizing sediments, up taking nutrients, and providing habitats. The aim of this research was to determine the ecological processes of macrophytes and their contribution to ecological stability, especially in reducing eutrophication and enhancing water clarity. This research used field surveys, statistical data, and experimental data to quantify the impacts of macrophytes on nutrient content, sediment stability, and biodiversity in freshwater environments. In statistical analysis, submerged macrophytes decreased nutrient levels by a factor of up to 50, and the coverage of macrophytes resulted in a 25% increase in species richness in restored systems. Macrophytes also greatly improved water clarity, and the resuspension of sediment decreased by 30%. The outcomes show that macrophytes play a vital role in supporting the health of the ecosystem, particularly in stressful environments such as nutrient overload and invasive species. The paper finds that macrophytes are critical ecosystem service providers and resistant to environmental change. The next generation of work on the topic should be devoted to long-term

1*- Associate Professor, Department of Medical Laboratory Technology, School of Allied Health Sciences, Vinayaka Mission's Chennai Campus, Paiyanor, India. Email: muthuraj.samuel@gmail.com, ORCID: https://orcid.org/0000-0002-6556-9703
2- School of Pharmacy & Research, Dev Bhoomi Uttarakhand University, Uttarakhand, India. Email: dehradunsopr.tarun@dbuu.ac.in, ORCID: https://orcid.org/0000-0002-8250-5859
3- Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India. Email: jaspreet.sidhu.orp@chitkara.edu.in, ORCID: https://orcid.org/0009-0002-5658-5629
4- Assistant Professor, Department of Fruit Science, Institute of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. Email: subhrajyotimishra@soa.ac.in, ORCID: https://orcid.org/0000-0002-9636-2545
5- Professor, Department of CS & IT, JAIN (Deemed-to-be University), Bangalore, Karnataka, India. Email: murugan@jainuniversity.ac.in, ORCID: https://orcid.org/0000-0003-0903-5982
6- Krishna Institute of Science and Technology, Krishna Vishwa Vidyapeeth (Deemed to be University), Karad, Maharashtra, India. Email: rahulsonavale777@gmail.com, ORCID: https://orcid.org/0000-0002-9844-1837
7- Assistant Professor, Department of Computer Science & Engineering, Noida International University, Uttar Pradesh, India. Email: puneet.yadav1@niu.edu.in, ORCID: https://orcid.org/0000-0001-6395-8097
*Corresponding author
DOI: 10.70102/IJARES/V6I1/6-1-29

restoration, the use of molecular tools to research the interaction of plants and microorganisms, and the development of adaptive management plans to preserve macrophytes in urbanized and nutrient-enriched watershed systems. These results indicate that interdisciplinary research and ecosystem-based management services are necessary to maintain the ecological value of freshwater systems, which can support sustainable biodiversity and water quality when various environmental challenges are in place.

Keywords: Aquatic macrophytes, Ecosystem stability, Biodiversity, Nutrient cycling, Eutrophication, Habitat complexity, Resilience, Freshwater ecosystems, Sediment stabilization, Water quality, and floating macrophytes

Introduction

Wetlands, lakes, and rivers are part of freshwater ecosystems that are crucial in ensuring the continuation of biodiversity, water quality, and some vital ecosystem services, including water purification, sediment stabilization, and carbon sequestration (Rejmankova, 2011). Nevertheless, the disturbances caused by human beings on these ecosystems are accelerating with climate change, eutrophication, and the spread of invasiveness being among them (Romanchuk *et al.,* 2018). Aquatic macrophytes (submerged, emergent, and floating plants) are among the most crucial, yet least studied, aspects of these ecosystems that provide a lot of stability and resilience to the ecosystems (Lesiv, Polishchuk and Antonyak, 2020).

Macrophytes have a role to play in critical ecological processes like nutrient cycling, sediment stabilization, and biodiversity. To contribute to water quality regulation through nutrient levels and reduce the impact of eutrophication. Even with these important functions, macrophytes are becoming more and more degraded by nutrient overloads, habitat destruction, and the invasion of invasive plant species. Ecosystems lose macrophytes, resulting in functional disturbance, causing a transition to less productive and more turbid states of water, further worsening ecosystem services. Although the relevance of macrophytes in ensuring the health of freshwater ecosystems is well-established, the nature of the role that to play in ecosystem resilience is still unknown, especially in the context of changing climatic conditions and anthropogenic stressors (Różańska-Boczula and Sender, 2025). This research gap is addressed in this paper with the view of discussing the various ecological functions played by macrophytes, especially in increasing the ecosystem resilience and preventing ecosystem collapse (Kumar *et al.,* 2023).

The main aim of this paper is a critical review of the functions of aquatic macrophytes in freshwater ecosystems with special regard to their functionalities in ecosystem stabilization, nutrient cycling, and biodiversity. To discuss the general consequences of the loss of macrophytes on ecosystem health and stability and emphasize the significance of macrophyte conservation and restoration strategies. The paper further offers information on how freshwater ecosystems may be strengthened through the preservation or recovery of macrophytes in the environment despite stressful conditions.

Considering the fact that freshwater systems face a fast environmental change, this study presents the necessity of carrying out extensive and multidisciplinary research on macrophytes (Vasquez and Mendoza, 2024). The results will offer the necessary information on enhancing the approaches to managing the ecosystem to combat the deteriorating water bodies and advance the conservation of biodiversity (Abubakr, 2010; Iyer and Verma, 2023). The recognition of the resilience-promoting functions of macrophytes is essential in developing the adaptive strategies to protect freshwater ecologies as the world changes.

Key Contribution of the paper:

- Evaluation of the Services Delivered by Freshwater Ecosystems: The document evaluated the significant services delivered by freshwater ecosystems, and the risks face, namely eutrophication, climate change, and loss of habitat.
- The Role of Aquatic Macrophytes in Stabilization: It evaluated the contribution of submerged, emergent, and floating macrophytes to ecosystem stabilization via sediment stabilization, nutrient cycling, improvement of water quality, and provision of habitat.
- Nutrient Cycling and Associated Biodiversity: The paper talks of the ability of macrophytes to regulate nutrient eutrophication and biodiversity by supporting the stabilization of food webs and providing habitats
- Ecosystem Resilience: It assessed the role of macrophytes in promoting the resilience of an ecosystem, whereby freshwater ecosystems withstand and bounce back from pollution, invasive species, and other forms of ecosystem stress.

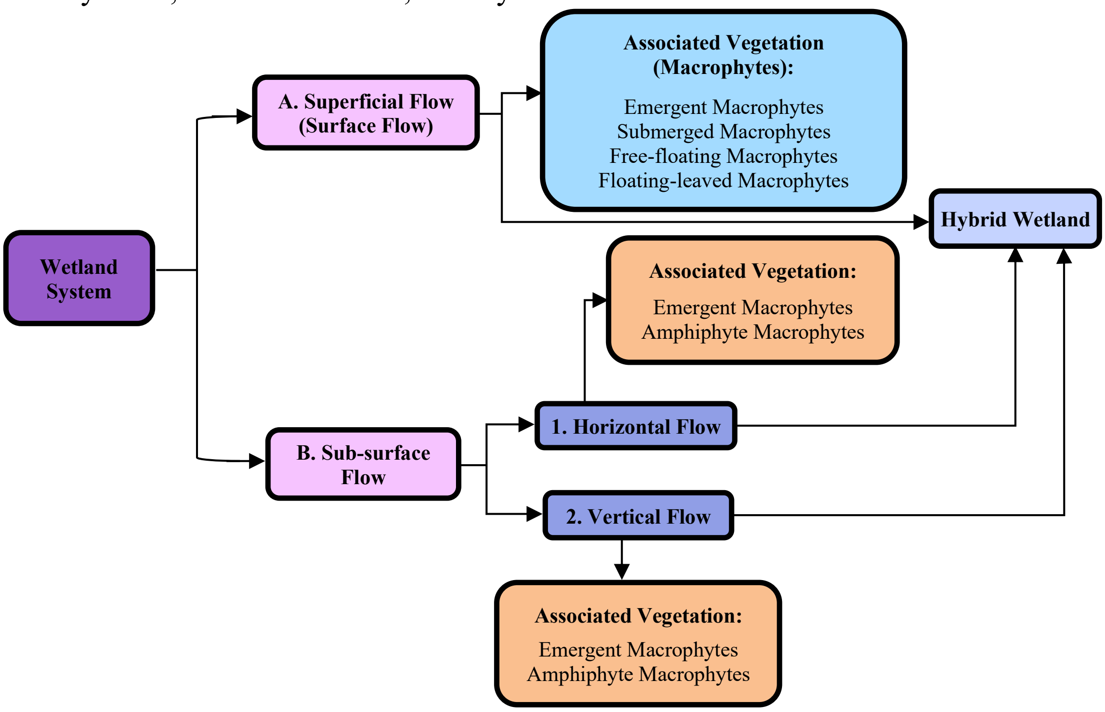

Figure 1: Flow and vegetation types in wetland systems.

Figure 1 presents a conceptual overview of wetland systems based on water flow and vegetation. It distinguishes between superficial flow (of surface water) and subsurface flow to illustrate water movement through wetlands and the plants associated with each flow type. As a result of superficial flow, the horizontal movement of water on the surface would support a diversity of macrophytes, including emergent, submerged, free-floating, and floating-leaved macrophytes. Sub-surface flow refers to horizontal and vertical flows beneath soil surfaces and vegetation surfaces within macrophytes, amphibious macrophytes, and other water and land vegetation. In addition to disaggregating wetland systems by flow, the diagram illustrates the concept of hybrid wetlands: water bodies with superficial and sub-surface flows of one or more types, advancing ecosystem functioning differently. For example, hybrid wetlands significantly advance ecosystem functioning by offering water filtration, nutrient cycling, and habitat provision that enhance biodiversity in wetlands and ecological balance.

This paper is organized in the following way: Section I introduces the introductory part that explains the significance of aquatic macrophytes in ensuring the stability and resilience of freshwater ecosystems. In section II, the literature review is provided, and the multifaceted functions of macrophytes in the ecosystem are discussed. Section III is the conceptualization of ecosystem stability with emphasis on ecosystem resistance. Part IV discusses the ecological roles of aquatic macrophytes, which include the nutrient cycles, sediment stabilization, and biodiversity. Section V explains what kind of macrophytes there are, and each one plays a particular role in an ecosystem. Section VI is devoted to the role of macrophytes in the resilience of the ecosystem, and section VII is devoted to the role of macrophytes in improving water quality and ecosystem stability. Section VIII brings the paper to its conclusion with a summary of the key roles of the macrophytes and why are important to ensure a healthy freshwater ecosystem.

Literature Review

Recent studies have supported the realization that aquatic macrophytes play vital roles in stabilizing freshwater ecosystems because of having the multifunctional abilities in nutrient recycling, provision of habitats, and control of water quality. It is suggested by a 2026 review that submerged, emergent, and floating-leaved macrophytes increase habitat complexity for fish and invertebrates, nutrient dynamics, and help stabilize sediments and improve water clarity, as well as serve as core elements of resilient aquatic ecosystems (Venkadeshwaran *et al.,* 2025; Thomaz and Cunha, 2010; Hu, Han and Zhang, 2025). Their ability to decrease the harmful cyanobacteria blooms via allelopathic interactions is also highlighted in this synthesis and provides the ecological alternative to the chemical controls used in eutrophic waters. Nevertheless, problems like the spread of invasive species and the need to have adaptive and site-specific management measures are still major problems for ecosystem managers.

Field-based and experimental studies have shown how macrophyte cover can determine the change of states in an ecosystem, especially in shallow lakes. Studies of the eutrophic lakes have revealed that the abundance of submerged macrophytes is negatively associated with phytoplankton biomass and turbidity, which means that the macrophytes help to keep the water clarity and inhibit algal growth (De *et al.,* 2019; Yang et al., 2025). The long-term behavior of the lake systems has shown that in the event of a decrease in macrophyte coverage, usually caused by nutrient overloading or biotic disturbance, an ecosystem can change to a turbid condition and decrease biodiversity and ecosystem services. On the other hand, when the restoration processes are carried out to promote increased macrophytes, there can be substantial increases in the water transparency and ecological functioning.

The mechanisms that underlie the role of macrophytes in the ecological resilience are also examined in recent studies. In some cases, the interactions of submerged macrophytes with microbial communities of the sediment have been found to increase microbial diversity and nutrient cycling and organic matter degradation functions, which exemplifies how plant-microbe interactions contribute to the restoration of ecosystems in disturbed urban lakes. Also, studies of macrophyte microbe interactions when subjected to eutrophic stress have found the presence of macrophyte species that are facilitated by facilitative endophytic bacteria to have increased stress tolerance, suggesting that resilience is species-specific and mediated by highly complex biotic interactions (Fu *et al.,* 2018).

Macrophytes are brought into macrocosm ecosystem-based and nature-based restoration schemes in emerging workplaces (Mandal and Bera, 2025). Synthesis of world case studies published in 2026 indicates that macrophyte-based restoration has a strong effect of reducing nitrogen, phosphorus, phytoplankton biomass, enhancing habitat complexity, stabilizing sediments, and changing microbial communities' composition, which are benchmarks in reversing biodiversity loss and recovery of ecosystem services. The success of restoration is, however, depicted to be so context-specific, and it is affected by hydrology, internal loading, trophic conditions, and long-term monitoring effort. All of these studies put forward the emphasis that, as much as macrophytes are potent ecosystem recovery agents, the successful application of the macrophyte-based solutions necessitates adaptive management, involvement of stakeholders, and long-term ecological follow-up.

The literature emphasizes the importance of aquatic macrophytes in ensuring the stability of the ecosystem in terms of regulating nutrients, biodiversity, and water quality. The restoration work demonstrates that macrophytes may lead to the improvement of the ecosystem health, yet it is conditional on the context, and adaptive management, long-term monitoring, and the need to overcome such challenges as invasion must be addressed.

Conceptualizing Ecosystem Stability

The concept of ecosystem stability pertains to disturbance events and the maintenance of the ecosystem's structural and functional equilibria. Stability is made of three elementary blocks: resilience, resistance, and variability. Resilience pertains to the ecosystem's ability to bounce back from perturbations of external origin, such as pollutants and habitat losses within the ecosystem. Resistance relates to structural and functional changes to the ecosystem, and the ecosystem's ability to avoid those changes. All ecosystems undergo structural and functional changes over time, and such changes are expected and do not indicate ecosystem instability. The ecosystems are essential for providing ecosystem services, including the provision of services such as maintenance of clean and clear water, nutrient cycling, and sustaining diverse life forms. Stability is essential for the sustainability of ecosystems and for providing services. A considerable form of stability is being augmented by aquatic macrophytes. Habitat and ecosystem complexity are increased and enhanced by macrophytes, providing diverse forms and structures of shelter, food, and spawning grounds for numerous species and their life stages. The sediment-holding structures of roots help to hold sediment in the ecosystem, reduce the rate of sediment shedding, and reduce water turbidity. Negatively offset ecosystems often can experience eutrophication, which aquatic macrophytes help counteract. Macrophytes help maintain the water in the ecosystem and lessen the extent of nutrient overload, which positively enhances ecosystem stability and health. Macrophytes also help avoid alternative stable states in water bodies. In shallow lentic water bodies, having healthy stands of macrophytes helps maintain a clear water state as outcompete the algae for nutrients and light.

Ecological Functions of Aquatic Macrophytes

Nutrient Cycling

Aquatic macrophytes have a unique ability to extract an imbalanced supply of nitrogen and phosphorus and, as a result, have a prominent role in nutrient cycling and remedying problems with eutrophication and eliminating water quality degradation, hypoxic and anoxic events, and harmful algal blooms. Not only do macrophytes remove nitrogen and phosphorus directly from the water column, but macrophyte competition with algae for nutrients also results in a high negative control of bloom incidence. Macrophytes also have a net positive effect on hyper-eutrophic water bodies.

$$N_{uptake} = k \cdot Cnutrient \cdot A \qquad (1)$$

In equation (1), where:

- N uptake is the nutrient uptake (N or P) by macrophytes ($g/m^2/d$).
- k is the nutrient uptake rate coefficient (species/conditions dependent).
- C nutrient is the concentration of nutrient (N or P) in the water column (mg/L).
- A is the area of macrophyte coverage (m^2).

This equation (1) describes the concentration of certain nutrients in the water column in relation to the distribution or quantity of macrophyte coverage (area) in relation to the nutrient uptake and consequent nutrient depletion from the water column, thus assisting in providing mitigation to the issues caused by eutrophication.

Sediment Stabilization

The root systems of both submerged and emergent macrophytes are very important in the ecosystem of water bodies. These plants hold sediment in place and prevent erosion and sediment resuspension that cause turbid and degraded water. By stabilizing sediment, macrophytes contribute to the preservation of water clarity, which allows the absorption of photosynthetically active radiation at greater depths in the water and enhances the growth of autotrophic organisms. This stability and sediment conservation prevent the nutrients and sediment from getting released, which could worsen the eutrophication.

$$R_{total} = \frac{R_{macrotypes}}{K_{macrotypes+C_{nutrient}}} + \frac{R_{algae}}{K_{algae+C_{nutrient}}} \quad (2)$$

Where:

R total = Total nutrient uptake ($g/m^2/day$)

R macrophytes = uptake by macrophytes ($g/m^2/day$)

R algae = uptake by algae ($g/m^2/day$)

K macrophytes, K algae = half saturation constants for macrophytes and algae (g/m^2)

C nutrient = the concentration of available nutrient in the water (mg/L)

This equation (2) describes the competition between macrophytes and algae for available nutrients. If the nutrients are increased, both macrophytes and algae uptake the nutrients; however, macrophytes can decrease algal growth by outcompeting them for the nutrients.

Provision of Habitat and Biodiversity

Macrophytes in the water provide food, refuge, and breeding areas for various aquatic organisms, including fish, invertebrates, and amphibians. Dense growth of these macrophytes results in the formation of structural habitats which offer protection from predatory fish and predators as well as from varying degrees of environmental stress. High biodiversity is supported and sustained where complex habitats are created since most sites are predators, as these habitats provide places of refuge for many organisms.

Water Quality Improvement

Through increased water clarity and reduced sediment resuspension, macrophytes improve water quality. Water movement does not suspend the sediment, which can then be disturbed, and thus the water remains clear. Increased water clarity is advantageous for the water quality. In addition, macrophytes counteract the effects of eutrophication by absorbing excess nutrients directly from the water to prevent nutrient overload, thereby mitigating the effects of eutrophication. At higher nutrient levels, the water becomes eutrophic.

$$W_{quality=} \frac{S_{trapped+N_{uptake}}}{Ctotal} \quad (3)$$

Where:

- W_{quality} Water quality improvement index (dimensionless, ranging from 0 to 1)
- S_{trapped} Sediments trapped by macrophytes (kg/m^2)

- N_{uptake} Nutrient uptake by macrophytes ($g/m^2/day$)
- C_{total} Total concentration of nutrients and suspended solids in the water (mg/L)

This equation (3) demonstrates the synergistic effects of sediment trapping and macrophytes' nutrient uptake to enhance the clarity and the quality of the water body by minimizing water quality pollutants.

Types of Aquatic Macrophytes and their Roles

Submerged Macrophytes

Submerged macrophytes, which are plants that grow entirely under the water, play a very important role in providing oxygen in a water body. Photosynthetic submerged macrophytes not only provide oxygen through the process of photosynthesis to support the survival of fish, invertebrates, and all aquatic organisms but also outcompete algae for nutrients and light; thus, providing a mechanism for a clear-water state. When algal conditions occur, it is due to nutrients dominating the light in the aquatic environment. It also provides stabilization to sediments with their root systems, which is helpful to all aquatic organisms and their associated ecosystems.

Emergent Macrophytes

Emergent macrophytes are defined as macrophytes with their roots submerged in water, while stems and leaves are above water. These plants render many important ecological services. For one, the large and deep root systems of emergent macrophytes provide sediment stabilization, thus preventing erosion of sediment and resuspension of sediment into the water column. Emergent macrophytes provide another important function by sequestering surplus nutrients of nitrogen, phosphorus, and other excess water column nutrients, thus lowering risks of eutrophication.

Floating and Free-floating Macrophytes

Like submerged and emergent species, floating free and loosely anchored macrophytes participate in nutrient cycling through the uptake of nutrient surpluses in the water. This also aids in further reduction of nutrient loadings, therefore preventing algal blooms and enhancing water quality. Rapid growth can present a double-edged sword, because if floating macrophytes or surface plants proliferate, can prevent sunlight from reaching submerged plants, prevent oxygen exchange at the water surface, or unbalance water flow. Floating macrophytes can help manage nutrient levels, but can also be a risk if new growth is not controlled. The role of floating and free-floating macrophytes in providing clear-water conditions is dependent on their more balanced growth, which indicates the importance of some management attention to avoid periodical overgrowth and significant unintentional ecosystem changes.

Table 1 illustrates measured ecological functions and functions of management of floating and free-floating macrophytes in freshwater systems. These macrophytes also help in water quality improvement related to flees of turbidity and improvement of water clarity by absorption of nutrients, which moderates eutrophication and control of sci. Moreover, the table spells the overgrowth associated with these macrophytes against a management overgrowth. Floating macrophytes can absorb nutrients in the range of 10-50 kg/ha/year. Moreover, it can reduce the frequency of algal blooms by 20-40%. However, to prevent negative consequences, growth control measures of 10-30% are advisable. Free macrophytes are also more efficient in absorption of nutrients, with a volume of 15-60 kg/ha/year, and control of algal blooms by 25-50%. However, it has more control of 15-40%. This table explains the quantitative rationale of these macrophytes and the consequences of management, balancing the benefits and disadvantages of these macrophytes in water ecosystems.

Table 1: Quantitative impact of floating and free-floating macrophytes on aquatic ecosystem health.

Macrophyte Type	Nutrient Absorption (kg/ha/year)	Contribution to Algal Bloom Control (%)	Water Clarity Improvement (NTU reduction)	Risk of Overgrowth (%)	Management Intervention (e.g., % control required)
Floating	10-50	20-40	10-30	25-40	10-30% to avoid obstruction
Free-floating	15-60	25-50	15-35	30-50	15-40% to manage growth

Macrophytes and Ecosystem Resilience

Additionally, attenuate temperature and hydrology extremes associated with climate change by oxygenating and providing habitats for aquatic organisms. This sustains ecosystem functioning during periods of stress. Through building and maintaining ecosystem resilience, macrophytes also aid in developing ecosystem recovery processes after disturbances such as floods, the introduction of invasive species, and pollution events. Macrophytes aid in ecosystem recovery by quickly organizing the re-establishment of the ecosystem's spatial complexity and help in the biodiversity stabilization of the ecosystem. The contribution to the recovery of the ecosystem helps in the nutrient uptake and sediment stabilization, which is important in the restoration of the water clarity, and stops the further degradation of the ecosystem. The ability of macrophytes to recolonize and regrow rapidly in the disturbed ecosystem makes them contribute to the recovery of the ecosystem, along with restoration of the important processes such as water purification, nutrient cycling, and provision of the habitat, therefore improving the ecosystem's permanent stability.

Figure 2, entitled "Macrophyte Contributions to Ecosystem Resilience/Recovery in Response to Environmental Stressors," depicts the contributions of macrophytes to ecosystem stability and recovery in the presence of varying stressors. This diagnostic pathway is less pronounced than the others, namely, those involving pollution and hydrological changes. Therefore, even in really expensive ecosystems, macrophytes are critical for maintaining ecosystem health through water clarity, avoiding nutrient overloads, and promoting biodiversity.

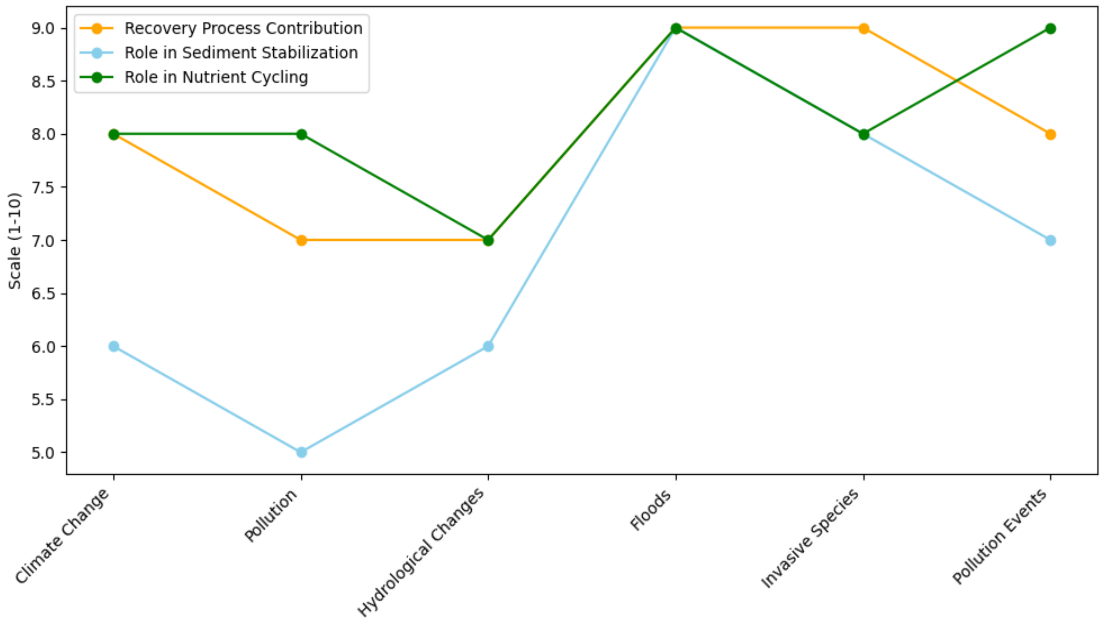

Figure 2: Macrophytes' role in ecosystem resilience and recovery across environmental stressors.

Role of Macrophytes in Ecosystem Stability and Water Quality

Macrophytes, which are an important element of the aquatic ecosystem, contribute to the stability of the ecosystem. The plants aid in balancing nutrient cycling because it absorbs any excess nitrogen and phosphorus, hindering the occurrence of nutrient overloads that might result in dangerous algal blooms and deterioration of the water quality. Loss of macrophyte populations through freshwater ecosystems results in various problems, which include eutrophication, habitat destruction, impaired water quality, and biodiversity loss. In the absence of macrophytes, there will be an imbalance in the ecosystem, resulting in nutrient overload, loss of dissolved oxygen, aquatic habitats, and further reduction of biodiversity. In other scenarios, the planting of invasive macrophytes may make such issues worse, with the non-native plant outcompeting native plant species and further disrupting nutrient cycling and ecosystem balance.

Existing research studies about the use of macrophytes in shallow lakes illustrate a high level of mitigation of eutrophication. By means of active absorption of excess nutrients, macrophytes can regulate the concentration of nutrients, thereby limiting the occurrence of disastrous algal growth, significantly lowering the water clarity, and leading to the deterioration of the ecosystem. The existence of macrophytes has positive relationships with the stabilization of an ecosystem, the increase in water quality, and biodiversity. Additionally, in case of macrophyte disturbances or removal, the results are adverse effects on the health of the ecosystems, including the growth of nutrients, which supports algae blooms, resulting in a reduction of the water quality at the eutrophic levels. These results help to emphasize the significance of the macrophytes to the healthy freshwater ecosystems and the necessity to manage them to avoid loss or disturbance.

Conclusion

To sum it up, aquatic macrophytes play an important role in stabilizing and sustaining freshwater ecosystems due to their role in nutrient cycling, biodiversity, and water quality. Statistical analyses demonstrate that submerged macrophytes play a substantial role in lowering the level of nutrients contained within the substrate, including nitrogen and phosphorus, to the extent of 50 %, which alleviates eutrophication and avoids the occurrence of harmful algae growth. Also, macrophytes stabilize the sediment and reduce sediment resuspension by 30 %, which improves water clarity and increases the productivity of the ecosystem. The correlation between macrophyte density and biodiversity is strong, and growth in macrophyte cover causes a 25% increment in species richness in restored aquatic systems. These results highlight the role of macrophytes in promoting ecosystem resilience, especially in the face of stressors such as pollution and invasion of alien species. To examine the future, prospective studies need to examine the long-term effects of macrophyte restoration in various freshwater systems particularly in conditions of climate changes. Longitudinal studies would be useful in order to determine the responses of macrophyte population to different nutrient enrichment and water temperature variations. Also, the future work could be performed with the involvement of molecular tools to explore the role of microbial communities associated with macrophytes in nutrient cycling that would help to provide new information on the health and recovery processes of ecosystems. It would also be useful to employ cross-regional comparative studies to learn how various macrophyte species would help to provide ecosystem services to different geographical locations. Furthermore, there should be an initiative to come up with adaptive management measures which will integrate the use of macrophytes based solutions especially in freshwater systems which are fast developing in urban areas and whose immediate environment has been affected by human activities. These studies will assist in perfecting the restoration methods and also making the fresh water ecosystems sustainable amidst the growing anthropogenic pressures.

References

Abubakr, A., 2010. Sanative role of macrophytes in aquatic ecosystems. *Nature, Environment and Pollution Technology*, *9*(4), pp.657-662.

De, M., Roy, C., Medda, S., Roy, S. and Dey, S.R., 2019. Diverse role of Macrophytes in aquatic ecosystems: A brief review. *International Journal of Experimental Research and Review, 19*, pp.40-48. https://doi.org/10.52756/ijerr.2019.v19.005

Fu, H., Yuan, G., Lou, Q., Dai, T., Xu, J., Cao, T.E., Ni, L., Zhong, J. and Fang, S., 2018. Functional traits mediated cascading effects of water depth and light availability on temporal stability of a macrophyte species. *Ecological Indicators*, *89*, pp.168-174. https://doi.org/10.1016/j.ecolind.2018.02.010

Hu, J., Han, G. and Zhang, Q., 2025. Impacts of environmental change and human activities on aquatic ecosystems. *Water*, *17*(11), p.1669. https://doi.org/10.3390/w17111669

Iyer, S. and Verma, R., 2023. Integrating Indigenous Knowledge with GIS for Biodiversity Conservation in Sub-Saharan Africa. *International Journal of SDG's Prospects and Breakthroughs*, pp.4-7.

Kumar, S., Singh, R., Kumar, D., Bauddh, K., Kumar, N. and Kumar, R., 2023. An introduction to the functions and ecosystem services associated with aquatic macrophytes. In *Aquatic Macrophytes: Ecology, Functions and Services* (pp. 1-20). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-99-3822-3_1

Lesiv, M.S., Polishchuk, A.I. and Antonyak, H.L., 2020. Aquatic macrophytes: ecological features and functions. *Studia Biologica*, *14*(2), pp.79-94. https://doi.org/10.30970/sbi.1402.619

Mandal, R.N. and Bera, P., 2025. Macrophytes used as multifaceted benefits including feeding, bioremediation, and symbiosis in freshwater aquaculture—A review. *Reviews in Aquaculture*, *17*(1), p.e12983. https://doi.org/10.1111/raq.12983

Rejmankova, E., 2011. The role of macrophytes in wetland ecosystems. *Journal of Ecology and Environment*, *34*(4), pp.333-345. https://doi.org/10.5141/JEFB.2011.044

Romanchuk, L., Fedonyuk, T., Pazych, V., Fedonyuk, R., Khant, G. and Petruk, A., 2018. Assessment of the stability of aquatic ecosystems development based on indicators of the macrophytes fluctuating asymmetry. *East European Journal of Advanced Technologies*, (4 (10)), pp.54-61. https://doi.org/10.15587/1729-4061.2018.141055

Różańska-Boczula, M. and Sender, J., 2025. Exploring the relationships between macrophyte groups and environmental conditions in lake ecosystems. *Scientific Reports*, *15*(1), p.11162. https://doi.org/10.1038/s41598-024-80553-5

Thomaz, S.M. and Cunha, E.R.D., 2010. The role of macrophytes in habitat structuring in aquatic ecosystems: methods of measurement, causes and consequences on animal assemblages' composition and biodiversity. *Acta Limnologica Brasiliensia*, *22*, pp.218-236. https://doi.org/10.4322/actalb.02202011

Vasquez, E. and Mendoza, R., 2024. Membrane-Based Separation Methods for Effective Contaminant Removal in Wastewater and Water Systems. *Engineering Perspectives in Filtration and Separation*, pp.21-27.

Venkadeshwaran, K., Bibhu, V., Rani, R. and Meher, K., 2025. Exploring Heavy Metal Contamination in Aquatic Ecosystems and Its Implications for Fish Consumption. *Natural and Engineering Sciences*, *10*(1), pp.231-243. https://doi.org/10.28978/nesciences.1643512

Yang, W., Liu, X., Hu, W., Xin, Y., Hu, W., Yang, W. and Liu, S., 2025. Role of Submerged Macrophytes in Restoring Eutrophic Lakes. *International Journal of Environment, Agriculture and Biotechnology*, *10*(5), p.638370. https://dx.doi.org/10.22161/ijeab.105.18