

Emphasizes macrophyte diversity as a tool for bioindication of Wetland Health: Insights from Ichhapore and Tena Wetlands, Surat District, Gujarat, India.

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Abstract:

Wetlands within the Surat District are integral to the preservation of ecological equilibrium, facilitating fisheries, agricultural activities, and the replenishment of groundwater resources; however, these vital ecosystems are increasingly imperiled by industrial effluents, urban runoff, and modifications in land use practices. This research endeavor sought to elucidate the aquatic macrophyte species that could function as ecological indicators pertinent to the conservation and management of wetland environments. Field assessments conducted across sites exhibiting diverse levels of anthropogenic impact demonstrated that species such as *Hydrilla verticillata*, *Eichhornia crassipes*, and *Nymphaea nouchali* predominated in conditions characterized by nutrient enrichment and eutrophication. The results substantiate that fluctuations in water quality exert a significant influence on macrophyte diversity and distribution, with rooted-floating and submerged species serving as dependable bioindicators of wetland ecological health. The research highlights the imperative for comprehensive management strategies that encompass pollution mitigation, restoration of indigenous vegetation, and active community engagement to preserve the ecological integrity and ecosystem services inherent to the wetlands of Surat.

Keywords: Biodiversity, Physico-chemical parameters, Vegetation, Ecology, Eutrophication, Anthropogenic pressure

1.Introduction

Wetlands represent one of the most productive and ecologically significant ecosystems on Earth. Acting as transitional zones between terrestrial and aquatic environments, they exhibit unique hydrological and biological characteristics that support a wide range of plant and animal life. These ecosystems provide numerous services, including water purification, flood mitigation, soil stabilization, groundwater recharge, and the supply of food, fuel, and raw materials essential for human livelihoods (Ramchandra et al., 2012).

In the context of ecological transitions, wetlands function as ecotones—neither fully terrestrial nor entirely aquatic—allowing them to adapt to seasonal variations and support both aquatic and semi-aquatic organisms (Sonowal et al., 2017). Among the biotic components of wetlands, aquatic macrophytes (hydrophytes) play a central role in maintaining ecosystem structure and function. These plants, adapted to grow in waterlogged conditions, influence the physicochemical properties of water, contribute to primary productivity, and provide habitat and food for various aquatic organisms.

Macrophytes occur in diverse morphological forms, including submerged, free-floating, rooted-floating, marshy, and amphibious types, each with distinct ecological functions (Khaparde et al., 2018). Their presence and abundance are closely linked to water quality parameters such as nutrient concentrations, pH, dissolved oxygen, and turbidity. As such, macrophytes are increasingly recognized as reliable bioindicators for assessing aquatic ecosystem health.

The aquatic environment supported by macrophyte diversity is vital to human needs, offering resources for agriculture, biofertilizers, energy production, industrial applications, and medicinal compounds (Patel et al., 2023). However, anthropogenic pressures—such as pollution, land-use change, and over-exploitation of wetland resources—have led to degradation of water quality and loss of biodiversity. These impacts manifest in ecological disturbances like algal blooms, fish mortality, and altered sensory characteristics of water (Barman et al., 2015).

Given the ecological importance of macrophytes and the threats facing wetland ecosystems, it is imperative to monitor and evaluate the relationship between aquatic vegetation and water quality. This study focuses on selected wetlands in Surat District, Gujarat, aiming to document macrophyte diversity and assess their role in water quality evaluation. By establishing correlations between plant assemblages and physicochemical parameters, the research seeks to contribute to informed conservation strategies and sustainable wetland management. The diversity and composition of aquatic macrophytes exhibit significant variations in response to alterations in water quality parameters, thereby rendering certain macrophyte groups as dependable bioindicators of wetland ecological integrity.

The study's conclusions highlight the critical function of aquatic macrophytes as organic markers of wetland health. The diversity and distribution of macrophytes in Surat District's wetlands show how sensitively these plant communities react to variations in water quality parameters like organic load, dissolved oxygen, and nutrient concentration. The findings of the study also directly affect conservation planning and wetland management. Targeted restoration initiatives, such as reintroducing native macrophytes to degraded areas or regulating nutrient-enriching activities, can be guided by an understanding of how species composition reflects environmental quality. All things considered, the study demonstrates that maintaining aquatic macrophyte variety is crucial for sustaining the functions of wetland ecosystems and also acts as a trustworthy instrument for monitoring environmental changes and directing evidence-based management decisions.

Objectives of the Research

The present study aims to record and examine the distribution and variety of aquatic macrophytes in a few chosen wetlands in Gujarat's Surat District. It further seeks to group macrophyte species that have been observed according to their ecological traits and growth styles. In addition, the study aims to evaluate the general water quality and the physicochemical characteristics of wetland water. Another objective is to investigate the connection between water quality indicators and macrophyte diversity. Finally, the study intends to find possible macrophyte species or groups that can be used as trustworthy bioindicators of the ecological status and health of wetland areas.

1.1 Study sites description

1.1.1 Site 1: Ichhapore Wetland

Ichhapore (Latitude 21.191772, Longitude 72.733135) is a semi-urban locality in the Surat District of Gujarat, India, situated within a tropical climate zone characterized by high humidity and elevated temperatures, particularly during the pre-monsoon months (March to May). The region experiences seasonal rainfall during the southwest monsoon, which significantly influences wetland hydrology and biological productivity.

The Ichhapore Wetland (Figure 1), located near Bhatha Gam, represents a dynamic freshwater ecosystem embedded within a rapidly urbanizing landscape. (Figure 1) This wetland functions as a critical ecological niche, supporting a rich diversity of macrophytes, planktonic organisms, avifauna, and amphibians. The presence of varied hydrophyte forms—including submerged, floating, and emergent species—indicates a complex trophic structure and high primary productivity. These plants play a vital role in nutrient cycling, sediment stabilization, and water filtration, thereby enhancing the wetland's self-purification capacity.

Ichhapore Wetland also serves as a seasonal refuge for migratory birds and supports breeding grounds for native fish species. Its ecotonal nature—situated between terrestrial and aquatic systems—facilitates biotic exchange and contributes to landscape-level biodiversity. However, increasing anthropogenic pressures such as urban runoff, encroachment, and waste discharge pose threats to its ecological integrity. The wetland's proximity to residential zones underscores the need for integrated conservation strategies that balance ecological preservation with sustainable urban development.

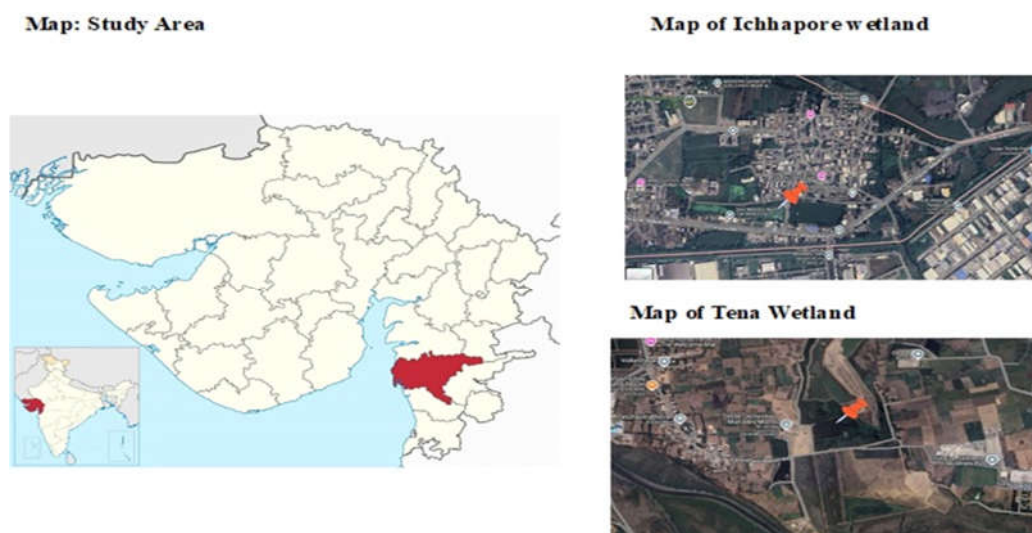
1.1.2 Site 2: Tena Wetland

Tena village (Latitude 21.226969 and Longitude 72.675756) is located on the western periphery of Surat District, approximately 15–16 kilometres from the city center. The Tena Wetlands (Figure 1) span an estimated 4 square kilometres and exhibit a shallow basin morphology, with a maximum depth of approximately 2 meters (Figure 1). These wetlands are predominantly monsoon-fed, with hydrological retention lasting 7–8 months annually. Seasonal desiccation occurs during the late summer months, leading to temporal shifts in habitat availability and species composition.

Ecologically, the Tena Wetlands support a mosaic of aquatic vegetation, including marshy and amphibious macrophytes that are well-adapted to fluctuating water levels. The wetland's hydroperiod influences the life cycles of various aquatic organisms, including macroinvertebrates, amphibians, and waterfowl. The presence of nutrient-tolerant species suggests moderate eutrophication, likely driven by agricultural runoff and domestic use.

The wetland plays a multifunctional role in the local socio-ecological system. It provides water for irrigation, livestock consumption, and domestic washing, although it is not utilized for potable purposes due to concerns over water quality. The surrounding agricultural fields benefit from the wetland's groundwater recharge and nutrient-rich sediments. However, unregulated use and lack of formal management have led to habitat fragmentation and declining biodiversity.

From an ecological standpoint, the Tena Wetlands represent a vulnerable yet valuable freshwater resource. Their seasonal dynamics and community dependence highlight the importance of participatory conservation approaches, ecological monitoring, and restoration initiatives to safeguard their long-term functionality.



*Source: www.googleearth.com

Figure 1. Study area (*source: www.googleearth.com)

2. Materials and Methods:

Study area

The current study was carried out in Gujarat's Surat District, namely in the wetland areas of Ichhapore and Tena. The ecological relevance and diversity of environmental variables that led to the selection of these wetlands.

Fieldwork and design of sampling

In order to conduct a thorough floristic survey of aquatic and wetland plants, fieldwork was conducted from January to December 2024, with monthly visits to the study areas. Plant variety and environmental features were documented through observations made during each visit.

Plant identification

Using a high-resolution digital camera, 'canon 1300D' specimens of aquatic macrophytes were viewed and captured in situ to record their growth patterns and natural habitat. Carefully chosen specimens were gathered and preserved by being sandwiched between blotting sheets. Later, these conserved samples were taken to Sir P.T. Sarvajanik College of Science's Botany Department Laboratory in Surat for a thorough analysis. The Flora of Gujarat State (Shah et al., 1978) and (Thothathri, K., & Basak, R. K. et al., 2024) served as the main source of

information for the analysis of morphological traits and the identification of species down to the genus or species level.

Sampling and analysis of Water

Simultaneously, water samples were taken from specific locations within each wetland during the day using sterile plastic containers to avoid contamination. To evaluate the water quality, the samples were examined for a number of physicochemical characteristics. The laboratory conducted tests for electrical conductivity, biological oxygen demand (BOD), and chemical oxygen demand (COD). Other metrics were either manually measured or subjected to specialist testing at the Pollucon Laboratory.

Diversity index

To quantify species richness and evenness, the Shannon–Wiener Diversity Index (H') was applied: a widely used metric that captures both species richness and evenness within ecological communities.

$$H' = - \sum_{i=1}^S P_i \ln (X_i)$$

Where, S = total number of species, i = proportion of individuals belonging to species I , i provides a comprehensive measure of community structure (Magurran et al., 2004).

3.Result and Discussion:

3.1 Ecological indicators for Wetland wetland assessment

Evaluating the diversity of aquatic flora and the quality of water within both wetland ecosystems is paramount for ascertaining their ecological integrity. Among these, the Macrophyte diversity index, such as the Shannon–Wiener Index, provides a quantitative measure of species richness and evenness among aquatic plants, offering insight into habitat complexity and environmental health (Hellawell et al., 1986). Furthermore, the growth forms of macrophytes—including submerged, floating, emergent, and amphibious types—serve as indicators of hydrological conditions, water depth, and nutrient status. For instance, dominance of emergent and amphibious forms may indicate fluctuating water levels or anthropogenic disturbance (Squires & van der Valk et al., 1992). The presence of specific indicator species, such as *Eichhornia crassipes*, *Typha* sp., and *Hydrilla verticillata*, can signal the trophic status of wetlands; for example, *Eichhornia crassipes* and *Hydrilla verticillata* are often associated with nutrient enrichment and eutrophic conditions, while their absence might suggest oligotrophic or less disturbed environments (Mukherjee et al., 2015).

Similarly, shifts in phytoplankton and zooplankton composition reflect changes in nutrient loading and ecosystem productivity. High biomass of cyanobacteria or dominance of small-bodied zooplankton can be symptomatic of eutrophication and poor water quality (Jeppesen et al., 2000). In addition, avifaunal diversity, including species richness and nesting behavior of birds, serves as a sensitive indicator of wetland functionality and habitat quality. According to Gibbs, (2000) and Ma (2010) Bird assemblages respond quickly to changes in vegetation structure, water levels, and food availability, making them reliable bioindicators for long-term monitoring. Together, these biological indicators offer a comprehensive understanding of ecological dynamics and are critical for the conservation and management of wetland ecosystems. Macrophytes serve as biotic indicators of pollution levels, whereas various parameters, including pH, dissolved oxygen, and turbidity, provide insight into the wetland's capacity to support aquatic biodiversity. This knowledge is also advantageous for adjacent

communities that depend on the wetlands for activities such as fishing, agriculture, and the collection of plant materials.

In the Tena wetland (Site-1), *Typha angustifolia* and *Eichhornia* were the predominant species along the peripheral margins. Water quality parameters—including pH, temperature, total dissolved solids (TDS), alkalinity, hardness, phosphate, free CO₂, chloride, turbidity, conductivity, chemical oxygen demand (COD), and biochemical oxygen demand (BOD)—were systematically analyzed in accordance with the methodologies established by the American Public Health Association (APHA) and the Indian Standards (IS). The findings revealed significant disparities between Ichhapore (Site-1) and Tena (Site-2). Both sites exhibited elevated levels of TDS and chloride, indicative of significant concentrations of dissolved salts and contaminants. The moderately high hardness levels suggest a heightened presence of calcium and magnesium ions. Phosphate concentrations were notably high at Site-1 (3.93 mg/L), indicating a potential risk for eutrophication, while at Site-2, the levels were substantially lower (0.648 mg/L).

3.2 Physicochemical indicators

These parameters are essential for evaluating water quality and its influence on aquatic biodiversity, especially macrophyte distribution and health. (Table-1).

Table – 1 Ecological relevance of wetland physico-chemical parameters

Parameter	Ecological Relevance
pH	Affects nutrient solubility, microbial activity, and species tolerance; extreme pH can stress aquatic life.
Temperature	Influences metabolic rates, dissolved oxygen levels, and seasonal species composition.
Total Dissolved Solids (TDS)	Indicates the concentration of dissolved ions; high TDS can affect osmoregulation in aquatic organisms.
Alkalinity	Reflects the buffering capacity of water; helps stabilize pH and supports biological processes.
Total Hardness	Measures calcium and magnesium levels; influences macrophyte growth and water chemistry.
Phosphate (PO₄³⁻)	A key nutrient; elevated levels can lead to eutrophication and algal blooms.
Free Carbon Dioxide (CO₂)	Affects pH and photosynthetic activity; excess CO ₂ may indicate organic pollution.
Chloride (Cl⁻)	High levels may signal contamination from domestic or industrial sources.
Turbidity	Reduces light penetration, affecting photosynthesis and macrophyte productivity.
Electrical Conductivity (EC)	Indicates total ionic concentration; useful for detecting salinity and pollution levels.
Chemical Oxygen Demand (COD)	Measures the amount of oxidizable organic and inorganic matter; high COD suggests pollution.
Biochemical Oxygen Demand (BOD)	Reflects the oxygen required by microbes to decompose organic matter; elevated BOD indicates organic pollution.

These indicators, when analysed collectively, provide a robust framework for assessing the ecological health of wetlands and their suitability for sustaining diverse macrophyte communities.

3.3 Habitat and landscape indicators

Habitat and landscape indicators are crucial for evaluating the structural and spatial dynamics of wetland ecosystems, which directly influence ecological functions and biodiversity. One key indicator is the hydroperiod, which refers to the duration, timing, and frequency of water presence in a wetland. According to Mitsch & Gosselink (2015) variable governs the establishment, survival, and reproductive cycles of both plant and animal species, thereby controlling ecosystem productivity and species composition. For instance, wetlands with prolonged inundation typically support hydrophytic vegetation and aquatic organisms adapted to saturated conditions, while seasonal wetlands favour species with greater tolerance to moisture fluctuations.

Another essential indicator is, as per Reddy & DeLaune (2008), sediment composition, including its organic matter content, texture, and nutrient status. Sediment characteristics play a pivotal role in determining the growth of wetland vegetation and microbial processes such as decomposition and nutrient cycling. High levels of organic matter and fine-textured soils enhance water retention and nutrient availability, creating favorable conditions for diverse plant communities and microbial activity.

Vegetation zonation, or the spatial distribution of plant communities along moisture and elevation gradients, further reflects the interplay of hydrological and edaphic factors. Zonation patterns provide insight into hydrological regimes and can serve as visual indicators of ecological succession, disturbance, and habitat heterogeneity (Keddy et al., 2010). For example, emergent macrophytes often dominate wetter zones, while shrubs and grasses may thrive in intermittently flooded or higher-elevation areas. Collectively, these habitat and landscape indicators provide a comprehensive understanding of wetland structure, functioning, and resilience. (Table - 2,3,5)

3.4 Anthropogenic pressure indicators

Anthropogenic pressure indicators are essential for assessing the extent of human influence on wetlands and their long-term sustainability. One such indicator is resource use patterns, which include activities like water extraction, livestock grazing, washing, and fishing. These practices, when unregulated, can lead to habitat degradation, altered hydrology, and declining biodiversity (Turner et al., 2000). Overextraction of water for agriculture or domestic use, for instance, can reduce wetland inundation periods, affecting species reliant on sustained moisture regimes.

Another significant indicator is the presence of pollution sources, both point (e.g., industrial discharge, sewage) and non-point (e.g., agricultural runoff, stormwater).

These inputs introduce nutrients, pathogens, and toxins that degrade water quality, promote eutrophication, and alter species composition (Carpenter et al., 1998). In many wetland systems, nutrient loading from nearby agricultural fields has been linked to algal blooms and the proliferation of opportunistic plant species.

Invasive species presence is also a critical indicator of anthropogenic stress. Non-native plants such as *Eichhornia crassipes* (water hyacinth) and *Salvinia molesta* can rapidly colonize wetland surfaces, obstructing sunlight, reducing oxygen levels, impeding water flow,

and outcompeting native vegetation (Villamagna & Murphy et al., 2010). Their spread is often exacerbated by nutrient-rich conditions resulting from human-induced pollution.

Lastly, understanding community perception and dependence through socio-ecological surveys provides valuable insights into how local populations use and value wetland resources. These surveys help assess community reliance on ecosystem services (e.g., fishing, fodder, water) and attitudes toward conservation, which are vital for the success of participatory management strategies (Pretty et al., 2003). Community engagement and stewardship are increasingly recognized as key components of sustainable wetland management.

Table- 2 List of plants from Site-1 Ichhapore wetland

No.	Botanical name	Family	IUCN Status	Habitat	Local name
1	<i>Pithecellobium dulce</i> (Roxb.) Benth.	Fabaceae	LC	Tree	Vilayati Ambli
2	<i>Leucaena leucocephala</i> (Lam.) de Wit	Fabaceae	LC	Tree/ Shrub	Liso baval/ Subaval
3	<i>Neltuma laevigata</i> (Humb. & Bonpl. ex Willd.) Britton & Rose	Fabaceae	LC	Tree	Smooth mesquite
4	<i>Samanea saman</i> (Jacq.) Merr.	Fabaceae	LC	Tree	Shirish
5	<i>Albizia lebbeck</i> (L.) Benth.	Fabaceae	LC	Tree	Saras/ Shirish
6	<i>Urochloa mutica</i> (Forssk.) T.Q.Nguyen	Poaceae	LC	Grass	Buffalo grass
7	<i>Chloris virgata</i> Sw.	Poaceae	G5	Grass	Feather finger grass
8	<i>Setaria viridis</i> (L.) P. Beauv.	Poaceae	LC	Grass	Kang
9	<i>Abutilon indicum</i> (L.) Sweet	Malvaceae	LC	Herb	Kansaki
10	<i>Urena Sinuata</i> L.	Malvaceae	LC	Herb	Vagadau Bhindo
11	<i>Grewia asiatica</i> L.	Malvaceae	LC	Shrub	Phalsa
12	<i>Ipomea aquatica</i> (Forssk.)	Convolvulaceae	LC	Herb	Nali ni Bhaji
13	<i>Calystegia sylvatica</i> R.Br.	Convolvulaceae	LC	Climber	Large bindweed
14	<i>Euphorbia hirta</i> L.	Euphorbeaceae	LC	Herb	Dudheli
15	<i>Ricinus</i> sp. L.	Euphorbeaceae	LC	Shrub	Castor
16	<i>Parthenium histerophorus</i> L.	Asteraceae	LC	Herb	Gajar ghas
17	<i>Cyanthillium cinereum</i> (L.) H. Rob.	Asteraceae	LC	Herb	Sadori
18	<i>Pistia stratiotes</i> L.	Araceae	LC	Aquatic herb	Jalkumbhi
19	<i>Portulaca oleracea</i> L.	Portulacaceae	LC	Herb	Luni
20	<i>Amaranthus deflexus</i> (L)	Amaranthaceae	LC	Herb	Dambho

21	<i>Sabal minor</i> (Jacq.) Pers.	Arecaceae	LC	Palm	Dwarf palmetto
22	<i>Typha</i> sp.	Typhaceae	LC	Aquatic herb	Ghabajariu
23	<i>Syzygium cumini</i> (L.) Skeels	Myrtaceae	LC	Tree	Jambu
24	<i>Quercus humboldtii</i> (Bonpl.)	Fagaceae	LC	Tree	Andean oak
25	<i>Musa basjoo</i> (Siebold)	Musaceae	LC	Herb	Japanese banana
26	<i>Datura stramonium</i> L.	Solanaceae	LC	Herb	Dhaturo
27	<i>Melothria scabra</i> (L.) Cogn.	Cucurbitaceae	LC	Climber	Cuca melon
28	<i>Sinapis arvensis</i> L.	Brassicaceae	LC	Herb	Khetri
29	<i>Phyllanthus urinaria</i> L.	Phyllanthaceae	LC	Herb	Bho-amli
30	<i>Cordylanthus ramosus</i> (L.) Benth.	Orobanchaceae	LC	Herb	Birds' beak
31	<i>Cordia myxa</i> L.	Boraginaceae	LC	Tree	Gunda
32	<i>Ziziphus nummularia</i> (Burm.f.) Wight & Arn.	Rhamnaceae	LC	Shrub	Chani-bor
33	<i>Lantana camara</i> L.	Verbenaceae	LC	Shrub	Tantani/ Ghaneri
34	<i>Tabebuia pallida</i> (Lindl.) Miers	Bignoniaceae	LC	Tree	Gulabi Pailu

LC- Least Concern G5- Global Rank indicating secure status

Table -3 List of plants from Site-2 Tena wetland

No.	Botanical name	Family	IUCN Status	Habitat	Local name
1	<i>Alternanthera philoxeroides</i> (Mart.) Griseb.	Amaranthaceae	LC	Herb	Alligator weed
2	<i>Suaeda nigra</i> (Raf.) J.F. Macbr.	Amaranthaceae	LC	Herb	amudra bhus
3	<i>Amaranthus spinosus</i> L.	Amaranthaceae	LC	Herb	Spiny amaranth
4	<i>Mimosa pudica</i> L.	Fabaceae	LC	Herb	Lajamani
5	<i>Abrus precatorious</i> L.	Fabaceae	LC	Shrub	Chanothi
6	<i>Neltuma juliflora</i> (Sw.) Raf.	Fabaceae	LC	Tree	Gando baval
7	<i>Bolboschoenus fluviatilis</i> (Torr.) Soják	Cyperaceae	LC	Herb	River bulrush
8	<i>Cyperus odoratus</i> L.	Cyperaceae	LC	Herb	Gandha
9	<i>Cyperus rotundus</i> L.	Cyperaceae	LC	Herb	Nagarmoth
10	<i>Azolla filiculoides</i> Lam.	Salviniaceae	LC	Herb	Water fern

11	<i>Azolla caroliniana</i> Forssk.	Salviniaceae	LC	Herb	Mosquito fern
12	<i>Ipomoea aquatica</i> Forssk.	Convolvulaceae	LC	Herb	Nali ni Bhaji
13	<i>Calystegia sylvatica</i> (L.) R.Br.	Convolvulaceae	LC	Herb	Greater bindweed
14	<i>Nymphaea rubra</i> Roxb.	Nymphaeaceae	LC	Herb	Poyna
15	<i>Nymphaea alba</i> L.	Nymphaeaceae	LC	Herb	Nilofar
16	<i>Typha orientalis</i> Presl.	Typhaceae	LC	Herb	Kumbhar
17	<i>Typha angustifolia</i> L.	Typhaceae	LC	Herb	Ghaabajariyu
18	<i>Chrysopogon zizanioides</i> (L.) Roberty	Poaceae	LC	Herb	khass
19	<i>Chloris virgata</i> Sw.	Poaceae	LC	Herb	Feather finger grass
20	<i>Lacuta serriola</i> L.	Asteraceae	LC	Herb	Kahu
21	<i>Blumea viscosa</i> (L.) Druce	Asteraceae	LC	Shrub	Blumea
22	<i>Oxystelma esculentum</i> (L.) R.Br.	Apocynaceae	LC	Herb	Jaldudhi
23	<i>Calotropis gigantia</i> (L.) W.T.Aiton	Apocynaceae	LC	Shrub	Aakado
24	<i>Solanum trilobatum</i> L.	Solanaceae	LC	Herb	Kankariya
25	<i>Datura stramonium</i> L.	Solanaceae	LC	Herb	Dhaturo
26	<i>Oscimum tenuiflorum</i> L.	Lamiaceae	LC	Herb	Tulsi
27	<i>Oscimum basilicum</i> L.	Lamiaceae	LC	Herb	Takmariya
28	<i>Pontederia crassipes</i> (Mart.) Solms	Pontederiaceae	LC	Herb	Jalkumbhi
29	<i>Momordica dioica</i> Roxb.	Cucurbitaceae	LC	Herb	Kantola
30	<i>Lemna minuta</i> Kunth.	Araceae	LC	Herb	Duck weed
31	<i>Tamarix chinensis</i> Lour.	Tamaricaceae	LC	Shrub	Chinese tamarisk
32	<i>Heliotropium curassavicum</i> L.	Boraginaceae	LC	Herb	Hathi sundhi
33	<i>Asparagus racemosus</i> Willd.	Asparagaceae	LC	Herb	Satavari
34	<i>Fallopia convolvulus</i> (L.) A.Löve & D.Löve	Polygonaceae	LC	Herb	Black bindweed

LC- Least Concern

3.5 Species richness and composition

A total of 68 hydrophyte species were recorded across the Ichhapore and Tena wetlands, reflecting a rich aquatic plant diversity within the study area. Interestingly, only five species were found to be common to both sites, highlighting the presence of distinct ecological niches and differing environmental conditions at each wetland. This low overlap suggests that

each site supports unique hydrological, edaphic, or anthropogenic factors influencing species composition. The Ichhapore Wetland (Site-1, Table- 2) supported 34 species belonging to 23 families, indicating a broader taxonomic spread. In comparison, the Tena Wetland (Site-2, Table-3) also hosted 34 species, but from only 19 families, suggesting possible dominance by a few plant families. This site-wise variation in family-level diversity further underscores the ecological uniqueness of each wetland system.

Table – 4 Dominant plant families of Ichhapore (site-1) and Tena (site-2)

Wetland	Dominant Families
Ichhapore	Fabaceae (notably dominant)
Tena	Amaranthaceae, Fabaceae, Cyperaceae

Fabaceae dominance at both sites suggests nitrogen-fixing potential, which can influence nutrient cycling.

Cyperaceae and Amaranthaceae in Tena indicate adaptation to saturated soils and nutrient-rich conditions.

3.6 Water quality assessment

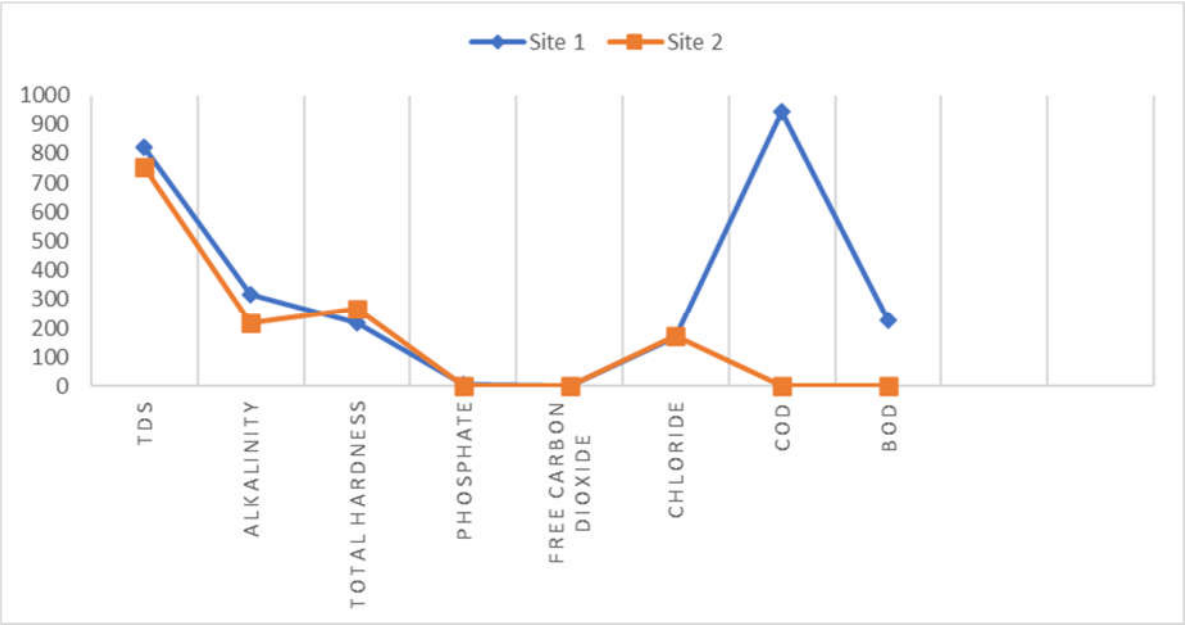


Figure 2 Water analysis of site-1 and site-2result

Table- 5 Physico- chemical parameters of site-1 and site-2 comparison.

Parameter	Ichhapore (site-1)	Tena (site-2)	Ecological implication
pH	7.42	7.96	Slightly alkaline; suitable for most aquatic plants
Temperature (°C)	30.0	29.9	Warm; enhances metabolic activity of aquatic life
TDS (mg/L)	823	756	High; indicates elevated dissolved solids
Alkalinity (mg/L)	316	220	Higher at Site-1; buffering capacity against pH changes

Total Hardness (mg/L)	220	268	Slightly higher at Site-2; affects aquatic species composition
Phosphate (mg/L)	3.93	0.648	Excessive at Site-1; potential eutrophication risk
Free CO ₂ (mg/L)	<0.1	<0.1	Low; minimal impact on pH
Chloride (mg/L)	167	171	High; may affect sensitive aquatic flora
Turbidity (NTU)	0.23	0.09	Low; indicates clear water, favorable for submerged plants
Conductivity (μS/cm)	1171	1075	High; correlates with TDS and ion concentration
COD (mg/L)	946	<5	Extremely high at Site-1; indicates organic pollution
BOD (mg/L)	228	<1	Very high at Site-1; suggests heavy organic load

3.7 Ecological role of macrophytes in water quality

Macrophytes play a crucial ecological role in maintaining and improving water quality through nutrient uptake, pollution mitigation, and habitat structuring in wetland ecosystems. In the Ichhapore Wetland (Site-1; Table-5), elevated Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) values indicate significant levels of organic pollution, likely from domestic or agricultural runoff. However, the presence of species such as *Pistia stratiotes*, *Ipomoea aquatica*, and *Typha* spp. suggests a natural potential for phytoremediation, as these plants are known for their capacity to absorb excess nutrients and organic matter (Zimmels et al., 2008; Rai et al., 2008). Additionally, members of the Fabaceae family, present in this site, contribute to nitrogen fixation, aiding in nutrient cycling; yet, excessive phosphate levels remain a concern, as they can promote algal blooms and further degrade water quality (Carpenter et al., 1998).

Conversely, the Tena Wetland (Site-2; Table-5) exhibits lower COD and BOD values, indicating relatively better water quality. The dominance of species from Cyperaceae and Amaranthaceae families reflects efficient nutrient uptake and sediment stabilization, crucial for maintaining ecosystem balance (Cronk & Fennessy et al., 2001). Moreover, the presence of small, fast-growing floating plants such as *Azolla*, *Lemna*, and *Pontederia* enhances nutrient absorption and assists in surface water purification, functioning as natural biofilters that limit nutrient loading and suppress harmful algal growth (Sood et al., 2012).

Beyond water quality improvement, macrophytes provide essential habitat structuring by offering shelter, breeding grounds, and food sources for a wide range of aquatic fauna. The diversity and structural complexity of macrophyte communities enhance ecosystem resilience, supporting multiple trophic levels and stabilizing ecological functions in the face of environmental disturbances (Keddy et al., 2010).

In summary, while both wetlands share equal species richness, they differ in family composition and functional roles. The Ichhapore Wetland reflects signs of organic pollution, potentially mitigated by the activity of native macrophytes, whereas the Tena Wetland maintains higher ecological integrity, supported by a functionally diverse plant community (Figure 2).

3.7.1 Ecological Role of Macrophytes

The dominance of Fabaceae in Ichhapore suggests nitrogen-fixing potential, which may influence nutrient dynamics. However, elevated phosphate, COD, and BOD levels indicate organic pollution, potentially mitigated by species such as *Pistia stratiotes*, *Ipomoea aquatica*, and *Typha* spp., known for their phytoremediation capabilities (Reddy & D'Angelo et al., 1997).

In contrast, Tena wetland exhibited better water quality, supported by diverse families like Cyperaceae and Amaranthaceae. The presence of *Azolla*, *Lemna*, and *Pontederia* species contributes to nutrient absorption and surface water purification (Zhao et al., 2015).

3.7.2 Biodiversity and Ecosystem Function

Macrophyte diversity enhances habitat complexity, supports aquatic fauna, and stabilizes sediments. The distinct species composition between sites reflects localized environmental conditions and anthropogenic pressures. The diversity of macrophytes contributes significantly to habitat complexity, facilitates the sustenance of aquatic fauna, and aids in the stabilization of sediments. The disparities in species composition among various sites are indicative of localized environmental conditions and differing levels of anthropogenic impact. Within aquatic ecosystems, macrophytes fulfill an essential ecological function. Nonetheless, in certain locations, prevalent species such as *Typha* sp. and *Pontederia crassipes* extensively dominate the water surface, thereby restricting the penetration of sunlight into the aquatic environment. This attenuation of light results in diminished oxygen availability, which subsequently precipitates a decline in zooplankton populations and other aquatic organisms. Such conditions adversely influence aquatic fauna by fostering the process of eutrophication. Conversely, particular wetlands characterized by mesotrophic conditions demonstrate elevated productivity and sustain a well-balanced ecosystem. Consequently, the growth of macrophytes necessitates careful management to mitigate ecological detriment and uphold the integrity of healthy aquatic environments (Bhanja et al., 2023).

3.7.3 Biological Indicators of Ecosystem Integrity

Biological indicators offer a robust framework for assessing the ecological health and biodiversity of wetland ecosystems. Aquatic macrophytes, in particular, serve as sensitive bioindicators due to their direct interaction with water chemistry, sediment dynamics, and hydrological regimes (Carpenter & Lodge et al., 1986; Birk et al., 2012).

3.8 Macrophyte diversity index

The Shannon–Wiener Diversity Index (H'), a popular statistic that measures both facets of biodiversity within biological groups, was employed to evaluate species richness and evenness. The index can be written as follows $H' = -\sum_{i=1}^S p_i \ln(p_i)$ where p_i is the percentage of individuals that belong to species i and S is the total number of species (Magurran et al., 2004). A total of 34 species, belonging to 23 groups, were identified at the Ichhapore Wetland (Site 1). With an estimated Shannon–Wiener index (H') of roughly 3.12, which reflects moderate species diversity, the dominance of the Fabaceae family suggests moderate evenness throughout the community. On the other hand, the Tena Wetland (Site-2) had a more evenly distributed distribution among families, supporting 34 species but

distributing them across 19 families. In comparison to Ichhapore, the estimated H' value of 3.36 indicates somewhat greater variety and evenness, suggesting a more stable and well-organized macrophyte community. In the Ichhapore Wetland (Site -1), a total of 34 macrophyte species belonging to 23 families were recorded. The dominance of the Fabaceae family, a group known for nitrogen-fixing species, indicates a somewhat moderate level of evenness, with some species likely more abundant than others. The estimated H' value of approximately 3.12 suggests moderate species diversity, reflecting a reasonably balanced but not entirely even community structure (Table -5). In contrast, the Tena Wetland (Site-2) also recorded 34 species, but from only 19 families, implying a slightly narrower taxonomic spread. However, species were more evenly distributed across families, contributing to an estimated H' value of 3.36, which indicates slightly higher diversity and evenness than Ichhapore. This suggests that the Tena wetland supports a more ecologically balanced macrophyte community, likely due to more stable environmental conditions and fewer dominant taxa. Overall, both wetlands demonstrate significant macrophyte diversity, but the Tena Wetland exhibits a more even and balanced community structure, indicative of a healthier and more resilient aquatic ecosystem. These findings align with established ecological theory, which links high diversity and evenness to greater ecosystem stability and functional redundancy (Whittaker et al., 1972; Pielou et al., 1975).

Table -6 Calculated Shannon–Wiener index.:

Wetland Site	Species Count (S)	Estimated $H' = \ln(S)$
Ichhapore	34	≈ 3.526
Tena	34	≈ 3.526

3.9 Macrophyte growth forms

The structural diversity of macrophytes—submerged, floating, emergent, and amphibious—provides insights into hydrological and nutrient conditions (Lacoul & Freedman et al., 2006) (Table -7). A variety of development types are displayed by the macrophyte communities in the Ichhapore and Tena wetlands, each of which reflects particular ecological circumstances. Stable water depth and regular submersion zones are indicated by submerged species like *Hydrilla verticillata* in Tena and *Urochloa mutica* and *Setaria viridis* in Ichhapore. Typically, nutrient-rich waters are linked to floating species, such as *Pistia stratiotes* in Ichhapore and *Azolla* spp. and *Lemna minuta* in Tena, indicating increased organic inputs and eutrophic conditions. The shallow margins are dominated by emerging macrophytes, such as *Typha* spp. and *Ipomoea aquatica* in Ichhapore and *Typha* spp. and *Pontederia crassipes* in Tena, which help stabilize the sediment and provide home for aquatic life. In contrast, amphibious species that can adapt to changing water levels, such *Alternanthera philoxeroides* and *Blumea viscosa* in Tena and *Amaranthus deflexus* and *Parthenium hysterophorus* in Ichhapore, thrive in regions that fluctuate between wet and dry periods. The distribution of various growth forms as a whole illustrates the hydrological dynamics and ecological heterogeneity of both wetlands. (Table-7).

Table -7 Macrophyte growth forms of site-1 and site-2

Growth form	Representative species (Ichhapore)	Representative species (Tena)	Ecological implication
Submerged	<i>Urochloa mutica</i> , <i>Setaria viridis</i>	<i>Hydrilla verticillata</i> (if present)	Indicates stable water depth

Floating	<i>Pistia stratiotes</i>	<i>Azolla</i> spp., <i>Lemna minuta</i>	Associated with nutrient-rich waters
Emergent	<i>Typha</i> spp., <i>Ipomoea aquatica</i>	<i>Typha</i> spp., <i>Pontederia crassipes</i>	Reflects shallow margins and sediment stability
Amphibious	<i>Amaranthus deflexus</i> , <i>Parthenium hysterophorus</i>	<i>Alternanthera philoxeroides</i> , <i>Blumea viscosa</i>	Adapted to fluctuating water levels

The presence of all four growth forms in both wetlands suggests hydrological heterogeneity and ecological resilience.

Macrophyte Growth Form Distribution across Ichhapore and Tena wetlands.

Table -8 Growth form distribution.

Growth Form	Ichhapore	Tena
Submerged	4	5
Floating	3	6
Emergent	8	9
Amphibious	19	14

The distribution of macrophyte growth types in the Ichhapore and Tena wetlands is shown in Table 8. According to the data, both locations sustain a wide variety of growth forms, which is indicative of their ecological heterogeneity and habitat circumstances. With 19 species identified, amphibious species dominated Ichhapore, followed by emergent (8), submerged (4), and floating (3) forms. The prevalence of amphibious macrophytes in Ichhapore indicates a high degree of habitat variety and varying water levels. The Tena wetland, on the other hand, had a somewhat more evenly distributed distribution, with six floating, nine emergent, five submerged, and fourteen amphibious species. At Tena, there are more floating and submerged species, which suggests more stable hydrological conditions and better water quality, which support a wider variety of aquatic plants. Overall, these findings demonstrate that the two wetlands have different biological traits, with Tena displaying more stable aquatic conditions and Ichhapore demonstrating a greater terrestrial effect.

3.10 Indicator species

Certain macrophytes are known to signal specific environmental conditions. The ecological value of the Ichhapore and Tena wetlands is shown by the examination of their indicator species. *Typha* species are found in both locations and exhibit resistance to both disturbed and eutrophic environments. While *Pontederia crassipes* and *Azolla* spp., which are found in Tena, suggest high nutrient loads and nitrogen-rich environments, respectively, *Pistia stratiotes*, which is found in Ichhapore, indicates nutrient enrichment and organic pollution. Given that *Ipomoea aquatica* is found in both wetlands and is frequently linked to slow-moving, nutrient-rich waters, the two locations may have different nutrient dynamics and water quality.

Table -9 Species and ecological interpretation.

Indicator species	Wetland presence	Ecological interpretation
<i>Typha</i> spp.	Both sites	Tolerant of eutrophic and disturbed conditions

<i>Pistia stratiotes</i>	Ichhapore	Indicates nutrient enrichment and organic pollution
<i>Pontederia crassipes</i>	Tena	Associated with eutrophication and high nutrient loads
<i>Azolla spp.</i>	Tena	Suggests nitrogen-rich conditions
<i>Ipomoea aquatica</i>	Both sites	Common in nutrient-rich, slow-moving waters

The dominance of *Typha* spp. and *Pistia stratiotes* in Ichhapore aligns with high COD and BOD values, indicating organic pollution and eutrophication. In contrast, Tena's presence of *Azolla*, *Pontederia*, and *Lemna* reflects nutrient uptake potential and better water quality (Table-9).

4. Conclusions

The investigation highlights the essential function of aquatic macrophytes in the regulation of water quality and the maintenance of ecological equilibrium within wetland ecosystems. The Ichhapore wetland demonstrates indications of organic contamination, in contrast, the Tena wetland exhibits comparatively healthier environmental conditions, likely attributable to its diverse and functional assemblage of macrophytes. Both wetlands are characterized by a significant species richness, with 34 species documented at each location; nevertheless, variations in familial composition, species dominance, and diversity indices reveal distinct ecological interactions. The values of the Shannon–Wiener Diversity Index—3.12 for Ichhapore and 3.36 for Tena—suggest moderate levels of diversity in Ichhapore and a marginally higher evenness in Tena, implying a more stable and resilient habitat under reduced anthropogenic stress. These results underscore the imperative for targeted conservation initiatives within comprehensive ecological management paradigms: enhancing phytoremediation and nutrient regulation in Ichhapore, while emphasizing preservation, monitoring, and resilience enhancement in Tena. Therefore, the maintenance of macrophyte diversity and evenness is crucial for the promotion of wetland health, the provision of ecosystem services, and the assurance of long-term ecological sustainability.

Recommendations include:

For Ichhapore, it is imperative to systematically assess the inflow of nutrients and the origins of organic waste. Strategic management interventions should prioritize the intentional incorporation of nutrient-absorbing macrophytes to enhance the phytoremediation capabilities of the wetland.

For Tena, the conservation of the extant vegetation and the reduction of anthropogenic disturbances are of paramount importance, while concurrently utilizing this location as a reference point for the rehabilitation of more severely degraded wetland ecosystems.

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Data availability

Data will be available upon request from the corresponding author.

Informed consent statement

No informed consent was required to conduct the study.

Conflict of interest

The authors declare no conflict of interest.

Authors' contribution**Conceptualization, methodology, data curation, formal analysis, writing original draft:**

Mamta Gajre, Anjali Varshney and Hitesh Solanki; Data collection: Mamta Gajre; Data analysis: Mamta Gajre, Anjali Varshney and Hitesh Solanki; Figure preparation and supervision Mamta Gajre, Anjali Varshney and Hitesh Solanki. All authors critically reviewed the manuscript and agreed to submit final version of the manuscript.

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