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# Diversity of aquatic and riparian macrophytes in oxbow streams of the upper Bengawan Solo River, Central Java, Indonesia

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**Abstract.** *Rahmawati D, Zahrani D, Naafi DA, Putri DS, Safira RN, Dewangga A, Setyawan AD. 2025. Diversity of aquatic and riparian macrophytes in oxbow streams of the upper Bengawan Solo River, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 28-39.* Oxbow streams represent dynamic transitional habitats that support diverse aquatic and riparian plant communities. This study investigates the diversity and ecological structure of aquatic and riparian macrophytes in three oxbow streams of the upper Bengawan Solo River, Central Java, Indonesia. A total of 45 species representing 25 families were identified, dominated by amphibious and riparian life forms. Species richness and life form composition varied across sites, reflecting differences in hydrology and habitat heterogeneity. Diversity indices showed the highest richness and evenness in Sidowarno, while Kadokan exhibited lower richness but relatively balanced species distribution. The Importance Value Index (IVI) revealed site-specific dominance by taxa such as *Ipomoea aquatica*, *Commelina diffusa*, and *Marsilea crenata*. Several of these structurally dominant species, including *Eichhornia crassipes* and *Colocasia esculenta*, are also recognized as bioaccumulators of heavy metals, highlighting their functional relevance for phytoremediation. Moderate inter-site similarity values (Jaccard index 0.45-0.58) suggest that each oxbow supports a partially distinct macrophyte community. These findings underscore the importance of conserving multiple oxbow units as complementary reservoirs of biodiversity and ecological function in tropical river-floodplain systems.

**Keywords:** Macrophyte diversity, oxbow streams, phytoremediation, riparian vegetation, river restoration, tropical wetlands

## INTRODUCTION

Riverine ecosystems provide a wide array of ecological functions and services that support both biodiversity and human livelihoods. Among the key components of these ecosystems are aquatic macrophytes, which play essential roles in stabilizing sediments, cycling nutrients, providing habitat for aquatic organisms, and improving water quality (O'Hare et al. 2018). Equally important are riparian macrophytes—plants that grow along riverbanks and floodplains—whose presence contributes to erosion control, nutrient retention, and ecological connectivity between terrestrial and aquatic systems (Tabacchi et al. 2000; Fickbohm and Zhu 2006). Understanding the composition and diversity of macrophytes, particularly in transitional zones such as oxbow streams, is crucial for developing sustainable strategies for riverine ecosystem management and conservation.

Oxbow streams, which originate from meandering rivers that are disconnected from the main channel, represent ecologically dynamic habitats with unique hydrological and geomorphological characteristics (Saha et al. 2022). These lentic water bodies are often influenced by seasonal flooding, sediment deposition, and human modifications. In tropical regions such as Indonesia, oxbow streams may support a rich variety of aquatic and riparian plant species, especially in areas where flood intensity and land use allow for vegetative colonization (Fraaije et al. 2018; Subehi et al. 2022). However, these systems are increasingly vulnerable to anthropogenic pressures, including pollution, agricultural encroachment, and the proliferation of invasive species (Suridiakusumah et al. 2020).

The Bengawan Solo River is the longest river on the island of Java, Indonesia, stretching over 600 kilometers from its headwaters in Central Java to its delta in East Java. The upper section of this river, particularly in the Sukoharjo and Klaten regions, is characterized by several oxbow formations—some permanent, others seasonal—that have become microhabitats for diverse aquatic and amphibious vegetation. Despite the ecological importance of these oxbow systems, there is limited documentation on the composition and diversity of macrophytes inhabiting them, especially in terms of their ecological roles and conservation value.

Indonesia is globally recognized for its high biodiversity, including its aquatic flora. The country ranks seventh in the world in terms of flowering plant species, with approximately 25% of the world's species found in Indonesia, many of which are endemic (Kusmana and Hikmat 2015). The aquatic plant component of this flora includes a wide range of floating, submerged, emergent, and amphibious species that contribute significantly to freshwater ecosystem functions. In oxbow streams, these macrophytes often coexist with riparian species in zones where water levels fluctuate, especially during seasonal inundation (Nasution et al. 2019). Nevertheless, macrophyte diversity in Indonesia's oxbow habitats remains understudied.

In addition to their ecological roles, some aquatic macrophytes are known to possess bioaccumulator properties, meaning they can uptake and store heavy metals such as cadmium (Cd) and lead (Pb) from the surrounding environment (Kamel 2013; Mandal and Bera 2024). This makes certain species valuable for phytoremediation and biomonitoring of polluted waters. Species such as *Salvinia × molesta*, *Pistia stratiotes*, and *Eichhornia crassipes* have been widely reported in this context (Fonseka et al. 2023). However, their dominance can also indicate ecological imbalance, particularly when invasive traits allow them to outcompete native vegetation. Understanding which species dominate in oxbow environments, and under what conditions, is therefore essential to assess both ecological health and restoration potential.

Previous studies in Indonesia have tended to focus on macrophytes in lakes, rivers, or rice fields (e.g., Fraaije et al. 2018; Pramono et al. 2024), but little is known about the species assemblages specifically in oxbow streams, especially in relation to their riparian counterparts. Moreover, while many studies emphasize the presence of macrophytes, few examine their diversity patterns across spatial gradients or assess their role as early indicators of habitat degradation.

Given this context, the present study was conducted to (i) assess the species composition and diversity of aquatic and riparian macrophytes in oxbow streams of the upper Bengawan Solo River, (ii) evaluate their ecological dominance and evenness, and (iii) identify species with known or potential roles as bioaccumulators. This study also aims to contribute baseline information for future conservation planning, water quality monitoring, and vegetation-based restoration in riverine wetlands of Central Java, Indonesia.

## MATERIALS AND METHODS

### Study area

This study was conducted in March 2024 at three oxbow stream sites located along the upper Bengawan Solo River, Central Java, Indonesia (Figure 1). The selected oxbow sites are situated within two districts: Sukoharjo and Klaten. These sites were chosen to represent variations in hydrological conditions, anthropogenic influence, and vegetation structure. All three sites are known to experience seasonal inundation and host a mosaic of aquatic and riparian vegetation.

Site I (Kadokan) is located in Grogol Sub-district, Sukoharjo District (7°35'27.978" S, 110°50'23.986" E). Slow-flowing waters, gentle embankments, and moderate human activity in the surrounding landscape, including agriculture and household wastewater discharge, characterize this site.

Site II (Tangkisan) lies further south in Grogol Sub-district (7°41'59.610" S, 110°47'57.191" E). It represents a shallow oxbow stream with stagnant water and abundant floating vegetation. This area receives inputs from nearby irrigation channels and rain-fed runoff during the wet season.

Site III (Sidowarno) is located in Wonosari Sub-district, Klaten District (7°39'43.369" S, 110°46'50.999" E). Unlike the other two sites, Sidowarno oxbow stream is semi-isolated from the main river channel and is surrounded by mixed agroforestry and residential zones.

These oxbow streams are remnants of the Bengawan Solo River's historical meandering paths and reflect diverse ecological conditions shaped by both natural processes and land use. The sampling locations were positioned along the fringe zones of these water bodies, capturing vegetation growing in shallow water, moist soil, and periodically flooded riparian edges.

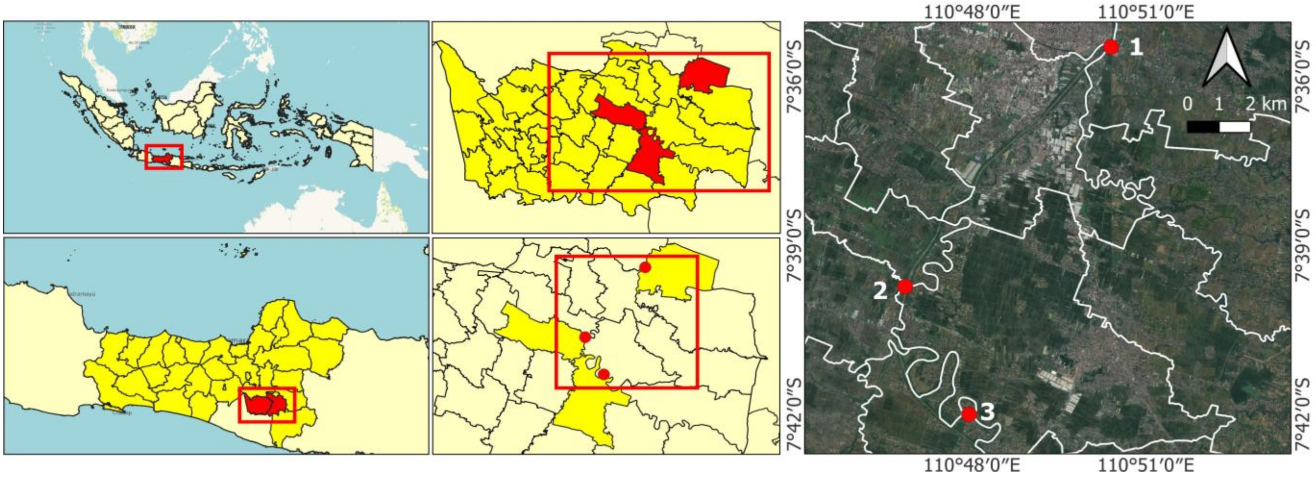

**Figure 1.** Map showing the location of the three oxbow stream sampling sites along the upper Bengawan Solo River, Central Java, Indonesia: Site I (Kadokan), Site II (Tangkisan), and Site III (Sidowarno)

**Plot design and sampling procedure**

Sampling was conducted using a purposive sampling method, targeting vegetated microhabitats along the margins of oxbow streams. At each of the three study sites, plots were placed in accessible fringe areas that included shallow water zones, semi-flooded soils, and riparian areas. These zones were selected based on the visible presence of aquatic or amphibious plant communities and their representativeness of local environmental gradients.

Vegetation sampling employed 1 m × 1 m quadrats, a standard size suitable for recording small to medium macrophytes while maintaining manageable effort across heterogeneous habitats (Kayima and Mayo 2018; Campbell et al. 2020). Within each quadrat, all vascular plant species were recorded, and the number of individual plants per species was counted. Plot placement continued until species accumulation reached saturation—that is, when no new species were detected in additional plots—at each station. In total, 33 quadrats were distributed across the three oxbow sites: (i) 11 plots at Kadokan (Site I), (ii) 11 plots at Tangkisan (Site II), and (iii) 11 plots at Sidowarno (Site III).

While the plots were primarily positioned to capture aquatic vegetation, riparian and edge species, particularly those found in seedling or juvenile form, were also recorded if they occurred within the quadrat boundaries. However, only herbaceous macrophytes and non-woody species were included in ecological index calculations, and large tree seedlings (e.g., *Samanea saman*, *Leucaena leucocephala*) were excluded from Importance Value Index (IVI) and diversity analyses. This approach allowed the study to capture the transitional nature of vegetation in oxbow stream ecosystems, where species composition often reflects fluctuating water levels and land-water interactions.

All sampled individuals were identified in the field to the lowest possible taxonomic level using standard identification keys, local floras, and cross-referencing with verified online databases. In cases where species identification could not be confirmed in situ, photographic documentation and morphological notes were taken for later verification.

**Species identification and classification**

All plant species recorded within the sampling plots were identified based on morphological characteristics observed in the field, supported by expert knowledge and validated taxonomic sources. Initial identification was guided by vernacular names provided by local residents, which were then cross-checked using floristic references (Heyne 1987; Walujo 2002) and confirmed through online taxonomic databases such as the Global Biodiversity Information Facility (GBIF, https://www.gbif.org) and Plants of the World Online (POWO, https://powo.science.kew.org).

Whenever possible, plants were identified to the species level. For individuals that could not be reliably identified due to incomplete morphological features—such as seedlings, vegetative fragments, or ambiguous taxa—identification was restricted to the genus or family level. Only taxa with valid scientific names recognized in GBIF and POWO were retained for ecological analysis, including use in diversity, richness, and dominance index calculations.

Each species was assigned to one of several ecological life form categories according to its structural growth pattern and relationship to water: (i) free-floating—plants that float independently on the water surface and are not rooted (e.g., *S. x molesta*, *P. stratiotes*); (ii) emergent—rooted in the substrate, with stems and leaves rising above the water surface (e.g., *Ipomoea aquatica*, *Limnocharis flava*); (iii) submerged—completely underwater (no representative species found in this study); (iv) amphibious— capable of growing in wet soils, periodically flooded areas, or alternating submerged-emergent conditions; this term is used in this study to encompass what is sometimes referred to as semi-aquatic species (e.g., *Colocasia esculenta*, *Cyperus rotundus*); and (v) riparian or terrestrial fringe—typically non-aquatic species found within the quadrats due to proximity to fluctuating water margins, often in seedling form. Although some quadrats included seedlings of woody species such as *S. saman* and *Muntingia calabura*, these were excluded from all diversity and dominance calculations, as they do not meet the ecological definition of macrophytes.

This classification was based on field observation and ecological descriptions from recent literature (Kusmana and Hikmat 2015; O'Hare et al. 2018; Nasution et al. 2019). While the main focus was on aquatic macrophytes, the inclusion of riparian species was ecologically justified due to the transitional nature of oxbow fringe habitats and their dynamic hydrology.

Digital photographs were taken for all uncertain specimens to enable post-survey verification. No physical voucher specimens were collected, in accordance with ethical considerations and site access limitations, but detailed field notes were archived for future reference.

**Data analysis**

Data collected from each quadrat were compiled into species-by-site matrices, with the number of individual plants per species used as the primary input for ecological index calculations. The following quantitative indices were computed to assess species diversity, structure, and ecological dominance across the three oxbow stream sites:

*Relative Density (RD):*

RD was calculated as the percentage of individuals of a given species relative to the total number of individuals across all species.

*Relative Frequency (RF):*

RF was determined by dividing a species' frequency (the number of plots in which it occurred) by the sum of all species' frequencies, also expressed as a percentage.

*Importance Value Index (IVI):*

IVI was a composite measure obtained by summing the Relative Density and Relative Frequency values for each species. It reflects the overall ecological dominance of species within a community. IVI was calculated independently for each site (Kadokan, Tangkisan, and Sidowarno), and the five most dominant species per site were selected based on the highest IVI values (Table 3).

*Shannon-Wiener Diversity Index (H'):*

This index measures species diversity by accounting for both species richness and evenness. It was calculated using the formula:

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

Where :

$p_i$ : Proportion of individuals belonging to species *i*

$S$ : Total number of species

*Margalef's Species Richness Index (Dmg):*

Dmg evaluates species richness independent of evenness, calculated using:

$$Dmg = \frac{S-1}{\ln N}$$

Where :

$S$ : Number of species

$N$ : Total number of individuals

*Evenness Index (E):*

Evenness quantifies the equitability of species distribution, derived by dividing the observed H′ value by the maximum possible diversity:

$$E = \frac{H'}{\ln S}$$

*Simpson's Dominance Index (C):*

This index reflects the degree to which a few species dominate the community:

$$C = \sum_{i=1}^{S} p_i^2$$

A value close to 1 indicates low diversity and high dominance, while values closer to 0 indicate more even species distributions.

*Jaccard Similarity Index ($S_i$):*

To compare species composition between sites, Jaccard's index was calculated as:

$$S_i = \frac{a}{a+b+c}$$

Where:

$a$ : Number of species common to both sites

$b$ : Species unique to site 1

$c$ : Species unique to site 2

All analyses were performed using Microsoft Excel and cross-checked manually to ensure accuracy. Species identified only at the genus or family level were included in the calculations if their taxonomic status was verified. Ecological metrics were computed exclusively for herbaceous macrophytes with valid species names. Large woody seedlings or non-macrophyte species observed in quadrats were excluded from diversity and dominance analyses. In addition, known bioaccumulator species listed in Table 5 were identified from peer-reviewed literature based on their ability to uptake heavy metals, and their IVI values were used to assess their structural prominence in the local vegetation.

## RESULTS AND DISCUSSIONS

*Species composition and taxonomic richness*

A total of 45 macrophyte species, representing 25 families and 41 genera, were recorded across the three oxbow stream sites of the upper Bengawan Solo River (Table 1). The most represented families were Cyperaceae (5 species), Fabaceae (4 species), and Amaranthaceae (3 species). Other moderately represented families included Araceae, Nymphaeaceae, and Pontederiaceae, which collectively contributed to the diversity of emergent, floating, and amphibious macrophytes.

Species occurrence was spatially heterogeneous, with only a few taxa found in all three sites. Notably, *Colocasia esculenta, Amaranthus spinosus,* and *E. crassipes* were among the species present at every location. In contrast, In contrast, *I. aquatica* was recorded exclusively in Sidowarno, where it had a high IVI (46.4), while *S. × molesta* was found only in Kadokan with a relatively low IVI (12.1), indicating localized but limited structural influence (Table 1). These differences underscore the spatial specificity of species occurrence and ecological roles within the oxbow habitats.

The relative proportion of aquatic to riparian species differed notably among sites. Tangkisan (Site II) showed the highest number of floating macrophytes, consistent with its more stagnant hydrological condition. Sidowarno (Site III) exhibited the highest overall species richness, particularly among amphibious and riparian forms, as illustrated in Figure 2, suggesting a greater microhabitat heterogeneity and hydrological gradient diversity. The presence of terrestrial-origin seedlings within some quadrats—especially in Sidowarno—reflects seasonal flooding effects that enable propagule input from surrounding upland vegetation.

### Life form categories and distribution patterns

Macrophyte species recorded in the study sites were classified into six ecological life form categories: riparian, floating, amphibious, floating-leaved, emergent, and submerged. These categories reflect species' structural adaptations and hydrological niches across the oxbow environments (Table 2). The most common life forms were amphibious species (13 species) and riparian species (11 species), followed by emergent species (9) and floating species (6). Fewer species were classified as submerged (4) or floating-leaved (2).

Site-specific differences in life form composition were evident. Sidowarno (Site III) exhibited the greatest diversity of life forms, with seven amphibious, five riparian, three submerged, and two floating-leaved species. Tangkisan (Site II) showed high representation of floating macrophytes, consistent with its shallow and stagnant waters, while Kadokan (Site I) was dominated by amphibious and emergent species, which thrive in semi-flooded and periodically exposed soils.

These differences are further illustrated in Figure 2, which shows stacked proportions of life form categories per site, and in Figure 5, which summarizes the total number of species per life form across sites. Floating and amphibious forms were generally more dominant in Tangkisan and Sidowarno, while riparian and emergent forms were more prevalent in Kadokan. This pattern reflects underlying hydrological gradients and microsite availability in each oxbow stream.

Although submerged species were the least represented group, their presence in Sidowarno and Tangkisan indicates occasional water clarity and oxygen availability sufficient to support underwater growth forms. Conversely, the absence of submerged forms in Kadokan may be linked to turbidity or unstable substrate conditions.

**Table 1.** Aquatic and riparian macrophyte species recorded from three oxbow stream sites in the upper Bengawan Solo River, Central Java, Indonesia

| Scientific name | Family | Life form | Occurrence (sites) | IVI score |
|---|---|---|---|---|
| *Commelina diffusa* Burm.f. | Commelinaceae | Riparian | Kadokan, Tangkisan | 54.8 |
| *Limnocharis flava* (L.) Buchenau | Onagraceae | Floating | All sites | 54.4 |
| *Sesbania bispinosa* (Jacq.) W.Wight | Fabaceae | Riparian | Tangkisan, Sidowarno | 51.6 |
| *Oenanthe javanica* (Blume) DC. | Apiaceae | Riparian | Sidowarno only | 50.6 |
| *Samanea saman* (Jacq.) Merr. | Fabaceae | Riparian | Tangkisan, Sidowarno | 48.8 |
| *Ipomoea aquatica* Forssk. | Convolvulaceae | Amphibious | Sidowarno only | 46.4 |
| *Colocasia esculenta* (L.) Schott | Araceae | Amphibious | All sites | 40.7 |
| *Nymphaea pubescens* Willd. | Nymphaeaceae | Floating-leaved | Tangkisan, Sidowarno | 45.2 |
| *Eleocharis dulcis* (Burm.f.) Trin. ex Hensch. | Cyperaceae | Emergent | Kadokan only | 45.1 |
| *Azolla pinnata* R.Br. | Azollaceae | Floating | Tangkisan, Sidowarno | 42.3 |
| *Marsilea crenata* C.Presl | Marsileaceae | Amphibious | Sidowarno only | 41.4 |
| *Cyperus rotundus* L. | Cyperaceae | Amphibious | Kadokan only | 40.4 |
| *Ipomoea fistulosa* Mart. ex Choisy | Convolvulaceae | Riparian | Tangkisan, Sidowarno | 38.5 |
| *Ammannia baccifera* L. | Lythraceae | Amphibious | Sidowarno only | 42.0 |
| *Utricularia aurea* Lour. | Lentibulariaceae | Submerged | Tangkisan, Sidowarno | 33.9 |
| *Marsilea quadrifolia* L. | Marsileaceae | Amphibious | Sidowarno only | 34.6 |
| *Zizania latifolia* (Griseb.) Hance ex F.Muell. | Poaceae | Emergent | Kadokan only | 33.7 |
| *Centella asiatica* (L.) Urb. | Apiaceae | Amphibious | Sidowarno only | 30.7 |
| *Eichhornia crassipes* (Mart.) Solms | Pontederiaceae | Floating | Tangkisan, Sidowarno | 28.9 |
| *Monochoria vaginalis* (Burm.f.) C.Presl | Pontederiaceae | Emergent | Kadokan, Tangkisan | 36.1 |
| *Fimbristylis miliacea* (L.) Vahl | Cyperaceae | Emergent | Tangkisan, Sidowarno | 26.9 |
| *Amaranthus spinosus* L. | Amaranthaceae | Riparian | All sites | 31.3 |
| *Persicaria hydropiper* (L.) Spach | Polygonaceae | Amphibious | Kadokan, Tangkisan | 29.5 |
| *Ludwigia adscendens* (L.) H.Hara | Onagraceae | Floating | Kadokan only | 30.1 |
| *Rotala indica* (Willd.) Koehne | Lythraceae | Amphibious | Tangkisan, Sidowarno | 29.2 |
| *Egeria densa* Planch. | Hydrocharitaceae | Submerged | All sites | 26.2 |
| *Hydrilla verticillata* (L.f.) Royle | Hydrocharitaceae | Submerged | Sidowarno only | 22.5 |
| *Aeschynomene indica* L. | Fabaceae | Riparian | Tangkisan, Sidowarno | 17.9 |
| *Myriophyllum aquaticum* (Vell.) Verdc. | Haloragaceae | Submerged | Tangkisan, Sidowarno | 18.8 |
| *Pistia stratiotes* L. | Araceae | Floating | Kadokan, Tangkisan | 20.6 |
| *Polygonum barbatum* Comm. | Polygonaceae | Amphibious | Kadokan, Tangkisan | 21.4 |
| *Typha angustifolia* L. | Typhaceae | Emergent | All sites | 16.8 |
| *Muntingia calabura* L. | Muntingiaceae | Riparian | Kadokan only | 23.0 |
| *Bacopa monnieri* (L.) Pennell | Plantaginaceae | Amphibious | Tangkisan, Sidowarno | 18.4 |
| *Eclipta prostrata* (L.) L. | Asteraceae | Riparian | Kadokan, Tangkisan | 21.1 |
| *Sagittaria sagittifolia* L. | Alismataceae | Emergent | Tangkisan, Sidowarno | 15.7 |
| *Jussiaea repens* L. | Fabaceae | Riparian | Kadokan only | 18.1 |
| *Cyperus difformis* L. | Cyperaceae | Emergent | Kadokan only | 11.6 |
| *Boerhavia diffusa* L. | Nyctaginaceae | Riparian | All sites | 13.3 |
| *Alternanthera philoxeroides* (Mart.) Griseb. | Amaranthaceae | Amphibious | Kadokan, Tangkisan | 15.0 |
| *Enydra fluctuans* Lour. | Asteraceae | Amphibious | Kadokan, Tangkisan | 9.4 |
| *Leucaena leucocephala* (Lam.) de Wit | Fabaceae | Emergent | All sites | 12.1 |
| *Salvinia × molesta* D.S.Mitch. | Salviniaceae | Floating | Kadokan only | 12.1 |
| *Scirpus grossus* L.f. | Cyperaceae | Emergent | All sites | 8.5 |
| *Nelumbo nucifera* Gaertn. | Nelumbonaceae | Floating-leaved | Tangkisan, Sidowarno | 9.3 |

Note: This table includes all macrophyte species recorded in the study, along with their family, ecological life form, site occurrence, and calculated Importance Value Index (IVI) score.

**Table 2.** Distribution of macrophyte species across ecological life forms and study sites in the upper Bengawan Solo River, Central Java, Indonesia

| Life form category | No. of species | Site I | Site II | Site III |
|---|---|---|---|---|
| Riparian | 11 | 4 | 6 | 5 |
| Floating | 6 | 3 | 3 | 2 |
| Amphibious | 13 | 5 | 6 | 7 |
| Floating-leaved | 2 | 0 | 2 | 2 |
| Emergent | 9 | 4 | 3 | 2 |
| Submerged | 4 | 0 | 2 | 3 |
| Total (all categories) | 45 | 16 | 22 | 21 |

Note: Site I (Kadokan), Site II (Tangkisan), Site III (Sidowarno)

### Species richness, diversity and dominance indices

The number of macrophyte species varied across the three study sites, with Tangkisan (Site II) exhibiting the highest species richness (22 species), followed by Sidowarno (Site III) with 21 species, and Kadokan (Site I) with 16 species (Table 2). These richness patterns suggest that Tangkisan and Sidowarno support more heterogeneous microhabitats compared to Kadokan, which may be limited by more uniform hydrological or substrate conditions.

Quantitative ecological indices reinforced these richness differences. Shannon–Wiener diversity index (H′) ranged from 2.53 in Kadokan to 2.72 in Sidowarno, while Margalef's richness index (Dmg) followed a similar trend, with the highest value also observed in Sidowarno (2.52) and the lowest in Kadokan (2.30) (Table 4). Evenness index (E) was highest in Sidowarno (0.81) and lowest in Tangkisan (0.76), indicating that although species were most numerous in Tangkisan, their distribution was slightly less balanced across taxa.

Simpson's dominance index (C) ranged from 0.20 in Kadokan to 0.23 in Sidowarno, indicating a moderate level of dominance by a few species at each site. These results are illustrated in Figure 3 (Shannon-Wiener Diversity Index (H′), Species Richness Index (Dmg), and Evenness Index (E)), Figure 4 (Simpson dominance index), and Figure 5 (dominant macrophyte species). Overall, Sidowarno combined relatively high species richness, diversity, and evenness, suggesting a well-structured macrophyte community under dynamic environmental conditions.

The slightly lower evenness and higher dominance in Tangkisan may reflect the abundance of floating species like *E. crassipes* and *S. x molesta*, which can suppress other growth forms under stagnant conditions. In contrast, the lower richness but higher evenness in Kadokan suggests a more uniform but compositionally constrained community.

### Species dominance and Importance Values (IVI)

The Importance Value Index (IVI) revealed distinctive patterns of species dominance across the three oxbow stream sites (Table 3). Each location harbored a unique set of structurally important species, reflecting site-specific environmental conditions and life form composition.

In Kadokan (Site I), the most dominant species was *Commelina diffusa* (IVI = 54.8), a fast-growing riparian herb commonly found in moist soils. This was followed by *Ludwigia adscendens* (54.4) and *S. bispinosa* (51.6). The dominance of riparian and amphibious herbs in Kadokan reflects the site's gently sloped banks and fluctuating water margins.

In Tangkisan (Site II), the leading species was *Oenanthe javanica* (IVI = 50.6), followed closely by *Ipomoea fistulosa* (syn. *Ipomoea carnea* subsp. *fistulosa* (Mart. ex Choisy) D.F.Austin) (48.8) and *Azolla pinnata* (42.3). The strong presence of floating and amphibious macrophytes in Tangkisan corresponds with its shallow, stagnant water conditions and abundant detrital input.

In Sidowarno (Site III), *I. aquatica* emerged as the most dominant species (IVI = 46.4), reflecting the site's more open water and nutrient-rich conditions. Other dominant species included *C. esculenta* (40.7) and *Marsilea crenata* (41.4), both of which are tolerant of intermittently flooded environments.

Figure 5 provides a visual comparison of the top ten dominant species across all sites based on IVI. The chart illustrates not only species-level dominance but also differences in life form contributions across locations. *A. spinosus*, *E. crassipes*, and *C. rotundus* also ranked among the most influential species in terms of structural presence and frequency, appearing prominently in multiple sites. These IVI results highlight ecological differentiation across the oxbow streams, with each site supporting a distinct subset of dominant taxa linked to local hydrology, nutrient status, and vegetation edge dynamics.

### Species similarity among sites

To evaluate floristic overlap between the three oxbow stream sites, Jaccard similarity indices were calculated based on shared species presence (Table 4). The highest similarity was found between Tangkisan and Sidowarno ($S_i$ = 0.58), indicating considerable species overlap, likely driven by comparable hydrological features and the presence of floating and amphibious macrophytes at both sites.

**Table 3.** Top five dominant macrophyte species based on Importance Value Index (IVI) at each oxbow stream site in the upper Bengawan Solo River, Central Java, Indonesia

| Site | Species name | IVI |
|---|---|---|
| Site I (Kadokan) | *Commelina diffusa* | 54.8 |
| | *Ludwigia adscendens* | 54.4 |
| | *Sesbania bispinosa* | 51.6 |
| | *Marsilea crenata* | 46.4 |
| | *Cyperus rotundus* | 35.5 |
| Site II (Tangkisan) | *Oenanthe javanica* | 50.6 |
| | *Ipomoea fistulosa* | 48.8 |
| | *Azolla pinnata* | 42.3 |
| | *Pistia stratiotes* | 34.1 |
| | *Eichhornia crassipes* | 32.1 |
| Site III (Sidowarno) | *Ipomoea aquatica* | 46.4 |
| | *Marsilea crenata* | 41.4 |
| | *Colocasia esculenta* | 40.7 |
| | *Cyperus rotundus* | 38.5 |
| | *Amaranthus spinosus* | 31.3 |

**Table 4.** Ecological indices of macrophyte communities at three oxbow stream sites in the upper Bengawan Solo River, Central Java, Indonesia

| Site | Shannon-Wiener Index (H′) | Margalef Richness Index (Dmg) | Evenness Index (E) | Simpson's Dominance Index (C) | Similarity Index ($S_i$) |
|---|---|---|---|---|---|
| Kadokan | 2.53 | 2.3 | 0.78 | 0.2 | 0.48 (vs Tangkisan) |
| Tangkisan | 2.65 | 2.43 | 0.76 | 0.22 | 0.58 (vs Sidowarno) |
| Sidowarno | 2.72 | 2.52 | 0.81 | 0.23 | 0.45 (vs Kadokan) |

Note: Higher values of H′ and Dmg indicate greater species diversity and richness, respectively. A higher E reflects a more uniform species distribution, while a higher C indicates stronger ecological dominance by a few species.

**Table 5.** Bioaccumulator potential of dominant macrophyte species in the upper Bengawan Solo River, Central Java, Indonesia

| Species name | Known accumulated metals | References | IVI |
|---|---|---|---|
| *Ipomoea aquatica* | Cd, Pb | Prasad (2004) | 46.4 |
| *Colocasia esculenta* | Pb, As | Miretzky et al. (2004) | 40.7 |
| *Cyperus rotundus* | Cd, Cr | Subashini and Swamy (2014) | 40.4 |
| *Amaranthus spinosus* | Pb, Cd | Singh and Agrawal (2010) | 31.3 |
| *Eichhornia crassipes* | Cd, Pb, Zn, Hg | Malik (2007) | 28.9 |
| *Pistia stratiotes* | Pb, Cd, Zn | Sood et al. (2012) | 20.6 |
| *Salvinia x molesta* | Cu, Pb, Cd | Rai (2008), Irawanto and Baroroh (2017) | 12.1 |

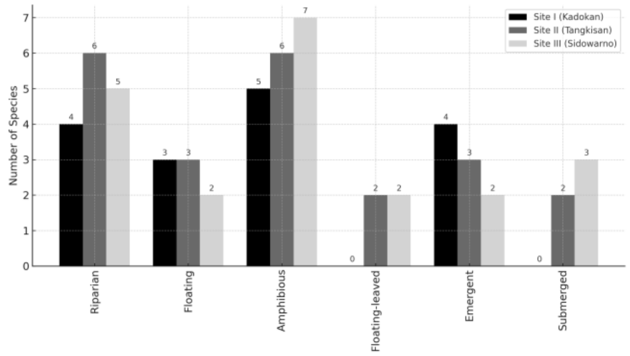

**Figure 2.** Life form composition across the three sites in the upper Bengawan Solo River oxbow streams, Central Java, Indonesia

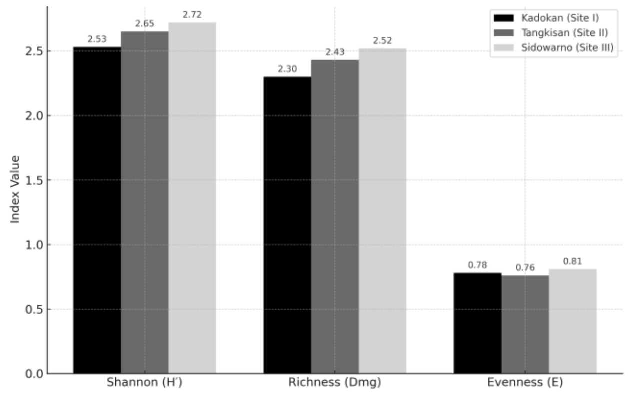

**Figure 3.** Comparison of diversity indices across oxbow stream sites. Bar chart comparing Shannon-Wiener Diversity Index (H′), Species Richness Index (Dmg), and Evenness Index (E) across the three oxbow stream sites in the upper Bengawan Solo River, Central Java, Indonesia

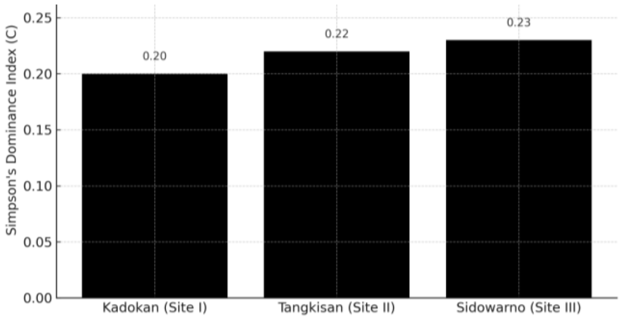

**Figure 4.** Simpson’s Dominance Index (C) across the three oxbow stream sites in the upper Bengawan Solo River, Central Java, Indonesia

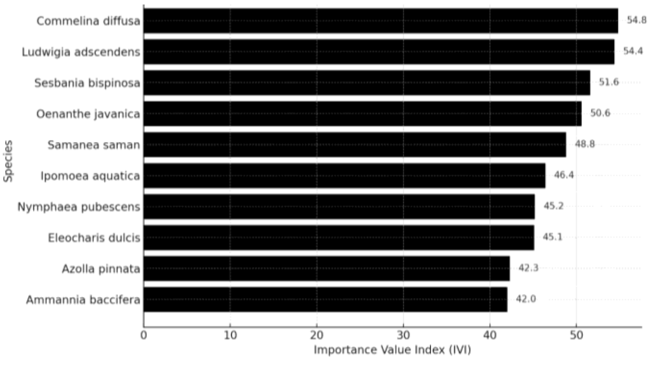

**Figure 5.** Bar chart of the top 10 dominant macrophyte species based on Importance Value Index (IVI) in the upper Bengawan Solo River oxbow streams, Central Java, Indonesia

Kadokan shared fewer species with the other two sites, yielding Jaccard indices of 0.48 with Tangkisan and 0.45 with Sidowarno, respectively. These lower similarity values suggest that Kadokan supports a more distinct macrophyte assemblage, possibly due to differences in flow regime, human disturbance, or bank morphology.

The moderate overall similarity levels ($S_i$ = 0.45–0.58) across site pairs reflect both shared generalist taxa and the presence of site-specific dominants. For instance, *S.* × *molesta* occurred only in Kadokan, while *I. aquatica* was found exclusively in Sidowarno, contributing to dissimilarities. Meanwhile, cosmopolitan species such as *C. esculenta*, *E. crassipes*, and *A. spinosus* were common to all sites and contributed to baseline similarity. These results emphasize that while all sites belong to the same riverine corridor, oxbow microhabitats support partially distinct macrophyte communities, shaped by local-scale environmental heterogeneity.

**Bioaccumulator macrophytes**

Several dominant macrophyte species identified in this study are known from the literature to possess heavy metal bioaccumulation capacity (Table 5). These species not only exhibit structural dominance in the oxbow communities (as indicated by high IVI values) but also have been documented to uptake and store toxic metals such as lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn).

The most prominent example is *A. spinosus*, which had an IVI of 31.3 and is recognized for its ability to accumulate Pb and Cd (Singh & Agrawal 2010). Similarly, *C. esculenta*, widespread across sites and with an IVI of 40.7, is known to take up Pb and arsenic (Miretzky et al. 2004). *E. crassipes*, another widespread species (IVI = 28.9), is extensively cited as a hyperaccumulator of Cd, Pb, Zn, and Hg (Malik 2007).

Other species of interest include *C. rotundus*, associated with Cd and Cr uptake, and *P. stratiotes*, which was present in Kadokan and Tangkisan with lower IVI values but has demonstrated potential for accumulating Pb, Cd, and Zn (Sood et al. 2012). *S.* × *molesta*, exclusive to Kadokan, also showed bioaccumulation potential for Cu, Pb, and Cd (Rai 2008).

The ecological relevance of these species extends beyond structural dominance, as their ability to sequester heavy metals makes them candidates for phytoremediation strategies in disturbed oxbow systems. Their natural occurrence in these habitats suggests a dual function: stabilizing macrophyte communities and contributing to pollutant mitigation. The integration of IVI data with published metal uptake references (Table 5) highlights the potential of using dominant native or naturalized macrophytes in site-specific bioremediation programs without introducing exotic species.

## Discussion

*Spatial variation in species composition and taxonomic richness*

The macrophyte flora recorded from the oxbow streams of the upper Bengawan Solo River reflected a moderate degree of taxonomic richness, with 45 species belonging to 25 families and 41 genera (Table 1). This richness is comparable to similar floodplain or lentic systems in Southeast Asia (Lacoul and Freedman 2006; Harun et al. 2019), although it remains lower than species counts from large tropical river deltas or lakes with more permanent and stratified aquatic zones (e.g., Triest et al. 2012).

Each site supported a distinct macrophyte assemblage, shaped by microhabitat conditions such as water depth, bank slope, and sediment stability. Sidowarno and Tangkisan harbored more diverse assemblages, likely due to broader microtopographic gradients and seasonal water level variation that create dynamic habitat mosaics. In contrast, Kadokan exhibited lower species richness (16 species), which may be attributed to its narrower vegetation zone and more uniform substrate.

Only a few generalist species, such as *C. esculenta*, *E. crassipes*, and *A. spinosus*, were shared across all sites, suggesting that these taxa possess broad ecological tolerances. Meanwhile, the presence of unique taxa at specific sites—e.g., *I. aquatica* in Sidowarno and *S.* × *molesta* in Kadokan—indicates niche specialization driven by site-specific hydrology.

This pattern of partial species turnover reflects the broader ecological principle that macrophyte diversity in floodplain water bodies is regulated by habitat heterogeneity and hydrological isolation (Bornette and Amoros 1996; Junk et al. 2013). Although the three sites are located within the same river corridor, their semi-isolation and differing degrees of connectivity to the main channel produce distinct floristic identities. These findings support the notion that small oxbow systems contribute significantly to landscape-scale biodiversity, even when spatially proximate, and should not be treated as ecologically redundant in conservation planning.

*Life form distribution and hydrological niche segregation*

The life form composition of macrophyte communities across the oxbow streams revealed clear ecological differentiation linked to water regime and habitat complexity. Six ecological life form categories were identified—riparian, floating, amphibious, floating-leaved, emergent, and submerged—with amphibious and riparian species comprising the largest groups (Table 2). This pattern aligns with prior studies in tropical floodplain systems where water level fluctuations promote the coexistence of amphibious and terrestrial-fringe flora (Lacoul and Freedman 2006; O'Hare et al. 2018).

Amphibious species (13 taxa), such as *C. esculenta*, *C. rotundus*, and *M. crenata*, were dominant in all three sites, particularly in areas with moist soils and seasonal drying. Their morphological plasticity enables survival under alternating submerged and emergent conditions, a trait advantageous in habitats like oxbow margins that experience pulsed inundation.

Floating macrophytes were most abundant in Tangkisan, where stagnant waters favored species such as *E. crassipes*, *A. pinnata*, and *P. stratiotes*. In contrast, submerged and floating-leaved forms were absent in

Kadokan, likely due to turbidity or shallow, unstable substrates that inhibit light penetration and anchorage.

Sidowarno exhibited the most complete representation of all life forms, including submerged (*Utricularia aurea*, *Hydrilla verticillata*), emergent, and floating-leaved taxa (*Nymphaea pubescens*, *Nelumbo nucifera*). This indicates greater hydrological gradient and vertical stratification at the site, possibly due to its semi-isolated position from the main river and more prolonged inundation.

Figure 5 illustrates the dominance of amphibious and riparian forms in Kadokan, the strong floating community in Tangkisan, and the balanced life form representation in Sidowarno. These patterns support the hypothesis that life form diversity and composition are regulated by site-level water dynamics, including duration, depth, and flow stability (Baattrup-Pedersen et al. 2006; Bornette et al. 2008).

Life form segregation across the oxbow sites reflects both adaptive strategies of macrophytes and the functional diversity of microhabitats, underscoring the importance of maintaining hydrological variation for sustaining species richness and ecosystem function.

### *Community diversity and structural evenness*

The diversity structure of macrophyte communities varied markedly among the three oxbow stream sites, reflecting differences in richness, evenness, and species dominance. Shannon–Wiener diversity index (H′) values ranged from 2.53 in Kadokan to 2.72 in Sidowarno, indicating moderately high species diversity across all sites (Table 4). These values are comparable to other studies in tropical freshwater habitats with mosaic vegetation structure (Triest et al. 2012; Wahyuningsih et al. 2020).

Margalef's richness index (Dmg) showed a similar trend, with Sidowarno exhibiting the highest richness (2.52) and Kadokan the lowest (2.30). These indices reflect the number of species normalized by the total individuals and suggest that Sidowarno supports a richer macrophyte flora, likely due to more diverse microhabitats and longer hydroperiods. Figure 3 visualizes these index values, emphasizing the relative advantage of Sidowarno in both species number and richness.

Evenness index (E) ranged from 0.76 in Tangkisan to 0.81 in Sidowarno, indicating that species in Sidowarno are more evenly distributed in terms of abundance. Tangkisan's lower evenness reflects moderate species dominance, especially by free-floating species such as *E. crassipes* and *A. pinnata*. In contrast, Kadokan showed higher evenness despite its lower richness, suggesting a more uniform distribution of a limited set of species.

Simpson's dominance index (C) supports these findings, with the highest value recorded in Sidowarno (0.23), followed by Tangkisan (0.22) and Kadokan (0.20). While this suggests slightly higher dominance in Sidowarno, the difference is marginal and may be due to the presence of highly adapted taxa such as *I. aquatica* and *M. crenata* that co-dominate specific zones. Figure 5 illustrates these dominance values. The diversity metrics indicate that Sidowarno hosts the most structurally balanced macrophyte community, combining richness, evenness, and moderate dominance. Kadokan is characterized by fewer species but a more equitable distribution, whereas Tangkisan shows species richness but slight skewness due to dominant floaters. These patterns are typical of riverine floodplain systems where site-level hydrology and disturbance regimes shape both taxonomic and structural diversity (Junk et al. 2013; Baattrup-Pedersen et al. 2018).

### *Ecological significance of dominant species*

Analysis of Importance Value Index (IVI) revealed site-specific dominance patterns, underscoring the ecological variability and structural organization of macrophyte communities in the oxbow streams (Table 3). High IVI values typically indicate species that not only occur frequently but also occupy large portions of vegetated space, playing key roles in defining habitat structure and ecological function.

In Kadokan (Site I), the dominance of *C. diffusa* (IVI = 54.8), *L. adscendens* (54.4), and *S. bispinosa* (51.6) reflects a community composed primarily of herbaceous riparian and amphibious plants. These species thrive in shallow, seasonally moist zones and tolerate intermittent desiccation. Their high frequency and widespread canopy coverage suggest that Kadokan is characterized by structurally cohesive but low-canopy vegetation.

In Tangkisan (Site II), the leading species included *O. javanica* (50.6) and *I. fistulosa* (48.8)—both fast-growing species commonly associated with disturbed, low-flow environments—as well as *A. pinnata* (42.3), a prolific floating fern. These taxa reflect Tangkisan's stagnant waters and high organic content, which favor floating and amphibious growth forms. The dominance of floaters may reduce light penetration and suppress submerged vegetation, influencing community structure and regeneration pathways.

In Sidowarno (Site III), *I. aquatica* (46.4), *M. crenata* (41.4), and *C. esculenta* (40.7) emerged as dominant species. Their presence reflects adaptation to prolonged submersion, fluctuating margins, and nutrient-rich substrates. Notably, *I. aquatica* is known to form dense mats that stabilize sediments and buffer edge habitats from erosion, suggesting a strong functional role in ecosystem resilience.

Figure 5 summarizes the top ten macrophyte species across sites, highlighting taxa with consistently high IVI scores. Species such as *A. spinosus* and *E. crassipes* ranked among the most influential species across sites. *S. × molesta*, while restricted to Kadokan and not structurally dominant, contributes to floating vegetation diversity under stagnant conditions. These findings suggest that dominant macrophytes not only shape spatial heterogeneity and vegetation architecture, but also reflect key environmental gradients such as flow stability, substrate type, and nutrient levels. Their dominance positions them as functional indicators for habitat health and potential targets for bioassessment or restoration efforts.

### *Species turnover and site similarity*

Floristic similarity among the three oxbow stream sites was moderate, indicating both shared and unique macrophyte assemblages. Jaccard similarity indices ranged from 0.45 (Kadokan–Sidowarno) to 0.58 (Tangkisan–Sidowarno), suggesting that while the sites share a number of core species, each also harbors distinct taxa shaped by local conditions (Table 4).

The highest similarity between Tangkisan and Sidowarno ($S_i$ = 0.58) reflects a substantial overlap in floating and amphibious species, likely driven by comparable hydrological stagnation and sediment environments. In contrast, Kadokan exhibited lower similarity with both other sites, pointing to a more distinct floristic composition shaped by site-specific factors such as channel connectivity, soil exposure, or disturbance intensity.

The presence of widespread species like *C. esculenta*, *A. spinosus*, and *E. crassipes* at all sites contributes to baseline similarity, representing adaptable taxa with broad ecological amplitudes. However, site-specific species such as *I. aquatica* (Sidowarno only) and *S.* × *molesta* (Kadokan only) highlight the role of microhabitat filters in driving species turnover.

These findings are consistent with the concept of species sorting and environmental filtering in semi-connected aquatic landscapes, where subtle gradients in water depth, hydrological permanence, and bank morphology create discrete niches (Bornette et al. 1994; Baattrup-Pedersen et al. 2018). The intermediate Jaccard values observed (0.45–0.58) underscore the conservation value of maintaining multiple oxbow units, as each supports complementary elements of the regional macrophyte pool.

From a management perspective, moderate species turnover implies that loss or degradation of a single site may result in the local extinction of narrowly distributed taxa, particularly those with low dispersal or site-specific habitat requirements. Therefore, oxbow systems should be treated as interconnected-yet-unique conservation units within riverine networks.

### *Functional implications of bioaccumulator species*

Beyond their ecological dominance, several macrophyte species identified in this study possess functional traits relevant to environmental remediation. Table 5 summarizes dominant taxa with known capacities to accumulate heavy metals, including cadmium (Cd), lead (Pb), zinc (Zn), and arsenic (As), as documented in previous studies (Malik 2007; Miretzky et al. 2004; Singh and Agrawal 2010).

Notably, *A. spinosus*, with an IVI of 31.3, is widely reported for its ability to absorb and store Pb and Cd. Likewise, *C. esculenta* (IVI = 40.7) is known to accumulate Pb and As from both water and sediments. *E. crassipes*, another structurally dominant species (IVI = 28.9), has been extensively studied as a bioaccumulator of Cd, Pb, Zn, and Hg in tropical aquatic systems (Sood et al. 2012).

Other relevant species include *C. rotundus*, associated with Cd and Cr uptake, and *P. stratiotes*, observed in Kadokan and Tangkisan, which has potential for bioaccumulating Zn and Pb. *S.* × *molesta*, although restricted to Kadokan, contributes to metal removal from eutrophic or wastewater-influenced waters (Rai 2008).

The ecological prominence of these species, combined with their phytoremediation potential, positions them as multifunctional elements within oxbow ecosystems. Their natural establishment and persistence suggest resilience under nutrient and pollutant enrichment, as well as functional roles in metal retention and sediment stabilization.

From a restoration and management perspective, prioritizing native or naturalized macrophytes with known bioaccumulative properties offers a cost-effective and ecologically safe approach to rehabilitating degraded riverine habitats. Moreover, since many of these taxa are already dominant or co-dominant (as indicated by high IVI scores), they may provide immediate ecosystem services without requiring artificial introduction or intensive maintenance. This highlights the value of integrating structural and functional traits in macrophyte-based assessments, allowing managers to identify species that simultaneously support biodiversity, habitat complexity, and water quality improvement.

In conclusion, this study assessed the diversity, life form composition, and ecological roles of macrophytes in three oxbow streams along the upper Bengawan Solo River, Central Java, Indonesia. A total of 45 species from 25 families were recorded, dominated by amphibious and riparian forms. Species richness and diversity indices varied across sites, with Sidowarno exhibiting the most heterogeneous community structure. Importance Value Index (IVI) revealed distinct dominant species per site, many of which—such as *A. spinosus*, *C. esculenta*, and *E. crassipes*—also possess bioaccumulative potential for heavy metals. Jaccard similarity indicated moderate species turnover, emphasizing the ecological uniqueness of each site. These findings suggest that oxbow habitats play a key role in maintaining aquatic plant diversity and may support phytoremediation functions. Management strategies should prioritize the protection of multiple oxbow units to conserve both structural and functional macrophyte diversity in regulated river systems.

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## REFERENCES

Campbell S, Greenwood M, Prior S, Shearer T, Walkem K, Young S, Bywaters D, Walker K. 2020. Purposive sampling: Complex or simple? Research case examples. J Res Nurs 25 (8): 652-661. DOI: 10.1177/1744987120927206.

Cantonati M, Poikane S, Pringle CM et al. 2019. Characteristics, main impacts, and stewardship of natural and artificial freshwater environments: Consequences for biodiversity conservation. Water 12 (1): 260. DOI: 10.3390/w12010260.

Chanamé-Zapata FC, Custodio-Villanueva M, Yaranga-Cano RM, Pantoja-Esquivel RA. 2018. Diversity of the riparian vegetation of high Andean wetlands of the Junín region, Peru. Rev Ambient Água 14 (3): e2271. DOI: 10.4136/1980-993X.

Coughlan NE, Cuthbert RN, Kelly TC, Jansen MAK. 2018. Parched plants: survival and viability of invasive aquatic macrophytes following exposure to various desiccation regimes. Aquat Bot 150: 9-15. DOI: 10.1016/j.aquabot.2018.06.001.

Da Silva RS, Ortega JCG, JACÓ TRF, Cabral GS, CORRÊA F, Virgilio LR, Montag LFA. 2024. Effect of local and regional factors on the structure of the fish communities associated with aquatic macrophyte stands in oxbow lakes on the Amazon floodplain. An Acad Bras Ciênc 96 (Suppl 1): e20230496. DOI: 10.1590/0001-3765202420230496.

de Neiff AP, Neiff JJ, Casco SL. 2006. Leaf litter decomposition in three wetland types of the Paraná River floodplain. Wetlands 26: 558-566. DOI: 10.1672/0277-5212(2006)26[558:LLDITW]2.0.CO;2.

Dong B-L, Qin B-Q, Gao G, Cai X-L. 2014. Submerged macrophyte communities and the controlling factors in large, shallow Lake Taihu (China): Sediment distribution and water depth. J Great Lakes Res 40 (3): 646-655. DOI: 10.1016/j.jglr.2014.04.007.

Fickbohm SS, Zhu W-X. 2006. Exotic purple loosestrife invasion of native cattail freshwater wetlands: Effects on organic matter distribution and soil nitrogen cycling. Appl Soil Ecol 32 (1): 123-131. DOI: 10.1016/j.apsoil.2004.12.011.

Fonseka HWL, Gunatilake SK, Jayawardana JMCK, Wijesekara SSRMDHR. 2023. KDU J Multidiscip Stud 5 (2): 34-44. DOI: 10.4038/kjms.v5i2.75.

Fraaije RGA, Poupin C, Verhoeven JTA, Soons MB. 2018. Functional responses of aquatic and riparian vegetation to hydrogeomorphic restoration of channelized lowland streams and their valleys. J Appl Ecol 56 (4): 1007-1018. DOI: 10.1111/1365-2664.13326.

Ghosh D, Biswas JK. 2015. Biomonitoring Macrophytes Diversity and Abundance for Rating Aquatic Health of an Oxbow Lakeecosystem in Ganga River Basin. Am J Phytomed Clin Ther 3 (10): 602-621.

Gopal B, Junk WJ, Davis J. 2000. Biodiversity in Wetlands: Assessment, Function and Conservation. Backhuys Publishers, The Netherlands.

Gopal B. 1990. Aquatic weed problems and management in Asia. In: Pieterse AH, Murphy KJ (eds). Aquatic Weeds. Oxford University Press, Oxford. DOI: 10.1093/oso/9780198541813.003.0016.

Heyne K. 1987. Tumbuhan Berguna Indonesia. Yayasan Sarana Wana Jaya, Jakarta. [Indonesian]

Irawanto R, Baroroh F. 2017. Kemampuan tumbuhan akuatik *Salvinia molesta* dan *Pistia stratiotes* sebagai fitoremediator logam berat tembaga. Pros Sem Nas Masy Biodiv Indon 3 (3): 438-445. DOI: 10.13057/psnmbi/m030324. [Indonesian]

Jones JI, Collins AL, Naden PS, Sear DA. 2011. The relationship between fine sediment and macrophytes in rivers. River Res Appl 28 (7): 1006-1018. DOI: 10.1002/rra.1486.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. In: Dodge DP (eds). Proceedings of the International Large River Symposium (LARS). Can Spec Publ Fish Aquat Sci 106: 110-127.

Junk WJ, Wantzen KM. 2004. The flood pulse concept: New aspects, approaches and applications - An update. In: Welcomme RL, Petr T (eds). Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries, Food and Agriculture Organization of the United Nations (FAO) and the Mekong River Commission (MRC). FAO, Bangkok.

Kamel KA. 2013. Phytoremediation potentiality of aquatic macrophytes in heavy metal contaminated water of El-Temsah Lake, Ismailia, Egypt. Middle East J Sci Res 14 (12): 1555-1568. DOI: 10.5829/idosi.mejsr.2013.14.12.7441.

Kawa D. 2021. The shapeshifting legend of amphibious plants explained. Plant Cell 33 (10): 3181-3182. DOI: 10.1093/plcell/koab196.

Kayima JK, Mayo AW. 2018. Characteristics of macrophytes in the Lubigi Wetland in Uganda. Intl J Biodivers Conserv 10 (10): 394-406. DOI: 10.5897/IJBC2018.1206.

Kusmana C, Hikmat A. 2015. Keanekaragaman hayati flora di Indonesia. J Pengelolaan Sumberdaya Alam dan Lingkungan 5 (2): 187-198. DOI: 10.19081/jpsl.5.2.187. [Indonesian]

Lopes A, Demarchi LO, Franco AC, Ferreira AB, Ferreira CS, Wittmann F, Santiago IN, da Cruz J, da Silva JS, Schöngart J, do Nascimento Gomes de Souza S, Piedade MTF. 2021. Predicting the potential distribution of aquatic herbaceous plants in oligotrophic Central Amazonian wetland ecosystems. Acta Bot Bras 35 (1): 22-36. DOI: 10.1590/0102-33062020abb0188.

Luke SH, Slade EM, Gray CL, Annammala KV, Drewer J, Williamson J, Agama AL, Ationg M, Mitchell SL, Vairappan CS, Struebig MJ. 2018. Riparian buffers in tropical agriculture: Scientific support, effectiveness and directions for policy. J Appl Ecol 56 (1): 85-92. DOI: 10.1111/1365-2664.13280.

Machado-Filho H, de Vasconcellos Barbosa MR, Torres CRM, de Fátima de Araújo M, Pedro-Silva L, de Melo JIM, Zickel CS. 2021. Plants associated with aquatic and marshy environments in the state of Paraíba, northeastern Brazil. Acta Bras 5 (1): 13-24. DOI: 10.22571/2526-4338454.

Malik A. 2007. Environmental challenge vis a vis opportunity: The case of water hyacinth. Environ Intl 33 (1): 122-138. DOI: 10.1016/j.envint.2006.08.004.

Mandal RN, Bera P. 2024. Macrophytes used as multifaceted benefits including feeding, bioremediation, and symbiosis in freshwater aquaculture-A review. Rev Aquac 17 (1): e12983. DOI: 10.1111/raq.12983.

Maranho LT, Gomes MP. 2024. Morphophysiological adaptations of aquatic macrophytes in wetland-based sewage treatment systems: Strategies for resilience and efficiency under environmental stress. Plants 13 (20): 2870. DOI: 10.3390/plants13202870.

Miretzky P, Saralegui A, Cirelli AF. 2004. Aquatic macrophytes potential for the simultaneous removal of heavy metals (Buenos Aires, Argentina). Chemosphere 57 (8): 997-1005. DOI: 10.1016/j.chemosphere.2004.07.024.

Mustafa HM, Hayder G. 2020. Performance of *Pistia stratiotes*, *Salvinia molesta*, and *Eichhornia crassipes* aquatic plants in the tertiary treatment of domestic wastewater with varying retention times. Appl Sci 10 (24): 9105. DOI: 10.3390/app10249105.

Naiman RJ, Décamps H. 1997. The ecology of interfaces: Riparian zones. Ann Rev Ecol Syst 28 (1): 621-658. DOI: 10.1146/annurev.ecolsys.28.1.621.

Nasution AS, Windarti W, Efawani E. 2019. Identification of macrophyta in the swamp area of the Sawah Village, Kampar Regency, Riau Province. Asian J Aquat Sci 2 (2): 95-106. DOI: 10.31258/ajoas.2.2.95-106. [Indonesian]

O'Hare MT, Baattrup-Pedersen A, Baumgarte I, Freeman A, Gunn IDM, Lázár AN, Sinclair R, Wade AJ, Bowes MJ. 2018. Responses of aquatic plants to eutrophication in rivers: A revised conceptual model. Front Plant Sci 9: 451. DOI: 10.3389/fpls.2018.00451.

Phillips G, Willby N, Moss B. 2016. Submerged macrophyte decline in shallow lakes: What have we learnt in the last forty years? Aquat Bot 135: 37-45. DOI: 10.1016/j.aquabot.2016.04.004.

Pramono CL, Alyodya DA, Restuti EJ, Meilani F, Sholiqin M, Dewangga A, Yap CK, Setyawan AD. 2024. Invasive and non-invasive macro aquatic plants in the Upper Bengawan Solo River, Indonesia. Intl J Bonorowo Wetlands 14 (1): 37-48. DOI: 10.13057/bonorowo/w140105.

Prasad MNV. 2004. Phytoremediation of metals in the environment for sustainable development. Proc Indian Natl Sci Acad B70 (1): 71-98.

Prasetyo S, Subehi L, Ismail SN. 2025. Biotic communities: Invasive macrophytes. In: Santos-Borja AC, Subehi L, Maghfiroh M, Rahmat A (eds). Progress on Ecosystem Restoration of Tropical Inland Waters. Springer, Singapore. DOI: 10.1007/978-981-96-2284-9_9.

Rai PK. 2008. Heavy metal pollution in aquatic ecosystems and its phytoremediation using wetland plants: An ecosustainable approach. Intl J Phytoremediation 10 (2): 133-160. DOI: 10.1080/15226510801913918.

Reddy KR, D'Angelo EM. 1997. Biogeochemical indicators to evaluate pollutant removal efficiency in constructed wetlands. Water Sci Technol 35 (5): 1-10. DOI: 10.1016/S0273-1223(97)00046-2.

Richardson DM, Rejmánek M. 2011. Trees and shrubs as invasive alien species - A global review. Divers Distrib 17 (5): 788-809. DOI: 10.1111/j.1472-4642.2011.00782.x.

Saha TK, Pal S, Sarda R. 2022. Impact of river flow modification on wetland hydrological and morphological characters. Environ Sci Pollut Res 29 (50): 75769-75789. DOI: 10.1007/s11356-022-21072-6.

Schultz R, Dibble E. 2011. Effects of invasive macrophytes on freshwater fish and macroinvertebrate communities: the role of invasive plant traits. Hydrobiologia 684: 1-14. DOI: 10.1007/s10750-011-0978-8.

Singh RP, Agrawal M. 2010. Variations in heavy metal accumulation, growth and yield of rice plants grown at different sewage sludge amendment rates. Ecotoxicol Environ Saf 73 (4): 632-641. DOI: 10.1016/j.ecoenv.2010.01.020.

Sood A, Uniyal PL, Prasanna R, Ahluwalia AS. 2012. Phytoremediation potential of aquatic macrophyte, *Azolla*. Ambio J Hum Environ 41 (2): 122-137. DOI: 10.1007/s13280-011-0159-z.

Subashini V, Swamy VS. 2014. Phytoremediation of cadmium and chromium contaminated soils by *Cyperus rotundus* L. Am Intl J Res Sci 6 (1): 97-101.

Subehi L, Uno H, Imroatushshoolikhah, Sulastri, Yustiawati, Toruan RL, Ajie GS, Jasalesmana T, Dianto A, Afandi AY, Sulawesty F, Julzarika A, Ramadhan Y, Triwati, Nakano S. 2022. Ecological heterogeneity of oxbow and floodplain lakes along the Kapuas Riverine system. IOP Conf Ser: Earth Environ Sci 1062: 012019. DOI: 10.1088/1755-1315/1062/1/012019.

Suridiakusumah A, Mulyani O, Sudirja R, Sofyan ET, Maulana MHR, Mulyono A. 2020. Analysis of water quality in the Cipeusing River, Indonesia using the pollution index method. Acta Ecol Sin 41 (3): 177-182. DOI: 10.1016/j.chnaes.2020.08.001.

Tabacchi E, Lambs L, Guilloy H, Planty-Tabacchi A-M, Muller E, Décamps H. 2000. Impacts of riparian vegetation on hydrological processes. Hydrol Proc 14 (16-17): 2959-2976. DOI: 10.1002/1099-1085(200011/12)14:16/17<2959::AID-HYP129>3.0.CO;2-B.

Thomaz SM, Carvalho P, Padial AA, Kobayashi JT. 2009. Temporal and spatial patterns of aquatic macrophyte diversity in the Upper Paraná River floodplain. Braz J Biol 69 (Suppl 2): 617-625. DOI: 10.1590/S1519-69842009000300016.

Van Geest GJ, Coops H, Roijackers RMM, Buijse AD, Scheffer M. 2005. Succession of aquatic vegetation driven by reduced water-level fluctuations in floodplain lakes. J Appl Ecol 42 (2): 251-260. DOI: 10.1111/j.1365-2664.2005.00995.x.

Verma M, Singh P, Dhanorkar M. 2023. Remediation of emerging pollutants using biochar derived from aquatic biomass for sustainable waste and pollution management: A review. J Chem Technol Biotechnol 99 (2): 330-342. DOI: 10.1002/jctb.7548.

Walujo EB. 2002. Les ecosystemes domestiques par l'homme and l'ancien royaume insana Timor. Reinwardtia 11 (5): 295-417.

Wang Q, Yuan X, Willison JHM, Zhang Y, Liu H. 2014. Diversity and above-ground biomass patterns of vascular flora induced by flooding in the drawdown area of China's Three Gorges Reservoir. PLoS One 11 (1): e0147452. DOI: 10.1371/journal.pone.0147452.