

Original Research

Macrophyte Diversity and Ecosystem Services in Wetlands of Eastern Ranchi: A Multi-site Analysis of Abundance, Frequency, and Importance Value Index Patterns

Jitendra Mahato¹, Sujit Ghosh^{2*}

Abstract

Macrophytes, visible aquatic and semi-aquatic plants, are integral components of wetland ecosystems, playing crucial roles in maintaining biodiversity, providing ecosystem services, and ensuring ecological stability. This research examines the distribution, abundance, frequency, diversity, and ecosystem services of macrophytes in several wetlands (W1-W7) located in the eastern part of Ranchi district, Jharkhand, India. The study sites include Bundu Lake, Hindalco Pond, Choga Bada Talab, Raja Bandh, Kita Uparbandh, Tamar Bada Talab, and Rukka Dam. A quantitative assessment using quadrat sampling and phytosociological methods was conducted from September 2022 to March 2023 to ensure accurate data collection and analysis. The study documented 78 macrophyte species belonging to 33 families and 58 genera. Emergent macrophytes were found to be the dominant life form, constituting 69% of the recorded species. Several species demonstrated high frequency and abundance across multiple study sites, including *Pontederia crassipes* Mart., *Alternanthera philoxeroides* (Mart) Griseb., *Hydrilla verticillata* (L.f.) Royle, *Ipomoea aquatica* Forssk., and *Nymphoides hydrophyllum* (Lour.) Kuntze. To assess the diversity and ecological characteristics of the macrophyte communities, various diversity indices were calculated. These included the Shannon-Wiener index, Simpson's index, Margalef index, and Pielou's Evenness index. The results of these analyses revealed high levels of macrophyte diversity and evenness within the studied wetlands. Twenty-one macrophytes were identified as key species and nine species as rare species based on their IVI (Importance Value Index) scores. The key species were found to provide essential ecosystem services, including erosion control, water quality improvement, nutrient cycling, carbon sequestration, and habitat provision for other organisms. This research contributes significantly to our understanding of macrophyte diversity patterns and traits-based ecosystem services in wetland

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ecosystems. The findings of this study have important implications for the development and implementation of effective conservation strategies for these vital wetland ecosystems in the eastern Ranchi (W1- W7).

Keywords

Ecosystem services, key species, macrophytes, quantitative assessment, wetland

Raznolikost makrofitov in ekološke funkcije v mokriščih vzhodnega Ranchija: Analiza vzorcev številčnosti, pogostosti in indeksa vrednosti pomembnosti na več lokacijah

Izvleček

Makrofiti so sestavni del mokriščnih ekosistemov, saj imajo ključno vlogo pri ohranjanju biotske raznovrstnosti, zagotavljanju ekosistemskih storitev in zagotavljanju ekološke stabilnosti. Ta raziskava preučuje razširjenost, številčnost, pogostost, raznolikost in ekološko funkcijo makrofitov v več mokriščih (W1-W7), ki se nahajajo v vzhodnem delu okrožja Ranchi v Džarkhandu v Indiji. Študijska območja vključujejo jezero Bundu, ribnik Hindalco, Choga Bada Talab, Raja Bandh, Kita Uparbandh, Tamar Bada Talab in jez Rukka. Kvantitativna ocena z uporabo kvadratnega vzorčenja in fitosocioloških metod je potekala od septembra 2022 do marca 2023, s čimer smo želeli zagotoviti natančnost zbranih podatkov in analiz. V študiji je bilo dokumentiranih 78 vrst makrofitov, ki pripadajo 33 družinam in 58 rodovom. Ugotovljeno je bilo, da so prevladujoča življenjska oblika emergentni makrofiti, ki so predstavljali 69 % zabeleženih vrst. Več vrst je pokazalo visoko pogostost in številčnost na več študijskih območjih, vključno s *Pontederia crassipes* Mart, *Alternanthera philoxeroides* (Mart) Griseb, *Hydrilla verticillata* (L.f.) Royle, *Ipomoea aquatica* Forssk in *Nymphoides hydrophyllum* (Lour.) Kuntze. Za oceno raznolikosti in ekoloških značilnosti združb makrofitov so bili izračunani različni indeksi raznolikosti. Med njimi so bili Shannon-Wienerjev indeks, Simpsonov indeks, Margalefov indeks in Pieloujev indeks enakomernosti. Rezultati teh analiz so pokazali visoko stopnjo raznolikosti in enakomernosti makrofitov v preučevanih mokriščih. Enaindvajset makrofitov je bilo opredeljenih kot ključne vrste, devet vrst pa kot redke vrste na podlagi njihovih ocen IVI (Importance Value Index). Ugotovljeno je bilo, da ključne vrste zagotavljajo bistvene ekosistemske storitve, vključno z nadzorom erozije, izboljšanjem kakovosti vode, kroženjem hranil, sekvestracijo ogljika in zagotavljanjem habitatov za druge organizme. Ta raziskava pomembno prispeva k razumevanju vzorcev raznolikosti makrofitov in ekosistemskih storitev, ki temeljijo na lastnostih, v mokrotnih ekosistemih. Ugotovitve te študije imajo pomembne posledice za razvoj in izvajanje učinkovitih strategij ohranjanja teh ključnih mokriščnih ekosistemov v vzhodnem Ranchiju (W1- W7).

Ključne besede

ekološka vloga, ključne vrste, makrofiti, kvantitativna ocena, mokrišče

Introduction

Wetlands are the most vital ecosystems on our planet, offering a wide range of ecological services such as water purification, flood control, carbon storage, and the conservation of biodiversity. These ecosystems help regulate water cycles and are rich sources of biodiversity, supporting numerous species, genetic variations, and

diverse ecosystems (Mitsch et al., 2015; Shiji et al., 2016). Among the key players in these environments are macrophytes, large aquatic plants that you can see with the naked eye. Macrophytes contribute significantly to the health of aquatic ecosystems by promoting sediment deposition, carbon capture, water filtration, and the removal of pollutants. Additionally, they serve as sources of bioenergy biochar and help mitigate the impacts of climate change.

Beyond these environmental roles, macrophytes provide natural medicines, fibres, and other resources that benefit human society, reinforcing the link between biodiversity and human well-being (Kumar et al., 2023). Unfortunately, these vital plants are increasingly under threat. Pollution, habitat destruction, invasive species, and climate change are all taking a toll on macrophyte populations, leading to degraded ecosystems and a loss of biodiversity (Lesiv et al., 2020). Human activities, such as unsustainable water management, overharvesting, sediment build-up, and the use of chemicals, further compound these challenges, damaging both macrophytes and the essential services they provide.

In the eastern part of Ranchi district, Jharkhand, India, several wetlands serve as important habitats for a variety of macrophyte species. Wetlands like Bundu Lake, Hindalco Pond, Choga Bada Talab, Raja Bandh, Kita Uparbandh, Tamar Bada Talab, and Rukka Dam host a diverse range of aquatic vegetation. These plants play a crucial role in maintaining the health and functioning of these ecosystems. Understanding how these macrophytes are distributed, how abundant they are, how frequently they appear, and what services they offer to the ecosystem is essential if we are to develop effective conservation and management strategies. Various studies have looked at macrophyte diversity and the ecological significance of wetlands in other regions (Swamy et al., 2016; Xu et al., 2019; Bhanja et al., 2023). In the Chota Nagpur Plateau, where Ranchi district is located, researchers have explored macrophyte diversity in places like Ranchi Lake and Kanke Dam. For instance, Lal and Lal (2021) found 36 macrophyte species in Kanke Dam and 17 species in Ranchi Lake. Other studies have mentioned the macrophyte diversity in various wetlands across the Ranchi district in their broader floristic surveys (Verma and Pandeya, 2008; Mukherjee and Kumar, 2020). However, most of these studies focus on individual sites and don't provide a broader picture of species distribution, abundance, or diversity across multiple wetlands. Although macrophytes are well known for their role in delivering ecosystem services (Thomaz, 2023), there is a lack of site-specific information in the wetlands of the eastern Ranchi region that connects species composition to ecosystem functions. Furthermore, the lack of precise suggestions based on in-depth ecological data in the region's current conservation strategies for wetlands impairs the development of efficient management strategies.

Comprehensive research on the distribution, abundance, frequency, diversity, and ecosystem services of

macrophytes in the seven selected wetlands in the eastern portion of Ranchi district is missing despite the ecological relevance of wetlands and the value of these plants. The lack of comparative study of species frequency and diversity indices, the scarcity of data on specific species distributions and abundances, and the lack of knowledge on ecosystem services are some of the major research gaps. To fill these gaps, a thorough investigation of the biological patterns and ecosystem services provided by the macrophyte species in these wetlands is necessary. The primary goal of this research is to explore the diversity of macrophytes, their abundance and distribution patterns, and the ecosystem services they provide across seven selected wetlands in the eastern Ranchi district.

Materials and Methods

The study area

The study was carried out in Ranchi District, the capital of Jharkhand, India, which is located between 85°15'-85°23' E longitude and 23°21'-23°87' N latitude, spanning 7,698 square kilometres of steep terrain. The district is located in the southern section of the Chota Nagpur Plateau, an extension of the Deccan Plateau, and is bordered to the north by Ramgarh, Hazaribagh, and Chatra, to the south by Khunti, to the west by Latehar, Lohardaga, and Gumla, and to the east by Saraikela and Purulia (West Bengal). Ranchi has a humid subtropical climate, with summer temperatures ranging from 20-40°C and winter temperatures ranging from 1-25°C, and it receives both seasonal and cyclonic rainfall (Rani et al., 2011). The Subarnarekha and its tributaries form the principal river system.

Selection of Wetlands

For the quantitative analysis of wetland biodiversity and ecological conditions, seven wetlands from the eastern region of the district were selected, each representing different blocks. The wetlands include Bundu Lake (W1), Hindalco Pond (W2), Choga Bada Talab (W3), Raja Bandh (W4), Kita Upar Bandh (W5), Tamar Bada Talab (W6), and Rukka Dam (W7) (Fig. 1). Table 1 provides general information about these selected wetlands, including their geographical coordinates, elevation, surface area, and macrophyte cover. The selection of these wetlands aimed to capture

both urban and rural settings, allowing for a comparative analysis of human influence and ecological health across varying landscapes.

The catchment areas and corresponding human influences on these wetlands were assessed to understand their ecological status. W1 (Bundu Lake), an urban wetland covering 40.47 hectares, is located near markets, human settlements, and agricultural land. It experiences heavy pollution due to urban sewage, domestic waste, agricultural runoff, and shrinkage caused by human settlement expansion, road adjacency, and recreational use. Similarly, W2 (Hindalco Pond), a smaller 2.43-hectare urban wetland near Muri Station, is significantly impacted by industrial activities and urban settlements. This wetland faces severe pollution from industrial and domestic sewage, siltation, and industrial encroachment. In contrast, W3 (Choga Bada Talab), a rural wetland spanning 10.93 hectares, is surrounded by agricultural land and open grasslands. Its pollution mainly stems from agricultural runoff, domestic use, and irrigation, but it is less affected by human interference compared to the urban wetlands. Another rural wetland, W4 (Raja Bandh), covering 9.41 hectares, has a catchment area consisting of hilly uplands, agricultural fields, and open grasslands.

Pollution sources in this wetland include road construction, domestic activities, cattle bathing, and the partial conversion of land for agriculture. W5 (Kita Uparbandh), an urban wetland of 2.02 hectares, is bordered by natural hilly vegetation, agricultural land, and a major road. It suffers from pollution caused by domestic sewage, proximity to human settlements, road adjacency, and shrinkage due to increasing urbanization. W6 (Tamar Bada Talab), a rural wetland of 5.67 hectares, is less affected by human activities, with catchment areas consisting of open grassland and agricultural land. Pollution in this wetland is primarily due to agricultural runoff and limited domestic use, making it one of the least impacted wetlands in the study.

Lastly, W7 (Rukka Dam) is a riverine, natural wetland with minimal human influence, spanning a large rural area (10199.77 hectares). Its catchment areas include agricultural land, open grasslands, and forested regions, with no major anthropogenic disturbances. Pollution in W7 is limited to agricultural runoff and occasional recreational activities, maintaining its status as a relatively pristine ecosystem. The variety of settings across these seven wetlands allows for a comprehensive analysis of how human activities influence wetland biodiversity and ecological conditions.

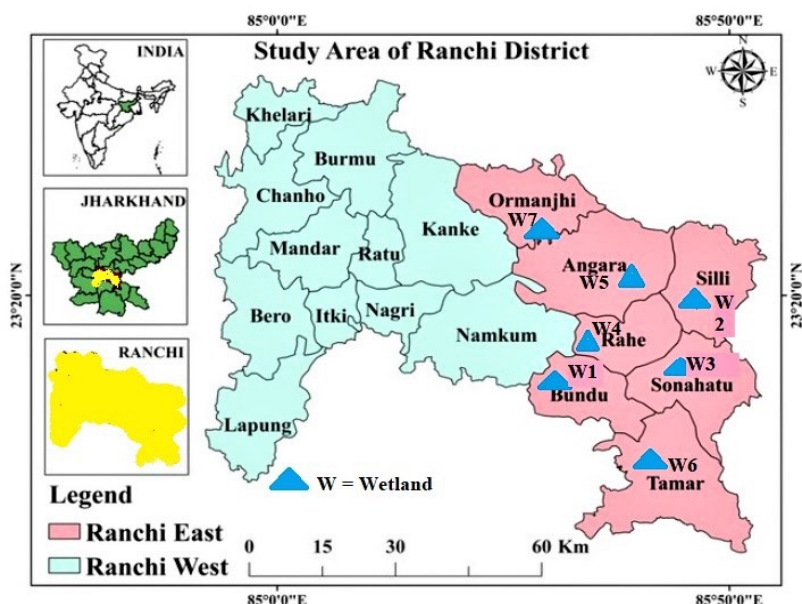


Figure 1. Location map of the study area with designated sampling sites (W1-W7) (Source: Mishra and Lal, 2023 and modified based on the location of wetlands).

Slika 1. Lokacijska karta območja študije z označenimi mesti vzorčenja (W1-W7) (Vir: Mishra in Lal, 2023 in spremenjeno na podlagi lokacije mokrišč).

Table 1. Overview of the selected wetlands.

Tabela 1. Pregled izbranih mokrišč.

Name of the Wetlands, (Blocks).	Latitude	Longitude	Altitude	Size hectares	Existing Sp.
Bundu Lake. (Bundu).	23.1614 N	85.586489 E	259.47 met.	40.47 ha.	31
Hindalco Pond. Muri, (Silli).	23.38126 N	85.867212 E	198.63 met.	2.43 ha.	25
Choga Bada Talab. Choga, (Sonahatu).	23.21299 N	85.7433049 E	190.09 met.	10.93 ha.	27
Raja Bandh. Rahe, (Rahe).	23.24986 N	85.6375088 E	251.66 met.	9.41 ha.	27
Kita Uparbandh. Kita, (Angara).	23.36492 N	85.765632 E	251.55 met.	2.02 ha.	25
Tamar Bada Talab. Tamar, (Tamar).	23.05430 N	85.65870 E	189.46 met.	5.67 ha.	29
Rukka Dam, (Ormanjhi, only Rukka portion.)	23.43663 N	85.462674 E	596 met.	10199.77 ha.	39

Sampling methodology

Fieldwork was conducted from September 2022 to March 2023, spanning the post-monsoon to winter seasons. Quadrat sampling was used to assess macrophytes qualitatively and quantitatively. Ten 1 m × 1 m quadrats were randomly placed throughout each wetland, with three replicates per site. Sampling was carried out up to 2 m from the wetland's periphery to its centre. The macrophytes that occurred or fell within each sampling unit were counted by hand and listed by species (Margalef, 1969).

Identification and nomenclature

Plant species were identified using standard protocols, work and keys provided by the books of 'Aquatic and Wetland Plants of India' (Cook 1996) and 'Wetland Flora of West Bengal' (Chowdhury and Chowdhury 2022). Valid scientific names were cross-checked using the Plants of the World Online (POWO 2024) and World Flora Online (WFO 2024) databases. Voucher samples of identified macrophytes were prepared and deposited at the Botany Department herbarium of Sidho-Kanho-Birsha University (SKBU), Purulia, West Bengal, India, for future reference and verification.

Data analysis

The phytosociological characteristics were determined using established procedures (Margalef, 1969). The diversity indicators, including Shannon-Wiener, Simpson's, species richness, and species evenness, were calculated using Magurran's (2004) methods. The number of individuals in

each species was counted to calculate phytosociological measures such as percent frequency, frequency class (Raunkiaer, 1934), relative frequency, abundance, density, relative density, and IVI (Importance Value Index) using the following formulas.

$$\text{Frequency (\%)} = \frac{\text{Total number of quadrants in which species has occurred}}{\text{Total number of quadrants studied}} \times 100$$

$$\text{Relative Frequency} = \frac{\text{Frequency of a particular species}}{\text{Sum of frequencies of all species}} \times 100$$

$$\text{Abundance} = \frac{\text{Total number of individuals of the species}}{\text{Total number of quadrants in which the species has occurred}}$$

$$\text{Relative Abundance} = \frac{\text{Abundance of a particular species}}{\text{Total abundance of all species}} \times 100$$

$$\text{Density} = \frac{\text{Total number of individuals of the species}}{\text{Total number of quadrants studied}}$$

$$\text{Relative Density} = \frac{\text{Density of a particular species}}{\text{Total density of all species}} \times 100$$

$$\text{IVI} = (\text{Relative Frequency} + \text{Relative Abundance} + \text{Relative Density}).$$

Statistical analyses

Microsoft Excel was used to conduct statistical analyses comparing macrophyte diversity and other factors among the seven wetlands (W1 to W7). The data was interpreted by the application of descriptive statistics and comparative analyses.

Results

Macrophyte Species Distribution and Abundance

Across the seven wetlands (W1 to W7), a total of 78 macrophyte species (Table 2) from 33 families and 58 genera were recorded. Emergent macrophytes dominated the flora, making up 69% of the total, followed by rooted floating-leaf species (12%), submerged species (11%), and free-floating species (8%).

Emergent macrophytes were the most prevalent, with 54 species recorded, including *Cyperus iria* L. particularly

abundant in Wetland W5, *Paspalum distichum* L. in Wetlands W3 and W5, and *Echinochloa colonum* (L.) Link. in Wetlands W4, W5, and W7. Rooted with floating-leaved macrophytes were represented by nine species, with *Nymphaea pubescens* Willd., *Nymphoides hydrophyllum* (Lour.) Kuntze, and *Trapa natans* var. *bispinosa* (Roxb.) Makino. being the most common. Free-floating macrophytes comprised six species, with *Lemna perpusilla* Torr. and *Spirodela polyrhiza* (L.) Schleid. frequently observed in Wetlands W1, W2, W6, and W7 (Table 2). Lastly, nine species of submerged macrophytes were documented, with *Potamogeton crispus* L. and *Potamogeton nodosus* Poir. dominating across the study sites.

Table 2. Distribution of macrophyte species with IVI and growth forms.
Tabela 2. Razporeditev vrst makrofitov z IVI in oblikami rasti.

Scientific Name	IVI W1	W2	W3	W4	W5	W6	W7	G.F.
<i>Acmella paniculata</i> (Wall ex DC.) R.K. Jansen	3.12	9.58			7.16		4.72	E
<i>Actinoscirpus grossus</i> (L.f.) Goetgh. & D.A. Simpson			7.01					E
<i>Aeschynomene indica</i> L.			7.36		4.17			E
<i>Alternanthera philoxeroides</i> (Mart) Griseb.	18.75	14.41			19.69	13.97	12.30	E
<i>Alternanthera sessilis</i> (L.) DC.	11.71	11.61		13.65	14.36	9.80	7.86	E
<i>Ammannia baccifera</i> L.				6.17				E
<i>Azolla pinnata</i> R.Br.	11.74	20.54				11.63	7.28	FF
<i>Bacopa monnieri</i> (L.) Wettst.			17.76					E
<i>Centella asiatica</i> (L.) Urb.					4.75		6.47	E
<i>Ceratophyllum demersum</i> L.						7.59		S
<i>Ceratopteris thalictroides</i> (L.) Brongn.					4.29		3.84	E
<i>Chenopodium ficifolium</i> Sm.		8.31						E
<i>Colocasia esculenta</i> (L.) Schott	3.86	7.16			5.01	4.54	2.87	E
<i>Cyperus brevifolius</i> (Rottb.) Hassk.							7.56	E
<i>Cyperus compressus</i> L.	10.40		14.52		12.55	13.25	10.75	E
<i>Cyperus difformis</i> L.	10.04			12.62	17.81	10.03		E
<i>Cyperus flavidus</i> Retz.							7.99	E
<i>Cyperus fuscus</i> L.							9.00	E,
<i>Cyperus iria</i> L.			14.25		17.94			E
<i>Cyperus polystachyos</i> Rottb.	5.98							E
<i>Dentella repens</i> (L.) J.R. Forst. & G. Forst.			13.42					E
<i>Echinochloa colonum</i> (L.) Link				15.10	16.24		11.18	E
<i>Eclipta prostrata</i> (L.) L.	7.03	9.39	7.66	9.29	9.44	7.68	6.05	E

<i>Eleusine indica</i> (L.) Gaertn.						12.51	9.49	E
<i>Evolvulus nummularius</i> (L.) L.	7.75		12.62				5.13	E
<i>Fimbristylis aestivalis</i> (Retz.) Vahl	9.51							E
<i>Fimbristylis albobiridis</i> C.B. Clarke			12.95					E
<i>Fimbristylis argentea</i> (Rottb.) Vahl			15.62					E
<i>Fimbristylis bisumbellata</i> (Forssk.) Bubani	11.10		17.28	12.34				E
<i>Fuirena ciliaris</i> (L.) Roxb.	10.55				17.09	10.03	8.76	E
<i>Grangea maderaspatana</i> (L.) Poir.			8.67					E
<i>Heliotropium indicum</i> L.	4.39		9.26					E
<i>Hydrilla verticillata</i> (L.f.) Royle	18.15	15.88				18.29		S
<i>Hygrophila auriculata</i> (Schumach.) Heine			9.01					E
<i>Ipomoea aquatica</i> Forssk.	9.84	12.98	10.84	10.16	11.90	8.76	7.54	RFL
<i>Ipomoea carnea</i> Jacq.	6.69	6.68	7.01	9.26		5.46	3.10	E
<i>Kyllinga melanosperma</i> Nees	12.05							E
<i>Lemna perpusilla</i> Torr.	17.57	24.81				15.48	10.12	FF
<i>Lindernia parviflora</i> (Roxb.) Haines			11.77					E
<i>Limnophila sessiliflora</i> (Vahl) Blume					14.25			S
<i>Ludwigia adscendens</i> (L.) H. Hara			9.09			8.05	8.03	RFL
<i>Ludwigia perennis</i> L.	4.57		9.31	5.07	5.01	3.63		E
<i>Louisiella paludosa</i> (Roxb.) Landge				13.65				E
<i>Marsilea minuta</i> L.		18.99	15.42	11.03	16.34	14.62	8.16	RFL
<i>Melilotus indicus</i> (L.) All.		7.16						E
<i>Nelumbo nucifera</i> Gaertn.	3.58		6.81			8.65		RFL
<i>Nymphaea nouchali</i> Burm.f.	3.69			3.67				RFL
<i>Nymphaea pubescens</i> Wild.	5.45	4.48	7.08	8.70	12.74	10.81		RFL
<i>Nymphoides hydrophyllum</i> (Lour.) Kuntze			22.84	20.23	12.39			RFL
<i>Nymphoides indica</i> (L.) Kuntze	12.80	p				13.43		RFL
<i>Oldenlandia corymbosa</i> L.			8.46	9.51	8.58	5.15		E
<i>Ottelia alismoides</i> (L.) Pers.		6.68						S
<i>Panicum repens</i> L.	12.95	21.07			17.32	13.53	10.83	E
<i>Paspalum distichum</i> L.			16.73	16.99	16.81	12.76		E
<i>Persicaria barbata</i> (L.) H. Hara							3.44	E
<i>Persicaria hydropiper</i> (L.) Delabre		7.16		10.81				E
<i>Persicaria glabra</i> (Willd.) M.Gomez			5.62				3.16	E
<i>Phyla nodiflora</i> (L.) Greene	9.16						5.79	E
<i>Pistia stratiotes</i> L.	10.22						15.15	FF
<i>Polygonum plebeium</i> R.Br.			14.52	12.62			7.28	E
<i>Pontederia crassipes</i> Mart.	20.72	21.91					17.20	FF

<i>Pontederia vaginalis</i> Burm.f.	6.68				4.18	E	
<i>Potamogeton crispus</i> L.			16.15		9.13	S	
<i>Potamogeton nodosus</i> poir.				11.28	9.24	S	
<i>Pouzolzia zeylanica</i> (L.) Benn.	4.48					E	
<i>Ranunculus sceleratus</i> L.	6.68					E	
<i>Rotala rotundifolia</i> (Buch. -Ham. ex Roxb.) Koehne			17.07		9.97	E	
<i>Salvinia cucullata</i> Bory					9.48	FF	
<i>Schoenoplectiella articulata</i> (L.) Lye.		5.62				E	
<i>Schoenoplectiella senegalensis</i> (Steud.) Lye			6.17		4.86	E	
<i>Scleromitron brachypodum</i> (DC.) T.C. Hsu			8.35			E	
<i>Spirodela polyrhiza</i> (L.) Schleid.	17.20	23.26		16.44	8.84	FF	
<i>Torenia crustacea</i> (L.) Chan & Schltdl.	9.08		7.35	7.88	6.71	E	
<i>Trapa natans</i> var. <i>bispinosa</i> (Roxb.) Makino	6.51		15.98		14.56	RFL	
<i>Typha domingensis</i> Pers.		9.58			4.58	E	
<i>Utricularia aurea</i> Lour.			8.98		4.85	S	
<i>Utricularia stellaris</i> L. f.	6.64	7.72	7.90	9.19	5.87	5.97	S
<i>Vallisneria spiralis</i> L.			9.75		7.34	6.00	S

(Abbreviations: G. F= Growth form, E = Emergent, S = Submerged, RFL = Rooted with floating leaves, FF = Free floating.)

Dominant families

To determine the dominant families across the study sites, a quantitative approach was employed. The proportion of species represented by each family was calculated by dividing the number of species within a particular family by the total number of species across all families. This proportion was then expressed as a percentage using the following formula:

Percentage of Family = $\frac{\text{Number of Species in a Particular Family}}{\text{Total number of Species across all Families}} \times 100$

The family with the highest percentage was identified as the dominant family, representing the largest contribution to the overall macrophyte diversity in the wetlands. This approach allowed for a clear assessment of the relative importance of each family in the macrophyte community. The Cyperaceae family was the most dominant based on species richness and percentage representation, with 16 species accounting for 20.51% of the total species.

Other notable families included Poaceae (6.41%),

Araceae (5.12%), Polygonaceae (5.12%), Hydrocharitaceae (3.85%), Convolvulaceae (3.85%), Asteraceae (3.85%), and Rubiaceae (3.85%). These families made significant contributions to the overall macrophyte diversity in the wetlands (Fig. 2).

Frequency and Distribution of Macrophyte Species

The frequency of occurrence of various plant species across different wetlands varied considerably. Species such as *Pontederia crassipes* Mart. and *Alternanthera philoxeroides*, *Hydrilla verticillata* exhibited high frequency across various wetlands, suggesting adaptability to a range of environmental conditions. *Nymphoides hydrophyllum* showed a particularly high frequency in Wetland 3 (W3) and Wetland 4 (W4), with occurrences of 90% and 83.33%, respectively. Conversely, low-frequency species like *Acmella paniculata*, *Pouzolzia zeylanica* (L.) Benn., *Persicaria glabra* (Willd.) M. Gómez and *Torenia crustacea* (L.) Chan & Schltdl. were restricted to specific areas, likely due to their sensitivity to habitat modifications (see Table 3 for details).

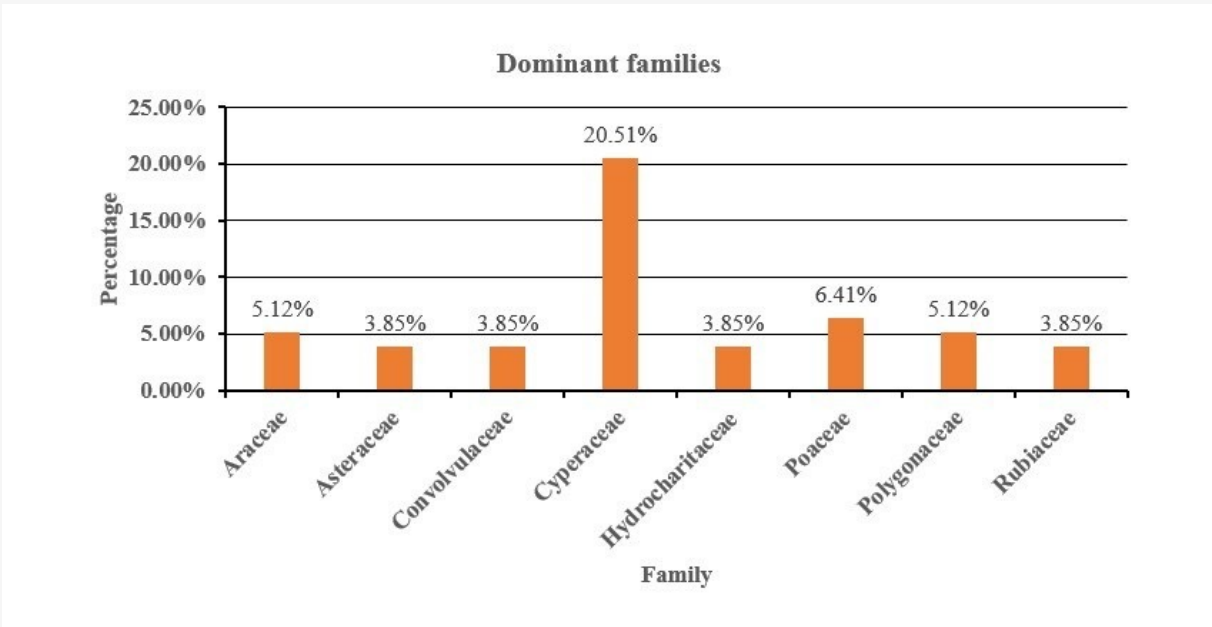


Figure 2. Distribution of dominant families across the study sites (W1-W7).
Slika 2. Porazdelitev dominantnih družin na raziskovalnih območjih (W1-W7).

Table 3. Frequency and distribution of macrophyte species.
Tabela 3. Pogostost in porazdelitev vrst makrofita.

High Frequency Species	Frequency (%)	Wetlands	High Frequency Species	Frequency (%)	Wetlands
<i>Pontederia crassipes</i>	85.71%, 70%, 81.25%	W1, W2, W7	<i>Acmella paniculata</i>	14.29%	W1
<i>Alternanthera philoxeroides</i>	64.29%, 62.5%, 62.5%	W1, W5, W7	<i>Torenia crustacea</i>	14.29%, 20%	W1, W2
<i>Alternanthera sessilis</i>	50%, 50%	W1, W5	<i>Chenopodium ficifolium</i>	10%	W2
<i>Hydrilla verticillata</i>	57.14%, 70%	W1, W6	<i>Pouzolzia zeylanica</i>	10%	W2
<i>Ipomoea aquatica</i>	50%, 50%, 43.75%	W2, W3, W7	<i>Bacopa monnieri</i>	20%	W3
<i>Nymphaea pubescens</i>	60%, 62.5%	W6, W5	<i>Persicaria glabra</i>	20%, 18.75%	W3, W7
<i>Panicum repens</i>	70%	W2	<i>Persicaria hydropiper</i>	16.67%, 20%	W4, W2
<i>Pistia stratiotes</i>	81.5%	W7	<i>Ammannia baccifera</i>	16.67%	W4
<i>Trapa natans</i> var. <i>bispinosa</i>	60%, 58.33%	W6, W4	<i>Fimbristylis albovidis</i>	16.67%	W4
<i>Ludwigia adscendens</i>	62.5%, 50%, 50%	W7, W3, W6	<i>Grangea maderaspatana</i>	16.67%	W4
<i>Nymphoides hydrophyllum</i>	90%, 83.33%	W3, W4	<i>Aeschynomene indica</i>	12.5%	W5
<i>Nymphoides indica</i>	50%, 50%	W2, W6	<i>Centella asiatica</i>	12.5%	W5
<i>Potamogeton crispus</i>	66.67%	W4	<i>Ceratopteris thalictroides</i>	12.5%, 25%	W7, W5
<i>Salvinia cucullata</i>	50%	W7	<i>Colocasia esculenta</i>	18.75%, 20%	W7, W6
<i>Cyperus difformis</i>	50%	W5	<i>Azolla pinnata</i>	10%	W6
			<i>Lemna perpusilla</i>	10%	W6
			<i>Spirodela polyrhiza</i>	10%	W6

Raunkiaer's Frequency Analysis

The frequency distribution of plant species within each wetland was calculated using Raunkiaer's law of frequency classes (1934). The results are presented in Table 4. By analyzing and comparing them to Raunkiaer's law of frequency classes ($A > B > C \geq D < E$, where the value of the frequency class comprises class A= 53%, B=14%, C=9%, D= 8% and E=16%) across all wetlands (W1 - W7), significant insights were gained into the spatial distribution and diversity of macrophytes. This analysis highlights the varying patterns of species diversity, their spatial distribution, and the ecological status of these wetlands.

Wetland W1 had the highest percentage in Class B (64.52%), indicating a heterogeneous vegetation structure, while Wetland W2 displayed higher disturbance with lower frequencies in Classes C and E (4.00% and 0.00%, respectively). In Wetland W3, Class B dominated with a frequency of 55.55%, indicating moderate and stable diversity, while Class D was absent. Wetland W4 also showed a strong presence of Class B at 48.15%, with Classes A and C equally

represented at 22.22%. Wetland W5 exhibited Class B at 48.00% and Class C at 36.00%, suggesting a less diverse community structure. In Wetland W6, Class B was again the most frequent at 44.83%, with limited diversity overall. Wetland W7 recorded Class B at 41.02% and Class A at 38.46%, reflecting a consistent distribution pattern across the wetlands. Hence, the study exposed distinct patterns of species diversity and ecological dynamics within these wetland ecosystems.

Diversity Indices and Evenness Analysis

The current study investigates macrophyte diversity and evenness across the wetlands under study (W1-W7) using several established biodiversity indices (Table 5), including the Shannon and Weiner diversity index (H'), Simpson's index of diversity ($1-D$), Margalef diversity index, and Pielou's evenness index (J'). These indices provide insights into the composition, richness, and evenness of macrophyte communities, offering a comprehensive view of their biodiversity status (Fig. 3).

Table 4. Raunkiaer's frequency classes (%) of the study sites (W1-W7).

Tabela 4. Raunkiaerjevi frekvenčni razredi (%) raziskovalnih območij (W1-W7).

Study sites	Class A	Class B	Class C	Class D	Class E	Raunkiaer's Frequency
W1	9.68	64.52	19.36	3.22	3.22	$A < B > C > D = E$
W2	52.00	36.00	4.00	8.00	0.00	$A > B > C < D > E$
W3	22.22	55.55	18.53	0.00	3.70	$A < B > C > D < E$
W4	22.22	48.15	22.22	3.70	3.70	$A < B > C > D = E$
W5	8.00	48.00	36.00	8.00	0.00	$A < B > C > D > E$
W6	34.48	44.83	17.24	3.45	0.00	$A < B > C > D > E$
W7	38.46	41.02	10.26	5.13	5.13	$A < B > C > D = E$

Table 5. Values of different diversity Indices and evenness.

Tabela 5. Vrednosti različnih indeksov raznolikosti in enakomernosti.

Index	W1	W2	W3	W4	W5	W6	W7
Shannon and Weiner Diversity Index (H'):	3.1903	2.9512	3.1383	3.1781	3.0264	3.2651	3.4968
Simpson's Index of Diversity ($1-D$):	0.9514	0.9367	0.9505	0.9545	0.9464	0.9542	0.9654
Margalef Diversity Index:	4.14533	3.853248	3.925082	3.887354	3.628268	4.207085	5.08069
Pielou's Evenness (J')	0.92904649	0.916832	0.952205	0.964278	0.940208	0.96965	0.954481

The Shannon-Weiner diversity index (H') revealed that Wetland W7 had the highest biodiversity ($H' = 3.4968$), indicating a well-diversified and evenly distributed species community. In contrast, Wetland W2 exhibited the lowest biodiversity ($H' = 2.9512$), suggesting reduced species richness and evenness. Simpson's Index of Diversity ($1-D$), which also considers species richness and evenness, showed high values for wetlands W1, W3, W4, W6, and W7, with scores ranging from 0.9505 to 0.9654. These high values indicate that these wetlands have diverse and stable ecosystems. However, W2 and W5 had slightly lower ($1-D$) values (0.9367 and 0.9464), consistent with their lower H' scores, reflecting reduced biodiversity or dominance by certain species.

The Margalef diversity index (DMg), which focuses on species richness, highlighted that W1 (4.14533), W3 (3.925082), W4 (3.887354), and W6 (4.207085) had relatively high species richness. Wetland W7 had the highest richness overall, while W5 exhibited the lowest species richness. The lower DMg values in W2 (3.853248) and W5 (3.628268) suggest that these wetlands experience reduced species richness, likely due to environmental stressors such as pollution and human activities. Pielou's

Evenness index (J'), which measures species distribution and ecological balance, showed high evenness in wetlands W3, W4, W5, W6, and W7, indicating stable environmental conditions. Wetland W6 had the highest evenness score (0.96965), whereas W1 (0.92904) and W2 (0.91683) displayed the lowest evenness, possibly due to the influence of environmental or anthropogenic factors.

Categorization of IVI Values

The analysis of IVI values across these wetlands (W1-W7) revealed distinct patterns in the distribution of species based on their ecological significance. The important value index (IVI) serves as an indicator of a species' role within the community, considering its abundance, frequency, and dominance. Table 6 illustrates the categorization and ranges of IVI scores for each study site, highlighting species with low, intermediate, and high IVI values. The percentage of species with low, intermediate, and high IVI values varied among the wetlands, highlighting the diverse ecological roles and dominance of macrophyte species. Species with low IVI values, such as *Acmella paniculata*,

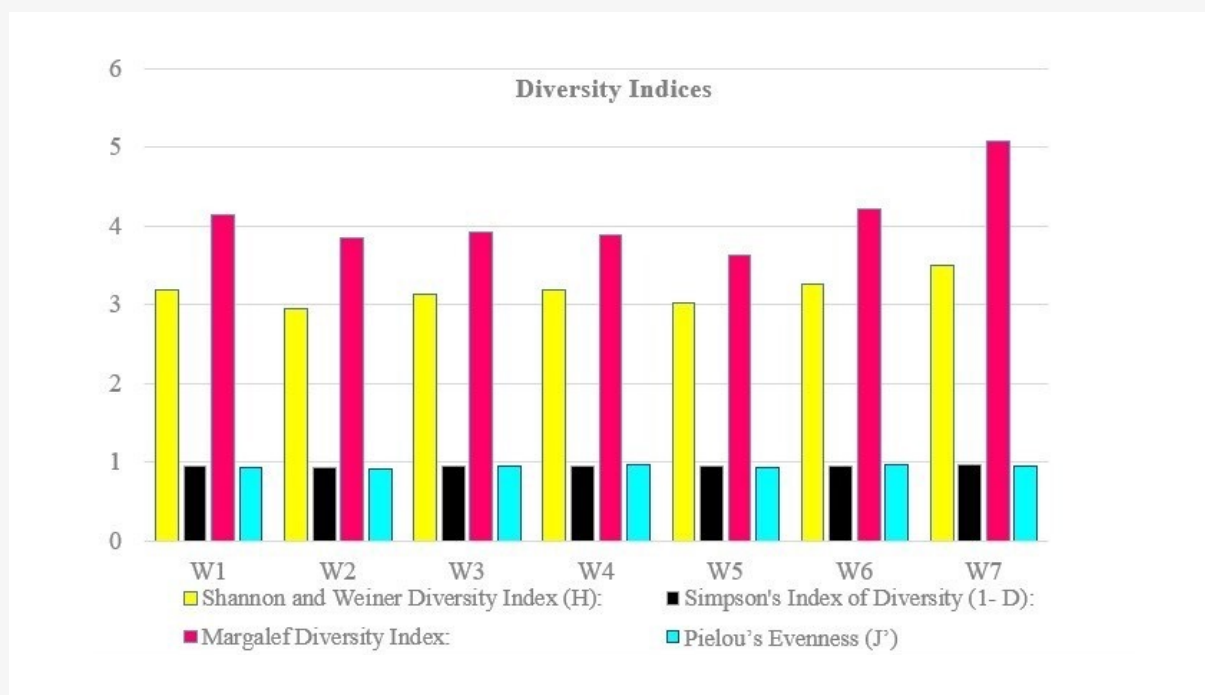


Figure 3. Comparative diversity indices of macrophytes at the study sites (W1-W7). (Shanon and Weiner, Simpson, Margalef, Pielou's index).

Slika 3. Primerjalni indeksi raznolikosti makrofitov na preučevanih območjih (W1-W7). (Shanon in Weiner, Simpson, Margalef, Pieloujev indeks)

Hydrilla verticillata, *Colocasia esculenta*, exhibit low abundance, frequency, or dominance across wetlands W1–W7, indicating their modest roles in wetland structure and functioning. Intermediate IVI species, which dominate most of the wetlands (W1–W7), make up 58–77% of the total macrophyte community. These species, such as *Alternanthera philoxeroides* and *Azolla pinnata*, contribute significantly to the stability of wetland ecosystems by maintaining biodiversity, habitat provisioning, and food supply for various organisms. High IVI species, like *Pontederia crassipes* and *Nymphoides hydrophyllum* are the most frequent and dominant, playing crucial roles in nutrient cycling, sediment retention, and habitat structuring.

Rare Species

Nine species were identified as rare based on their low relative density, frequency, dominance and importance value index (IVI). Significant rare species included *Grangea maderaspatana* (IVI 8.67) and *Scleromitron brachypodium* (DC.) T.C. Hsu (IVI 8.35), both crucial for habitat provision and soil stabilization. These species were primarily found in W3 and W4 and are vulnerable to environmental changes and anthropogenic disturbances. Other rare species included *Actinoscirpus grossus* (IVI 7.01), *Schoenoplectiella articulata* (L.) Lye (IVI 5.62), *Ranunculus sceleratus* L. (IVI 6.68), *Ammannia baccifera* (IVI 6.16), *Ottelia alismoides* (L.) Pers. (IVI 6.68), *Ceratopteris thalictroides* (IVI 4.29) and *Pouzolzia zeylanica* (IVI 4.48).

Trait-Based Ecosystem Services of Macrophytes

In this study, 21 dominant macrophyte species were recognized as key species due to their high IVI, abundance, and density, contributing significantly to numerous ecosystem services (Table 7). These species include 52% emergent macrophytes, 10% submerged, 24% free-floating, and 14% rooted floating-leaved species.

Traits such as extensive root systems, dense root hairs, and rhizome formation are vital for soil stabilization, nutrient absorption, and sediment retention in wetlands. Species like *Alternanthera philoxeroides*, *Bacopa monnieri*, *Potamogeton crispus*, *Azolla pinnata*, *Lemna perpusilla* are particularly efficient at trapping sediments, preventing erosion and preserving the structural integrity of wetlands. Their rapid root growth, deep rooting systems and rhizome formation further enhance their ability to stabilize sediments and promote overall wetland health through significant above-ground biomass production. Dense root networks, fibrous roots and fine root hairs play a key role in retaining sediments, contributing significantly to the resilience and stability of wetland ecosystems.

In terms of water quality improvement, species such as *Hydrilla verticillata*, *Lemna perpusilla*, and *Spirodela polyrrhiza* play key roles in nutrient uptake and pollutant absorption through root exudates. These species, along with *Nymphoides hydrophyllum*, *Pontederia crassipes* and *Rotala rotundifolia* contribute to sediment retention and

Table 6. Categorization and ranges of IVI scores of macrophytes in the study sites (W1–W7).

Tabela 6. Kategorizacija in razponi ocen IVI makrofita na preučevanih območjih (W1–W7).

Study sites	Ranges of IVI	Low IVI Score	Intermediate IVI Score	High IVI Score
W1	3.12 - 20.72	<i>Acmella paniculata</i> (IVI-3.12)	<i>Azolla pinnata</i> (IVI- 11.74)	<i>Pontederia crassipes</i> (IVI- 20.72)
W2	4.48 - 24.81	<i>Nymphaea pubescens</i> (IVI 4.48)	<i>Alternanthera philoxeroides</i> (IVI 14.41)	<i>Lemna perpusilla</i> (IVI – 24.81)
W3	5.62 – 22.84	<i>Persicaria glabra</i> (IVI – 5.62)	<i>Cyperus iria</i> (IVI – 14.25)	<i>Nymphoides hydrophyllum</i> (IVI - 22.84)
W4	3.67 – 20.23	<i>Nymphaea nouchali</i> (IVI – 3.67)	<i>Fimbristylis bisumbellata</i> (IVI – 12.34)	<i>Nymphoides hydrophyllum</i> (IVI – 20.23)
W5	4.17 – 19.69	<i>Aeschynomene indica</i> (IVI – 4.17)	<i>Ipomoea aquatica</i> (IVI – 11.90)	<i>Alternanthera philoxeroides</i> (IVI – 19.69)
W6	3.63 – 18.29	<i>Ludwigia perennis</i> (IVI – 3.63)	<i>Nymphaea pubescens</i> (IVI- 10.81)	<i>Hydrilla verticillata</i> (IVI – 18.29)
W7	2.87 – 17.20	<i>Colocasia esculenta</i> (IVI - 2.87)	<i>Rotala rotundifolia</i> (IVI- 9.97)	<i>Pontederia crassipes</i> (IVI – 17.20)

biomass production, creating surface area for gas exchange and improving water quality. For fodder production, species such as *Alternanthera philoxeroides*, *Cyperus iria*, *Panicum repens*, and *Paspalum distichum*, exhibit high biomass production and dense vegetation cover, making them valuable as palatable fodder for livestock while contributing to the stability and productivity of wetland ecosystems.

Discussion

The study found a diverse array of macrophyte species across these seven wetlands (W1-W7), with emergent plants dominating (69%), aligning with Vymazal's (2013) findings on free-water surface-constructed wetlands. The presence

of all four growth forms indicates a complex ecosystem with diverse microhabitats crucial for supporting aquatic fauna and ecosystem functions (Jeppesen et al., 2012). The low percentage of submerged species (11%) might suggest water clarity or quality issues, as noted by Blindow et al. (2000). Localized dominant macrophytes play vital roles in wetland ecosystems. Species like *Lemna perpusilla*, *Spirodela polyrhiza*, *Bacopa monnieri*, and *Azolla pinnata* thrive in specific environmental conditions. *L. perpusilla* and *S. polyrhiza* prefer shallow, nutrient-rich waters with high light intensity and warm temperatures (Smith and Barko, 1990; Brock, 1997). *B. monnieri* adapts to various light conditions in shallow depths (Smith, 2014), while *A. pinnata* tolerates diverse water depths and can thrive in nutrient-poor waters due to its nitrogen-fixing ability

Table 7. Traits and ecosystem services of key species.

Tabela 7. Lastnosti in ekosistemske storitve ključnih vrst.

Traits of the macrophytes	Name of the macrophytes
Soil erosion control, soil stabilization and nutrient absorption	
Extensive root system	<i>Alternanthera philoxeroides</i> , <i>Bacopa monnieri</i> , <i>Cyperus iria</i> ,
Root surface area	<i>Cyperus difformis</i> , <i>Cyperus compressus</i> , <i>Echinochloa colonum</i> ,
Root hair density	<i>Fimbristylis bisumbellata</i> , <i>Fimbristylis argentea</i> ,
Root length, root depth	<i>Panicum repens</i> , <i>Paspalum distichum</i> , <i>Rotala rotundifolia</i> ,
Root exudates	<i>Pistia stratiotes</i> , <i>Potamogeton crispus</i>
Mycorrhizal associations	
Sediment Retention	
Dense root network	<i>Alternanthera philoxeroides</i> ,
Fibrous roots	<i>Bacopa monnieri</i> , <i>Potamogeton crispus</i> ,
fine root hairs	<i>Azolla pinnata</i> , <i>Lemna perpusilla</i> , <i>Pistia stratiotes</i> ,
Rapid root growth	<i>Nymphoides hydrophyllum</i> , <i>Trapa natans</i> var. <i>bispinosa</i> ,
Root depth	<i>Pontederia crassipes</i> , <i>Spirodela polyrhiza</i> ,
Rhizome formation	<i>Hydrilla verticillate</i> , <i>Fimbristylis bisumbellata</i>
Above ground biomass	
Water Quality Improvement	
Root exudates and high nutrient uptake	<i>Alternanthera philoxeroides</i> , <i>Hydrilla verticillate</i> ,
Dense root network and pollutant absorption	<i>Lemna perpusilla</i> , <i>Azolla pinnata</i> , <i>Spirodela polyrhiza</i> ,
High biomass production and mycorrhizal associations	<i>Nymphoides hydrophyllum</i> , <i>Pistia stratiotes</i> ,
Surface area for gas exchange	<i>Pontederia crassipes</i> , <i>Potamogeton crispus</i> ,
	<i>Trapa natans</i> var. <i>bispinosa</i> , <i>Bacopa monnieri</i> ,
	<i>Rotala rotundifolia</i>
Fodder	
High biomass production	<i>Alternanthera philoxeroides</i> , <i>Cyperus iria</i> , <i>Cyperus difformis</i> ,
Palatability for livestock	<i>Cyperus compressus</i> , <i>Echinochloa colonum</i> ,
High biomass	<i>Fimbristylis bisumbellata</i> , <i>Fimbristylis argentea</i> ,
Dense vegetation cover	<i>Panicum repens</i> , <i>Paspalum distichum</i>

(Lumpkin and Plucknett, 1982). These species significantly contribute to wetland biodiversity and ecological dynamics. The dominance of Cyperaceae (20.51%) is common in tropical and subtropical wetlands (Gopal, 2016). Sedge-dominated vegetation supports food webs, creates habitats, and removes toxic compounds from water. It provides food for insects, birds, and mammals, with some species utilized by humans (Mishra et al., 2016). Cyperaceae species are well-adapted to wetland conditions and play crucial roles in nutrient cycling and sediment stabilization. The significant presence of Poaceae (6.41%) further emphasizes the importance of graminoid species. The diversity of other dominant families (Araceae, Polygonaceae, Hydrocharitaceae), including existing families suggests a complex wetland flora supporting various ecological niches, potentially indicating overall health and resilience to environmental changes (Mitsch and Gosselink, 2015). Further research is needed to understand the specific ecological roles and interactions of these families within the studied wetlands.

The species frequency analysis reveals distinct distribution patterns across the wetlands. High-frequency species like *Pontederia crassipes*, *Alternanthera philoxeroides*, and *Hydrilla verticillata* demonstrate adaptability to various conditions, with *A. philoxeroides* being a known invasive species (<https://www.iucngisd.org/gisd/>). The abundance of *Nymphoides hydrophyllum* and *N. indica* aligns with Preston and Croft's (2022) findings on species with effective reproductive strategies. High frequencies of *Pistia stratiotes* and *Potamogeton crispus* may indicate nutrient enrichment (Guntenspergen et al., 2020), potentially due to wastewater inflow. Low-frequency species like *Acmella paniculata* and *Torenia crustacea* show localized distributions, suggesting specific habitat requirements or less competitiveness (Mishra et al., 2016). The restricted distribution of *Bacopa monnieri* and *Persicaria glabra* indicates potential habitat specificity or vulnerability to competition and disturbance. Urban wetlands face significant anthropogenic pressures affecting sensitive species (Grime, 2001). *Azolla pinnata*, *Lemna perpusilla*, and *Spirodela polyrrhiza*, observed with low frequencies in W6, may be restricted due to environmental factors (Gopal, 2015). The species range reflects wetland ecosystem complexity, with high-frequency species shaping habitats and supporting ecosystem functions, while low-frequency species contribute to biodiversity and resilience (Mishra et al., 2016).

In comparison to Raunkaier's law of frequency classes (1934), all the wetlands (W1-W7) revealed heterogeneous

vegetation structures, consistent with similar research conducted in the Hokersar wetland in the Kashmir Himalaya (Mir et al., 2009). W1 displayed an even species distribution, suggesting a more stable ecosystem likely resulting from balanced environmental conditions and minimal extreme disturbances. Similarly, sites W4 and W7 showed some degree of balance, contributing to ecological resilience. The importance of species distribution and evenness for ecosystem stability in wetlands is further emphasized by the work of Mälson et al. (2008). Their study on rich fen vegetation revealed that drainage significantly reduced biodiversity, while the slow recovery observed post-rewetting underscores the critical role of maintaining evenness for ecosystem resilience. Conversely, W2, W3, W5, and W6 exhibited complex patterns of species dominance and potential instability, with deviations from Raunkaier's normal frequency. Particularly, sites W2 and W5 exhibited notable species dominance, with W2 showing a higher frequency in class B than Raunkaier's normal frequency, while W5 displayed a decrease in class A, increases in classes B and C, and an absence of class E. These patterns suggest less stable ecosystems facing extreme conditions and competitive interactions (Tilman, 1982). Zedler and Kercher (2005) highlighted wetlands' vulnerability to invasions, noting that 24% of the world's most invasive plants are wetland species. They attributed this to wetlands acting as landscape sinks accumulating debris, sediments, water, and nutrients conditions that can facilitate invasions by creating canopy gaps or promoting opportunistic plant growth. Luo et al. (2010) demonstrated that intraspecific and interspecific competition influence biomass accumulation nutrient accumulation in marsh plants, with competition strongest at lower water levels, while facilitation is more pronounced at higher water levels. The analysis reveals the complex interplay of environmental factors, competitive interactions, and ecosystem stability in these wetlands, emphasizing the utility of Raunkaier's frequency classes in understanding wetland ecosystems and the importance of conservation efforts to maintain species evenness for long-term ecosystem stability.

The analysis of four different biodiversity indices across seven wetlands (W1-W7) provides a comprehensive understanding of ecosystem health, species richness, and distribution patterns. The Shannon-Wiener diversity index (H') revealed varying levels of species complexity, with W7 exhibiting the highest biodiversity (3.4968) and W2 the lowest (2.9512). This pattern aligns with studies on the Hanjiang River wetlands, which demonstrated varied H' values

based on plant community structure and human impact (Li et al., 2022). Simpson's index of diversity (1-D) corroborated these findings, showing high values (0.9505 to 0.9654) for W1, W3, W4, W6, and W7, indicating diverse and stable ecosystems. However, W2 and W5 displayed slightly lower (1-D) values (0.9367 and 0.9464, respectively), suggesting potential biodiversity reduction or species dominance, consistent with findings on the impact of urbanization in the Bamenda Municipality (Asongwe et al., 2022). The Margalef Diversity Index (DMg) provided insights into species richness, with W1, W3, W4, W6, and W7 showing relatively high values (3.887354 to 4.207085), indicating rich species diversity and favourable conditions for plant life. These high values likely reflect optimal environmental conditions and effective conservation efforts, aligning with the diverse and healthy ecosystems observed in Lake Alakol (Zaparina et al., 2024). Conversely, W2 (3.853248) and W5 (3.628268) exhibited lower DMg values, suggesting reduced species richness, possibly due to environmental stressors such as pollution, human activities, or invasive species (Saluja and Garg, 2017). These findings mirror challenges faced by ecosystems impacted by anthropogenic influences, similar to observations in the tropical lakes of the Central Ganga Plain (Dubey et al., 2022). Pielou's Evenness (J') analysis revealed high evenness values for W3, W4, W5, W6, and W7 (0.94020 to 0.96965), indicating stable environmental conditions with minimal species dominance. Interestingly, while W5 showed lower values in other indices, it maintained high evenness, suggesting a relatively balanced distribution of species despite potential reductions in overall diversity. W1 (0.92904) and W2 (0.91683) displayed lower evenness, aligning with their performance in other indices. These findings are consistent with Zhao et al. (2021), who reported that farmland abandonment positively influences evenness by transitioning plant communities from annual to perennial species. The lower values of W1 and W2, as noted by Sharma and Singh (2017), may reflect the effects of seasonal fluctuations and vegetation on evenness. The combined analysis of these four biodiversity indices paints a nuanced picture of the seven wetlands' ecological health. W7 consistently emerges as the most diverse and stable ecosystem, followed closely by W3, W4, and W6. These wetlands likely benefit from optimal environmental conditions and effective conservation efforts. W5 presents an interesting case, with lower diversity and richness but maintaining high evenness, suggesting a need for targeted conservation strategies to enhance its overall biodiversity

while preserving its balanced species distribution. W1 and W2 consistently show signs of ecological stress across all indices, indicating they are prime candidates for intensive conservation and restoration efforts. These findings underscore the importance of comprehensive biodiversity assessments in wetland management and highlight the need for tailored conservation strategies that address the specific challenges faced by each wetland ecosystem. Long-term monitoring, such as that conducted in the Yellow River Delta since 2001, has shown that restored wetlands can significantly improve water quality and soil conditions, with vegetation quickly re-establishing and providing habitat for diverse bird species (Cui et al., 2009). Implementing such targeted conservation strategies could help improve diversity in degraded wetlands and ensure long-term ecological health across various wetland ecosystems.

The Important Value Index (IVI) of each macrophyte of the studied wetlands reveals significant patterns in species composition and ecological importance (Mori et al., 2015). The findings indicate a clear stratification of species based on their IVI values: Low IVI species, such as *Acmella paniculata* and *Hydrilla verticillata*, exhibit limited ecological roles but contributed to overall biodiversity (Junk et al., 2013). The majority of species, comprising 58-77% across study sites (W1-W7), demonstrated intermediate IVI values. These species, including *Ipomoea aquatica* and *Nymphoides indica*, play crucial roles in maintaining ecological stability and highlight the complexity of wetland ecosystems. Of particular concern are the high IVI species, approximately 21 in total, including *Alternanthera philoxeroides*, *Pontederia crassipes*, and *Pistia stratiotes*, which emerge as key invasive components of the wetland ecosystems (Zedler and Kercher, 2005). These dominant species, while indicative of successful adaptation to the wetland environment, raise concerns about their potential negative impacts on native biodiversity and ecosystem functions, necessitating careful monitoring and management strategies. The dominance of emergent species, followed by submersed, rooted floating-leaves, and free-floating growth forms, aligns with other wetland studies (Junk et al., 2013). This pattern suggests possible terrestrialization or eutrophication processes (Mitsch and Gosselink, 2015). While IVI provides valuable insights, it has limitations in capturing the functional roles of less abundant species (Frieswyk et al., 2007). The study emphasizes the need for balanced management strategies that consider both high and low IVI species to maintain biodiversity and ecosys-

tem resilience (Zedler and Kercher, 2005). This analysis provides a comprehensive understanding of wetland plant community structure and species importance, highlighting the need for accurate, adaptive management approaches. Future research should focus on long-term monitoring and integration of functional trait analyses with IVI data to gain deeper insights into ecosystem processes and community assembly mechanisms in these wetland ecosystems. The identification of nine rare species is significant for conservation. Species like *Grangea maderaspatana* and *Scleromitron brachypodum*, with higher IVI values among rare species, are of particular interest. Their rarity may be due to specific habitat requirements or environmental sensitivity (Grime, 2001). Rare submerged species such as *Ottelia alismoides* and *Ceratopteris thalictroides* are noteworthy, as they are often sensitive to water quality and habitat changes (Carpenter and Lodge, 1986). Their low abundance could indicate ecosystem stress, possibly from urbanization and pollution in wetlands W2 and W5. Elo et al. (2018) examined how environmental factors and human activities affect aquatic macrophyte diversity and rarity. The rarity of *Pouzolzia zeylanica* in W2, potentially due to habitat degradation and pollution, emphasizes the need for targeted conservation strategies. Salgado et al. (2023) found that protected land enhances native aquatic macrophyte survival and limits invasive species' spread. Monitoring and managing the impact of invasive species like *Pontederia crassipes* on rare species populations is crucial for maintaining ecological balance.

The study has highlighted the crucial role of plant functional traits, particularly root traits, in delivering various ecosystem services (Faucon et al., 2017; Bardgett et al., 2014; Burylo et al., 2012). Root traits contribute significantly to various ecosystem functions. For instance, sediment retention is enhanced by dense root networks, fine root hairs, rhizome formation, rapid root growth, fibrous roots, and substantial aboveground biomass (Stokes et al., 2009; Borin et al., 2005; Blanco-Canqui et al., 2004). In terms of water quality improvement, macrophytes exhibit high nutrient uptake, pollutant absorption, root exudates, high biomass production, and mycorrhizal associations (Vymazal, 2007). Furthermore, erosion control and soil stabilization are facilitated by extensive root systems and high root hair density. Based on these findings, macrophytes such as *Bacopa monnieri*, *Alternanthera philoxeroides*, *Cyperus spp.*, *Echinochloa colonum*, *Fimbristylis spp.*, *Panicum repens*, *Paspalum distichum*, *Rotala rotundifolia*, *Pistia*

stratiotes, and *Pontederia crassipes* exhibit traits such as extensive root systems and high root hair density. These traits enable these species to provide essential ecosystem services, including erosion control, soil stabilization, and nutrient absorption. In addition to these services, they also offer wildlife habitat, food, and fodder. Aquatic macrophytes play a crucial role in wastewater treatment and the management of algal blooms by providing essential ecosystem services. The provisioning services they offer include direct benefits such as nutrient removal and biomass production, which significantly improve water quality and create habitats for aquatic organisms. For example, *Azolla pinnata* excels in nutrient uptake and pollutant absorption (Rai, 2008), while *Lemna perpusilla* rapidly absorbs nutrients, effectively mitigating eutrophication (Vymazal, 2007). Additionally, regulating services are evident in how these species help to maintain ecological balance. *Hydrilla verticillata*, with its high root hair density that increases surface area, is particularly effective in treating nutrient-rich wastewater (Dhir, 2013), and *Pontederia crassipes* contributes high biomass production that aids in pollutant absorption (Raven et al., 2005). Furthermore, *Spirodela polyrhiza* supports nutrient cycling and overall ecosystem health through its rapid nutrient uptake (Cronk and Fennessy, 2016). Collectively, these species not only enhance water quality but also foster biodiversity within aquatic ecosystems. Similarly, *Potamogeton crispus*, *Hydrilla verticillata* also provides habitat and food resources for various aquatic organisms. In terms of provisioning services, species like *Azolla pinnata*, *Lemna perpusilla*, *Pistia stratiotes*, and *Spirodela polyrhiza* are utilized as animal feed and biofertilizers, promoting agricultural sustainability. Furthermore, *Nymphoides hydrophyllum*, *Marsilea minuta* and *Ipomoea aquatica* serve as fodder for livestock, with *M. minuta* and *Ipomoea aquatica* also being consumed as a vegetable. Traditional medicinal practices utilize plants such as *M. minuta* and *Bacopa monnieri* for their therapeutic properties. Additionally, *Trapa natans* var. *bispinosa* produces edible seeds that are valuable for both human diets and traditional medicine.

Conclusion

This pioneering study in the Eastern Ranchi District of Jharkhand, India, identified 78 macrophyte species across seven wetlands (W1-W7), revealing a predominance of

emergent species (69%) and underscoring the richness of these ecosystems. The analysis documented nine rare species and 21 key species that contribute significantly to essential ecosystem services like soil stabilization and water quality improvement. High-frequency species such as *Pontederia crassipes* (85.71% in W1) and *Hydrilla verticillata* (57.14% in W1) demonstrated resilience across diverse habitats, while low-frequency species like *Acmella paniculata* (14.29% in W1) were limited to specific areas due to habitat sensitivity. Raunkiaer's frequency analysis indicated a dominance of Class B species in most wetlands, particularly W1 (64.52%), while W2 exhibited signs of disturbance with a higher proportion of Class A species (52%) and fewer in Classes C and E. Wetland W7 had the highest biodiversity ($H' = 3.4968$) and richness ($DMg = 5.08069$), while W2 had the lowest values, and Wetland W6 showed the highest evenness ($J' = 0.96965$), indicating ecological stability. Intermediate IVI species dominated most wetlands (58–77%), with *Pontederia crassipes* (IVI = 20.72) prominent in W1, and *Acmella paniculata* (IVI = 3.12) less so. This study provides essential baseline data for developing targeted conservation strategies to address ecological stress in urban wetlands (W1, W2, and W5). It emphasizes the crucial role of macrophytes in sustaining ecosystem services, highlighting their importance for wetland conservation and biodiversity management.

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Author's contributions

Conceptualization, S.G.; methodology, J.M.; data curation, J.M.; formal analysis, J.M.; manuscript preparation—original draft preparation, J.M.; supervision, S.G.; visualization, S.G.; writing—review and editing, S.G. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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