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Diversity and economic assessment of aquatic plants: A review perspective

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Abstract
Aquatic plants play a vital role in maintaining ecological balance and supporting biodiversity in freshwater ecosystems. This review provides a comprehensive assessment of the diversity, ecological importance, economic potential, and conservation status of aquatic plants, with a focus on riverine habitats. Aquatic macrophytes are broadly classified into submerged, floating, emergent, and amphibious types, each contributing uniquely to ecosystem functions such as water purification, nutrient cycling, and providing habitat for aquatic fauna. The review explores the diversity of aquatic flora in river systems, highlighting the richness of native species, the growing threat of invasive plants, and the influence of environmental variables on plant distribution. Special emphasis is given to the economic utility of these plants in traditional medicine, food systems, livestock feed, composting, and various industrial applications. Despite their value, aquatic plants face numerous threats including pollution, habitat degradation, overexploitation, and climate change. Conservation strategies such as in-situ and ex-situ efforts, community involvement, and policy frameworks are critical to sustaining aquatic plant resources. The review also identifies significant research gaps, particularly in economic valuation and sustainable utilization models, which could unlock their potential in rural development and climate resilience strategies. Ultimately, this synthesis aims to support future ecological and socioeconomic research, guide policy development, and foster balanced utilization and conservation of aquatic plant diversity.

Keywords: Aquatic plant diversity, freshwater ecosystems, economic importance, ecological services, invasive species, conservation strategies, sustainable utilization

1. Introduction
1.1 Background and Importance of Aquatic Plants
Aquatic plants, also known as macrophytes or hydrophytes, are critical components of freshwater ecosystems. They contribute significantly to the ecological functioning, productivity, and sustainability of aquatic environments. These plants play a vital role in oxygen production, nutrient cycling, sediment stabilization, and providing shelter and breeding grounds for various aquatic organisms. Their ability to support primary productivity makes them indispensable for maintaining aquatic biodiversity and food web dynamics (Li *et al.* 2011) [23].

Moreover, aquatic plants are natural biofilters, effectively removing pollutants such as heavy metals, excess nutrients (nitrogen and phosphorus), and organic matter from water bodies through a process known as phytoremediation (Barznji, 2014) [5]. This makes them useful for the restoration and management of polluted wetlands and rivers, especially in developing regions where cost-effective water treatment strategies are needed (Nagajyothi *et al.* 2025) [27].

In addition to ecological services, many aquatic plants have substantial economic value. They are used for medicinal purposes, animal fodder, composting, biofuel production, and even as human food in various traditional and modern systems. Their multifaceted utility underlines the need to conserve and sustainably manage these biological resources (Racine, 2022) [31].

1.2 Scope of the Review
This review encompasses a multidisciplinary examination of aquatic plants, focusing on their taxonomic diversity, ecological significance, and economic potential, particularly in the context of riverine ecosystems such as the River Arpa. The scope extends beyond simple

species documentation to incorporate functional roles, utilization patterns, and conservation challenges associated with aquatic macrophytes.

The specific scope includes

- **Geographical Scope:** While the primary focus is on aquatic plant species found in the River Arpa, the review also includes references to comparable riverine ecosystems in India and other tropical/subtropical regions to provide broader ecological and socio-economic context.
- **Ecological Scope:** The review discusses different categories of aquatic plants—emergent, submerged, free-floating, and rooted floating species—and evaluates their roles in ecosystem functioning, such as water purification, oxygenation, erosion control, and habitat support for aquatic organisms.
- **Economic Scope:** Special attention is given to species with economic relevance, including their use in traditional medicine, agriculture (as fodder and green manure), local cuisine, handicrafts, and phytoremediation. The review also considers market potential and livelihood generation, especially for rural and indigenous communities.
- **Temporal Scope:** The study draws upon past and recent literature from peer-reviewed journals, theses, government reports, and field studies conducted over the last two decades to ensure a comprehensive understanding of historical trends and present challenges.
- **Policy and Conservation Scope:** The review highlights major threats to aquatic plant biodiversity—such as pollution, invasive species, and habitat destruction—and evaluates existing conservation efforts and policy frameworks, suggesting improvements for sustainable management.

2. Methodology

This review paper is based on a comprehensive analysis of secondary data obtained from peer-reviewed journals, research articles, books, and official reports focusing on the classification, ecological roles, economic uses, and conservation of aquatic plants in freshwater ecosystems. A systematic literature review approach was adopted to ensure the credibility and relevance of the information.

2.1 Data Collection

Relevant literature was sourced from reputable academic databases such as Google Scholar, ScienceDirect, PubMed, Scopus, and the Directory of Open Access Journals (DOAJ). Search keywords included "aquatic plant diversity," "economic uses of aquatic macrophytes," "riverine aquatic flora," "invasive aquatic plants," "wetland conservation," and "ecological services of aquatic vegetation."

2.2 Inclusion and Exclusion Criteria

Only articles published between 1995 and 2024 in English were considered. Priority was given to peer-reviewed articles, systematic reviews, and case studies relevant to tropical and subtropical freshwater environments. Grey literature, unpublished theses, and anecdotal reports were excluded to maintain scientific integrity.

Quantitative data (e.g., economic value, species richness) were tabulated where applicable, and qualitative findings were described thematically. Case studies from different regions were also compared to highlight common patterns and regional variations.

3. Classification and Diversity of Aquatic Plants

Aquatic plants, also known as macrophytes or hydrophytes, are essential components of freshwater ecosystems. These plants are generally classified based on their growth forms and habitat preferences into four major categories: submerged, emergent, floating-leaved (rooted floating), and free-floating plants. This classification provides a basis for understanding the ecological roles and biodiversity contributions of each type within aquatic environments.

Aquatic plants, or hydrophytes, are classified based on their growth forms and adaptations to aquatic environments. Submerged plants (e.g., *Hydrilla verticillata*) grow entirely underwater, with roots in the sediment and leaves adapted for nutrient uptake and photosynthesis in low-light conditions. Floating plants, such as *Eichhornia crassipes* (water hyacinth), have leaves that float on the water surface, with roots dangling below. Emergent plants, like *Typha latifolia* (cattail), have roots in the sediment but stems and leaves extending above the water. Free-floating plants (e.g., *Lemna minor*, duckweed) drift on the surface without anchoring roots. These classifications reflect adaptations to varying water depths, light availability, and nutrient conditions (Lacoul & Freedman, 2006) [21].

3.1 Submerged Plants

Submerged plants are completely underwater for most of their life cycle. Common examples include *Hydrilla verticillata*, *Ceratophyllum demersum*, and *Egeria densa*. These species play a crucial role in oxygen production, habitat provisioning for aquatic fauna, and nutrient cycling. According to Abu Bakar *et al*. (2013) [1], submerged macrophytes are efficient at absorbing heavy metals and improving water quality. Nafea and Zyada (2015) [26] emphasized their potential in mitigating water pollution through phytoremediation.

3.2 Emergent Plants

Emergent macrophytes are rooted in the substrate but extend above the water surface. Typical species include *Typha* spp. and *Phragmites australis*. These plants stabilize sediments, prevent erosion, and serve as breeding and nesting grounds for many aquatic and semi-aquatic species (Vymazal, 2013; Zhang *et al.* 2015) [39, 42]. Their robust root systems enhance water filtration by trapping particles and excess nutrients.

3.3 Floating-Leaved Plants

Floating-leaved plants are rooted in the substrate, but their leaves float on the water surface. Examples include *Nymphaea* spp. and *Potamogeton* spp. These plants regulate light penetration, reduce algal growth, and provide shade and shelter for aquatic organisms (Bornette *et al.* 1998; Stevens *et al.* 2001) [7, 36].

3.4 Free-Floating Plants

Free-floating macrophytes, such as *Lemna minor*, *Spirodela polyrhiza*, *Azolla pinnata*, and *Pistia stratiotes*, are not attached to the substrate. They can rapidly colonize water surfaces and are widely used in phytoremediation due to their high nutrient uptake capacity (Ali *et al.* 2020) [2]. These species are vital for nutrient cycling and habitat formation.

3.5 Taxonomic Overview

Aquatic macrophytes span multiple taxonomic groups, including orders like Alismatales, Ceratophyllales, and Nymphaeales. Sculthorpe (1967) [35] and Barrett and Graham (1997) [4] noted that aquatic life forms have evolved independently in several lineages, reflecting diverse morphological and physiological adaptations.

Aquatic plants span multiple taxonomic groups, primarily within the angiosperms (flowering plants), but also include non-vascular plants like algae and bryophytes. Common families include Poaceae, Cyperaceae, Nymphaeaceae, and Hydrocharitaceae, with Poaceae being notably diverse in wetlands (Hossain *et al.* 2017) [19]. Taxonomic diversity is lower in aquatic compared to terrestrial ecosystems due to environmental constraints like anoxia and limited light. Molecular phylogenetics reveal low genetic differentiation within species, attributed to clonal reproduction and broad ecological tolerances (Chambers *et al.* 2008) [10].

3.6 Biodiversity in Freshwater Ecosystems

Freshwater ecosystems host a rich diversity of macrophytes due to varying hydrological and environmental conditions. According to Bornette *et al*. (1998) [7], species diversity is influenced by factors like connectivity, nutrient availability, and disturbance regimes. These plants form complex communities that support a wide range of aquatic organisms and ecosystem processes.

Freshwater ecosystems, occupying less than 1% of Earth's surface, host disproportionate biodiversity, with aquatic plants playing critical roles in ecosystem stability (Collen *et al.* 2012) [11]. Species richness varies by region, with higher diversity in warm temperate latitudes and lower in tropical systems due to environmental stressors (Crow, 1993) [12]. Environmental heterogeneity, such as varying water chemistry and habitat availability, drives diversity patterns, particularly for submerged and emergent species (Zelnik *et al.* 2025) [41].

4. Overview of Riverine Aquatic Flora

Aquatic flora in riverine ecosystems varies considerably based on hydrology, substrate type, light availability, and disturbance frequency. These ecosystems often support a mosaic of submerged, emergent, and floating species that contribute significantly to habitat complexity and biodiversity.

Emergent macrophytes, such as *Phragmites australis* and *Schoenoplectus* spp., are commonly found along riverbanks and floodplains. They reduce water flow velocity, trap sediments, and enhance fish feeding efficiency. Floating and free-floating species provide shade, reduce water temperature, and create habitats for invertebrates and juvenile fishes (Taihu Lake Basin Study).

Freshwater ecosystems, although covering only a small portion of the Earth's surface, support a disproportionately high level of biodiversity. Approximately 10% of known species inhabit freshwater systems, and nearly 24% are at risk of extinction due to pollution, habitat alteration, and invasive species.

Tropical and subtropical river systems exhibit unique patterns of aquatic plant distribution influenced by monsoonal flow regimes and human interventions. These factors create dynamic habitats that promote high species turnover and niche differentiation.

4.1 General Features of Aquatic Flora in River Ecosystems

Riverine aquatic flora includes submerged, floating, and emergent plants adapted to dynamic flow regimes. These plants often have flexible stems, aerenchyma for oxygen transport, and extensive root systems to anchor against currents (Bornette & Puijalon, 2011) [6]. Species like *Potamogeton pectinatus* thrive in fast-flowing waters, while *Nuphar lutea* prefers slower pools. Their morphology supports resilience to mechanical stress and fluctuating water levels (Amoros *et al.* 2000) [3].

4.3 Environmental Conditions Influencing Plant Diversity

Environmental factors such as water flow, nutrient availability, and light penetration significantly influence riverine plant diversity. High flow velocities increase erosion, promoting species richness by creating heterogeneous microhabitats (Bornette *et al.* 2000) [8]. Nutrient-rich waters favor fast-growing species, but excessive nutrients can reduce diversity by favoring dominants like *Phragmites australis* (Phillips *et al.* 1978) [30]. Water chemistry, particularly pH and phosphate levels, shapes community composition, with submerged plants sensitive to habitat availability (Liu *et al.* 2023) [25].

5. Aquatic Plant Diversity in Central Indian Riverine Systems (Case Review)

While specific studies on certain rivers in Central India are limited, regional assessments provide insight into the general composition and ecological roles of aquatic macrophytes. Emergent species such as *Typha* spp. and *Phragmites australis* are dominant in many slow-flowing and stagnant stretches. Free-floating genera like *Azolla pinnata* and *Lemna minor* are also prevalent.

5.1 Reported Species

Studies in similar ecological zones have documented:

- **Emergent:** *Typha angustifolia*, *Phragmites australis*
- **Free-floating:** *Azolla pinnata*, *Lemna minor*, *Spirodela polyrhiza*
- **Submerged:** *Hydrilla verticillata*, *Ceratophyllum demersum*

5.2 Ecological Roles and Habitat Preferences

- *Typha* and *Phragmites* form dense stands that trap sediments and provide cover for birds and amphibians.
- *Azolla* contributes to nitrogen fixation and improves water fertility.
- Submerged species enhance oxygenation and serve as refuges for small fishes and invertebrates (Abu Bakar *et al.* 2013) [1].

5.3 Invasive vs. Native Species

Invasive macrophytes, such as *Pistia stratiotes* and *Eichhornia crassipes*, often outcompete native species, leading to reduced biodiversity and altered ecosystem functioning. Their proliferation is frequently linked to nutrient enrichment and hydrological modifications.

5.4 Reported Species in a River Ecosystem

This river ecosystem supports a diverse aquatic flora, including *Potamogeton natans* (floating pondweed), *Myriophyllum spicatum* (spiked watermilfoil), and

Phragmites australis (common reed), identified in regional surveys of freshwater ecosystems (Fayvush *et al.* 2010) [14]. Emergent species like *Typha angustifolia* and submerged plants such as *Ceratophyllum demersum* are also present, reflecting the river's varied microhabitats.

5.5 Ecological Roles and Habitat Preferences
Aquatic plants in this river stabilize sediments, reduce erosion, and provide habitat for fish and invertebrates. Submerged species like *Myriophyllum spicatum* prefer deeper, slower-moving waters with high light availability, while emergent *Phragmites australis* thrives in shallow, nutrient-rich zones (Bornette & Puijalon, 2011) [6]. These plants contribute to nutrient cycling by absorbing nitrogen and phosphorus, enhancing water quality (Caffrey *et al.* 2006) [9].

5.6 Invasive vs. Native Species
Invasive species, such as *Elodea canadensis*, pose threats to the river's native flora by outcompeting for light and nutrients. Native species like *Potamogeton natans* are adapted to local conditions but face displacement risks. Invasive plants often dominate due to rapid growth and lack of natural predators, reducing biodiversity (Fayvush *et al.* 2010; Wu & Ding, 2019) [14, 40].

6. Economic Importance of Aquatic Plants
Aquatic plants offer substantial economic value across various sectors, including medicine, agriculture, industry, and traditional livelihoods. Their applications highlight the need for sustainable utilization and conservation.

6.1 Medicinal Uses
Several aquatic plants have documented medicinal properties. *Ipomoea aquatica* is traditionally used to treat liver disorders and is a source of antioxidants (Li *et al.* 2007) [24]. *Azolla* has anti-inflammatory properties and is used in traditional remedies in parts of Asia. Aquatic plants like *Centella asiatica* and *Nelumbo nucifera* are valued for their medicinal properties, with extracts showing anticancer and antioxidative effects (Bornette & Puijalon, 2011) [6]. *Ludwigia adscendens* roots and stems exhibit lipoxygenase inhibitory activity, used in traditional medicine for inflammation (Chambers *et al.* 2008) [10].

6.2 Edible Aquatic Plants
Ipomoea aquatica, known as water spinach, is widely consumed in Southeast Asia and parts of India. It is rich in vitamins and minerals and has culinary significance. Duckweeds and *Azolla* are also used as supplementary vegetables in rural diets (Pandey, 2011) [29]. Species such as *Ipomoea aquatica* (water spinach) and *Nasturtium officinale* (watercress) are consumed globally, providing nutritional benefits like vitamins and minerals. These plants are harvested from freshwater systems for local diets and commercial markets (Hossain *et al.* 2017) [19].

6.3 Livestock Feed and Compost
Aquatic plants like *Azolla* are excellent sources of protein and are used as livestock feed, particularly in integrated rice-fish farming systems. *Ipomoea aquatica* is fed to cattle, pigs, and poultry, enhancing nutritional intake and reducing feed costs (Bangladesh aquaculture studies). Aquatic plants like *Lemna minor* are used as livestock feed due to their high protein content. They are also composted to enrich soil, particularly in regions with nutrient-poor substrates, supporting sustainable agriculture (Caffrey *et al.* 2006) [9].

6.4 Industrial and Commercial Applications
Floating macrophytes such as *Pistia stratiotes* and *Salvinia* are employed in constructed wetlands for wastewater treatment and heavy metal removal. Submerged species like *Hydrilla* and *Ceratophyllum* are used in aquaria and ecological restoration projects (Ali *et al.* 2020) [2]. Aquatic plants are used in phytoremediation to treat wastewater, with species like *Phragmites australis* removing nitrogen and phosphorus in constructed wetlands (Roongtanakiat *et al.* 2007) [34]. Water hyacinth is processed into biofuels and crafts, contributing to local economies.

6.5 Traditional Practices and Rural Livelihoods
In many rural communities, aquatic plants support livelihoods through fishing, composting, and the production of handicrafts. They also play roles in cultural and religious practices, reflecting their socio-economic importance (East Kolkata Wetlands case). In many cultures, aquatic plants are integral to traditional practices, such as weaving mats from *Typha* species or using *Nymphaea* in rituals. They support rural livelihoods through harvesting for food, medicine, and crafts (Hossain *et al.* 2017) [19].

Table 1: Economic Uses of Aquatic Plants and Their Applications

Use Category	Aquatic Plant Species	Application	Source
Medicinal	*Eichhornia crassipes, Azolla pinnata*	Used in traditional medicine for inflammation, skin disease, and wound healing	Ghosh *et al.* (2004) [17]; Vymazal (2013) [39]
Edible	*Ipomoea aquatica, Nelumbo nucifera*	Consumed as vegetables or snacks; seeds and roots eaten	Pandey (2011) [29]; Hasan & Chakrabarti (2009) [18]
Livestock Feed	*Lemna minor, Azolla filiculoides*	High protein content; used as poultry and cattle feed	Hasan & Chakrabarti (2009) [18]
Compost and Green Manure	*Salvinia natans, Hydrilla verticillata*	Used for composting, increasing organic matter in soils	Ghosh *et al.* (2004) [17]; Nafea & Zyada (2015) [26]
Industrial/Commercial	*Typha angustifolia, Eichhornia crassipes*	Used in handicrafts, paper pulp, fiberboard, biogas production	Vymazal (2013) [39]; Ali *et al.* (2020) [2]
Traditional Use	*Nelumbo nucifera, Ipomoea aquatica*	Used in religious ceremonies, cultural practices	Pandey (2011) [29]; Dudgeon *et al.* (2006) [13]

Table 2: Economic Values of Aquatic Plant–Dominated Wetlands in India

Location / Ecosystem	Approx. Value (₹ per ha / yr)	Key Services (Including Aquatic Plant Benefits)	Source & Authors (Year)
Karnataka freshwater wetlands	~1,005,600 ₹/ha/yr (1.005 million ₹)	Provisioning, regulating, cultural services involving macrophytes, water purification	Ramachandra *et al.* (2024) [33] (ResearchGate)
Karnataka state wetlands (total)	~285 billion ₹/yr statewide (~41,286 ₹/ha)	Fish & plant harvesting, flood control, groundwater recharge, recreation	Ramachandra *et al.* (2024) [33] (SpringerLink, ResearchGate)
Tumakuru district, Karnataka	~47.1 billion ₹/yr total	Wetland services including provisioning and regulating mediated by aquatic plants	IISc study met SEEA methods (2021) [20] (WGBIS)
Kole Wetlands, Kerala	~₹390 crore (~3.9 billion ₹) total	Paddy cultivation, fishing, lotus farming, duck-rearing, carbon sequestration	Neha & Tamhankar (2021) [28] (Krishikosh)
Ashtamudi Estuary, Kerala	₹66.8 million per yr (~₹668 /ha for small area)	Navigation, coconut retting, recreation, fisheries	Market valuation (2007)
Sundarbans estuarine ecosystem	₹69,527 lakh (~6.95 billion ₹ total)	Fisheries, tourism, agriculture, carbon storage, flood protection	Ekka, Pandit, Katiha & Biswas (2021) [15] (eBook Icar)

7. Environmental and Ecological Services

Aquatic plants contribute to numerous ecosystem services that support environmental sustainability and biodiversity.

7.1 Water Purification and Nutrient Cycling

Macrophytes absorb excess nutrients, filter pollutants, and stabilize water quality. Emergent species like *Typha* and *Phragmites* are effective in removing nitrogen and phosphorus, while submerged plants trap suspended solids and enhance oxygenation (Vymazal, 2013) [39]. Aquatic plants absorb excess nutrients like nitrogen and phosphorus, reducing eutrophication. *Phragmites australis* and *Typha latifolia* are used in constructed wetlands for wastewater treatment, promoting denitrification through root-associated microbes (Roongtanakiat *et al.* 2007) [34]. They enhance nutrient cycling by transferring nutrients from sediments to the water column (Caffrey *et al.* 2006) [9].

7.2 Soil Stabilization and Erosion Control

Emergent plants stabilize riverbanks and reduce soil erosion through extensive root systems. Their presence helps maintain sediment balance and prevent land degradation (Taihu Lake Study). Emergent plants like *Juncus acutus* stabilize riverbanks with extensive root systems, reducing erosion caused by currents and waves. Submerged plants slow water flow, promoting sediment deposition and preventing shoreline degradation (Bornette *et al.* 2000) [8].

7.3 Habitat for Aquatic Fauna

Macrophyte beds provide critical habitat for fish, amphibians, and macroinvertebrates. They offer spawning grounds, refuge from predators, and feeding areas, thereby supporting aquatic biodiversity and fisheries productivity (Bornette *et al.* 1998) [7].

Aquatic plants create microhabitats for fish like Gambusia affinis, amphibians, and invertebrates. Submerged species provide breeding grounds, while floating plants offer shade and shelter. This habitat complexity increases faunal diversity and density (Law *et al.* 2024) [22].

In conclusion, aquatic plants play indispensable roles in ecological functioning, economic development, and environmental management. Their conservation and sustainable utilization are vital for maintaining the health of freshwater ecosystems and supporting human livelihoods.

8. Threats to Aquatic Plant Diversity

Aquatic plant diversity is increasingly threatened by a combination of anthropogenic and natural factors that degrade habitat quality and disrupt ecological balance.

8.1 Pollution and Habitat Degradation

Pollution, particularly from agricultural runoff, industrial effluents, and domestic sewage, introduces excessive nutrients and toxic substances into aquatic ecosystems. This leads to eutrophication, algal blooms, and hypoxia, which suppress the growth of native aquatic macrophytes and alter community composition (Nafea & Zyada, 2015; Vymazal, 2013) [26, 39]. Heavy metals and persistent organic pollutants also accumulate in sediments and plant tissues, impairing physiological functions and reproduction. Simultaneously, habitat degradation through dredging, damming, and land reclamation alters hydrology and destroys critical zones for plant growth such as wetlands and floodplains (Dudgeon *et al.* 2006) [13].

8.2 Overexploitation and Invasive Species

Overharvesting of aquatic plants for food, fodder, and commercial use can lead to localized extinction of sensitive species. Traditional practices, when unsustainable, may further exacerbate this decline (Ghosh, Sen, & Mondal, 2004) [17]. The introduction and rapid proliferation of invasive species such as *Eichhornia crassipes*, *Pistia stratiotes*, and *Salvinia molesta* displace native flora by monopolizing light, nutrients, and space (Barrett & Graham, 1997) [4]. These invasives often form dense mats that hinder photosynthesis and reduce oxygen levels, leading to altered food web dynamics and decreased biodiversity (Ali *et al.* 2020) [2].

8.3 Climate Change Impact

Global climate change poses long-term threats to aquatic plant diversity. Changes in temperature, rainfall patterns, and frequency of extreme weather events can shift hydrological regimes, affecting germination, growth, and reproductive cycles of aquatic macrophytes (Bornette, Amoros, & Lamouroux, 1998) [7]. Species with narrow ecological tolerance are particularly vulnerable, potentially resulting in shifts in species distributions and local extinctions. Climate-induced sea-level rise also leads to salinization of freshwater habitats, further stressing native aquatic vegetation (Dudgeon *et al.* 2006) [13].

Table 3: Major Threats to Aquatic Plant Diversity and Their Impacts

Threat	Source	Impacts on Aquatic Plants	Example Species Affected
Nutrient Pollution	Agricultural runoff, sewage	Eutrophication, algal blooms, suppressed growth	*Vallisneria spiralis*, *Nymphaea spp.*
Heavy Metal Contamination	Industrial effluents	Toxicity, reduced photosynthesis, inhibited reproduction	*Hydrilla verticillata*
Habitat Alteration	Dams, land reclamation, urban encroachment	Loss of wetlands, change in flow regimes, disrupted life cycles	*Typha angustifolia*
Invasive Species	Introduction by humans or animals	Competition for light/nutrients, monoculture formation	*Eichhornia crassipes*
Climate Change	Global warming, erratic rainfall	Range shifts, phenological changes, stress on sensitive species	*Limnophila indica*

Source: Compiled from Bornette *et al*. (1998) [7]; Dudgeon *et al*. (2006) [13]; Ali *et al.* (2020) [2]

9. Conservation and Sustainable Utilization Strategies

To mitigate the loss of aquatic plant biodiversity and ensure sustainable use, a multifaceted approach combining scientific, traditional, and policy-based strategies is essential.

9.1 In-situ and Ex-situ Conservation

In-situ conservation focuses on preserving aquatic plant species within their natural habitats. Protected wetlands, biosphere reserves, and Ramsar sites offer vital refuges for aquatic macrophytes and associated fauna (Vymazal, 2013) [39]. Ex-situ methods, such as botanical gardens, seed banks, and controlled aquaculture systems, help safeguard germplasm and support reintroduction programs (Li, Kong, & Tang, 2007) [24]. Advances in tissue culture and cryopreservation further facilitate conservation of rare and endemic species.

9.2 Community Involvement and Traditional Knowledge

Integrating local communities in conservation initiatives promotes sustainable resource use and fosters environmental stewardship. Indigenous knowledge systems often include sustainable harvesting practices, seasonal use patterns, and ethno-botanical understanding that can enhance conservation outcomes (Ghosh *et al.* 2004) [17]. Participatory management models, such as community-based wetland management, empower local stakeholders and improve compliance with conservation guidelines.

9.3 Policy and Regulatory Framework

Legislation and policy support are critical for regulating exploitation and ensuring conservation of aquatic flora. National Biodiversity Acts, wetland protection policies, and sustainable development goals provide the legal basis for conservation interventions. Effective implementation, however, requires coordination between government agencies, research institutions, and community organizations (Dudgeon *et al.* 2006) [13]. Environmental impact assessments (EIA) and integrated water resource management (IWRM) are additional tools to safeguard aquatic habitats during development activities.

10. Research Gaps and Future Perspectives

Despite growing interest, significant knowledge gaps remain in understanding the ecology, utility, and management of aquatic plants, especially in tropical and subtropical regions.

10.1 Need for Detailed Ecological and Economic Studies

There is a pressing need for comprehensive ecological assessments of aquatic plant diversity across different aquatic ecosystems. Quantitative studies on species distribution, biomass production, ecological roles, and interactions with fauna are limited (Bornette *et al.* 1998) [7]. Similarly, economic evaluations of ecosystem services provided by aquatic plants—such as nutrient cycling, water purification, and livelihood support—remain underexplored, hindering their inclusion in policy frameworks (Pandey, 2011) [29].

10.2 Potential for Commercialization and Cultivation

Several aquatic plants, including *Ipomoea aquatica*, *Azolla*, and duckweeds, have high potential for commercial applications in food, feed, biofertilizer, and wastewater treatment sectors (Hasan & Chakrabarti, 2009; Ali *et al.* 2020) [18, 2]. Developing protocols for large-scale cultivation, processing, and market linkages can enhance rural income and promote sustainable use. Innovations in aquaponics, hydroponics, and integrated farming systems offer viable avenues for scalable production.

10.3 Integration into Rural Development Programs

Aquatic plant utilization can be integrated into rural development programs focusing on nutrition, income generation, and environmental sustainability. Government schemes on wetland management, climate resilience, and biodiversity conservation can include components for aquatic plant cultivation, conservation education, and capacity building. Linking research outputs with extension services can improve adoption at the grassroots level (Feng, Wang, & Zhang, 2025) [16].

11. Conclusion

11.1 Summary of Key Findings

Aquatic plants are vital components of freshwater ecosystems, contributing to ecological stability, biodiversity support, and socio-economic development. They serve multiple roles—from oxygen production and nutrient cycling to food, medicine, and habitat provision. The diversity of aquatic macrophytes is shaped by environmental conditions and anthropogenic pressures, with Central Indian riverine systems harboring a variety of emergent, submerged, and floating species.

However, aquatic plant diversity is under serious threat from pollution, habitat degradation, invasive species, and climate change. Addressing these challenges requires a combination of conservation strategies, community involvement, policy reforms, and scientific research. While several aquatic plants have demonstrated economic value, their sustainable utilization remains limited due to knowledge and market constraints.

11.2 Importance of Balancing Utilization and Conservation

To ensure the long-term sustainability of aquatic ecosystems, it is crucial to balance the utilization of aquatic plants with their conservation. This involves adopting an ecosystem-based approach that recognizes the intrinsic value of biodiversity while promoting livelihoods. In-situ and ex-situ conservation, integrated with traditional knowledge and modern science, can help preserve aquatic flora for future generations. Additionally, filling research gaps and embedding aquatic plant management in rural development and policy agendas will be key to enhancing both ecological and economic outcomes.

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