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Invasive and non-invasive macro aquatic plants in the Upper Bengawan Solo River, Indonesia

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[2]Department of Biology, Faculty of Science, Universiti Putra Malaysia. 43400 UPM Serdang, Selangor, Malaysia
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Abstract. *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: 37-48.* Macrophytes or aquatic plants are plants that have habitats in water. The uncontrolled growth of macrophytes causes the invasion of alien plant species in the Bengawan Solo River, Indonesia. This study aimed to identify the diversity of invasive and non-invasive macrophytes in the upstream, midstream and downstream of Bengawan Solo River. The methods used were a combination of cruising survey and purposive sampling using line transects. Vegetation data was collected in December 2023 and subject to the analysis of the Shannon-Wiener Species Diversity Index, Simpson Diversity Index, Evenness Index, and Margalef Species Richness Index. The results showed there were 23 macrophyte species with 2,391 individuals spread across three observation stations. There were two types of growth, i.e., free-floating and emergent growth, and they were divided into aquatic and semi-aquatic species. There were 17 invasive plant species, with the most common being *Eichhornia crassipes,* and 6 non-invasive species, with the most common being *Digitaria nuda.* Based on the results of the vegetation analysis, invasive plants had an index of 2.11 (medium), and non-invasive plants had a 0.82 (low). The total Simpson Diversity Index was 0.74 (high), with invasive plants at 0.73 (high) and non-invasive plants at 0.73 (high). The total Evenness Index was 0.69 (high), with invasive plants at 0.74 (high) and non-invasive at 0.46 (medium). The total Margalef Species Richness Index was 1.69 (low), with invasive plants at 1.30 (low) and non-invasive at 0.76 (low). The uncontrolled growth of invasive macrophytes can lead to reduced integrity of the aquatic ecosystem. Thus, invasive alien species must be managed with effective strategies to control their growth.

Keywords: Aquatic, diversity, invasive, plant

INTRODUCTION

Bengawan Solo River is the longest river in Java Island, Indonesia, extending 600 km and encompassing two provinces, namely Central Java and East Java (Lusiana et al. 2022). The Bengawan Solo watershed is divided into three sub-watersheds, namely the upstream, the midstream, and the downstream (Apriana et al. 2017). Bengawan Solo River plays an important role for the surrounding communities as the source of consumed water and agriculture irrigation, especially in Central Java (Ningsih et al. 2020; Hasan et al. 2023). Bengawan Solo River has fairly high anthropogenic pressures in the form of agricultural activities upstream, while in the midstream, there are densely populated areas and industrial activities, and downstream, there are fish pond businesses (Valen et al. 2022). Such activities have negative impacts on aquatic organisms living in the river (Yusron and Jaza 2021).

Macrophytes are aquatic plants that float, sink, and grow on the bottom, surface or submerged in the waters (Nasution et al. 2019). Macrophytes are one of the important elements in aquatic ecosystems (Bucholc et al. 2014) due to their role in both biota and humans (Ali et al. 2020; Swe et al. 2021). Macrophytes serve as food sources of aquatic fauna and a place for fishes to attach their eggs, and their presence increases the complexity and heterogeneity of habitats that greatly affect other aquatic organisms, such as micro-and macro-invertebrates (Budka et al. 2019; Inayah et al. 2023; Thomaz 2023)

Bengawan Solo River contains various species of macrophytes (Le Moal et al. 2019). However, with increasing human pressures, there is uncontrolled growth of macrophytes, causing the widespread occurrence of invasive alien species, including water hyacinths or *Eichhornia crassipes* (Mart.) Solms and *Pistia stratiotes* L (Zahro and Nisa 2020). Invasive alien plants are plant species that originate outside the natural habitat of a region and spread rapidly and aggressively, inhibiting the formation and growth of native plants and disrupting existing local ecosystem components, such as soil cover, nutrient cycles, fire patterns, and hydrology (Weidlich et al. 2020). The dominating nature of the habitat is the main characteristic of invasive species (Rahmawati and Rosleine 2023).

In recent years, the water quality in the Bengawan Solo watershed has decreased. This is due to the large amount of industrial and domestic wastes discharged into water bodies, causing the concentration of organic matter to exceed water quality standards (Aboyitungiye et al. 2021). This condition leads to increased nutrient concentrations in the waters, triggering the growth of several macrophytes, particularly invasive alien plants, and eventually affecting plant and animal diversity and composition (Kusumastuti et al. 2021).

Macrophytes can be used as bioindicators of water pollution due to the increase of concentrations of organic matter where some species flourish while some others die because of such conditions (Wang et al. 2021; Amrillah et al. 2023). These organic matters can be sourced from livestock activities, agriculture, fish farming, and household waste in rivers (Lusiana et al. 2022). The increase in organic matter in the water leads to the uncontrolled growth of some macrophytes, especially water hyacinths (Aida et al. 2022). Fitrihidajati and Nurfadlillah (2022) state that several species, including *E. crassipes*, can be used as bioindicators for lead pollution since they can absorb lead dissolved in river water.

The existence of aquatic plants needs to be maintained naturally to preserve ecosystem integrity and species diversity, as in the case of the aquatic garden in the Eka Karya Botanic Garden in Bali (A'tourrohman 2020). Merly et al. (2023) found that the diversity of aquatic plants is useful to maintain the ecosystem integrity of Mayo Swamp with the presence of species such as *Typha angustifolia* L., which is effective in remediating contaminated soil and water. Considering the negative impacts of invasive alien species, it is necessary to assess the diversity of invasive and non-invasive macrophytes. Therefore, this study aims to investigate the diversity of invasive and non-invasive species of macroaquatic plants in the Bengawan Solo River. The results of this study can be used to inform suitable management strategies in the Bengawan Solo River, including the prevention of invasive species.

MATERIALS AND METHODS

Study area and period

The research was conducted in the Upper Bengawan Solo River, Central Java, Indonesia (Figure 1), with several sampling locations established in the upstream (Wonogiri District), midstream (Sukoharjo District and Surakarta City), and downstream (Karanganyar and Sragen Districts), which was determined based on the adjacency of the districts (Adjie and Utomo 2017). This research was conducted on 15-17 December 2023. The upstream in Wonogiri consisted of 2 sampling points. In comparison, the midstream in Sukoharjo and Surakarta and the downstream in Karanganyar and Sragen each consisted of 4 sampling points (Table 1), which were determined based on the accessibility of each location (Kaky et al. 2020) and data reliability and validity (Orr et al. 2021).

Table 1. Distribution of stations, sampling locations and geographical coordinates in the Upper Bengawan Solo River, Central Java, Indonesia

Station	Point ID	Sampling location	Geographical coordinate
Upstream	1	Wonogiri (Pokohkidul)	7°50'00"S 110°55'34"E
	2	Wonogiri (Giritirto)	7°49'31"S 110°55'34"E
Midstream	3	Sukoharjo (Bacem Bridge, Semanggi)	7°36'49.9"S 110°49'10.5"E
	4	Sukoharjo (Colo Dam, Nguter)	7°45'03"S 110°54'01"E
	5	Surakarta (Jurug Bridge, Jebres)	7°34'00"S 110°51'39"E
	6	Surakarta (Sewu Village)	7°34'37"S 110°50'39"E
Downstream	7	Karanganyar (Ringroad Bridge, Dalon)	7°32'46"S 110°52'19"E
	8	Karanganyar (Ngabean, Kebakramat)	7°31'26"S 110°52'27"E
	9	Sragen (Sidokerto, Plupuh)	7°29'22"S 110°53'33"E
	10	Sragen (Pringanom, Masaran)	7°26'48"S 110°54'56"E

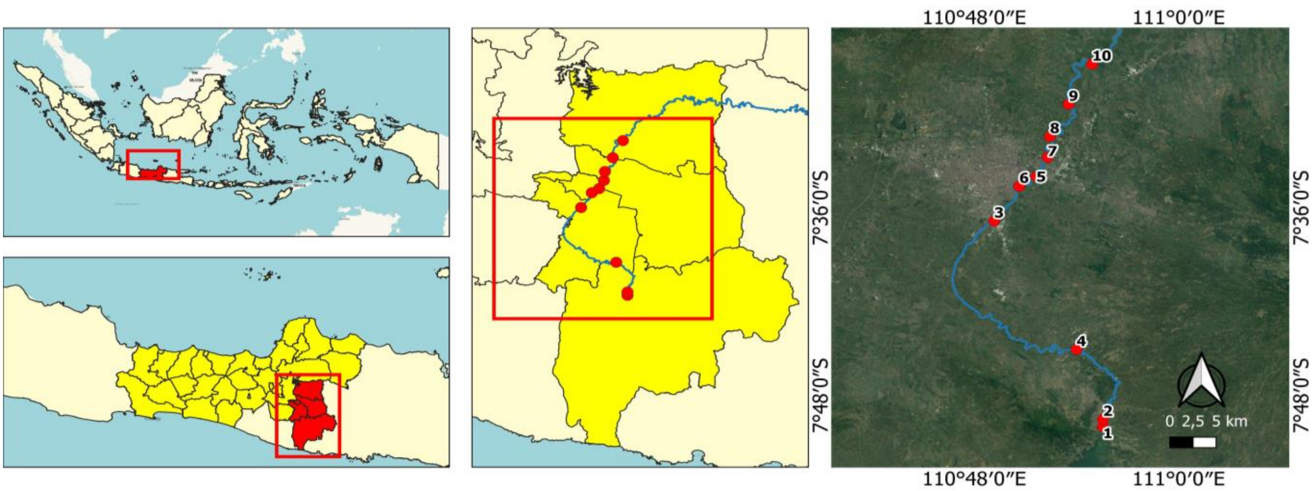

Figure 1. Map of study area showing the sampling points along Upper Bengawan Solo River, Central Java, Indonesia

Data collection procedures

Data was collected using the cruising method and purposive transect line. We explored the river at a deliberately determined length at each location, combined with the establishment of a 500-meter transect line and a sub-transect with a length of 250 m (Nino 2019). Along the transect line, a rope was stretched from the edge of the land toward the river, with a length of 5 m (Yunita et al. 2023). Along this line, we documented aquatic plants. The research tools and materials included plant nets, tally sheets and smartphones. Species were identified using online databases, including gbif.org and Inaturalist and the book "Guide Book to Invasive Alien Plant Species in Indonesia," published by the Ministry of Environment and Forestry (2015).

Data analysis

The vegetation data obtained was classified based on growth type, habitat (aquatic/semi-aquatic), number of individual species, invasive/non-invasive, and the use of these aquatic plants. Vegetation analysis was done to calculate the Shannon-Wiener Species Diversity Index, Simpson Dominance index, Evenness Index, and Margalef Species Richness Index (Sutrisna et al. 2018).

Shannon–Wiener diversity index (Shannon and Weaver 1949)

$$H' = -\sum_{i=1}^{s} \left(\frac{ni}{N}\right) \ln\left(\frac{ni}{N}\right)$$

Where:
H' : Shannon-Wiener Species Diversity Index
Pi : ni/N
ni : Number of species i
N : Total number of individuals
S : The sum of all individuals

The Shannon-Wiener Species Diversity Index was classified as low (H'<1), medium (1<H'<3) and high (H'>3).

Simpson Dominance Index (Thukral 2017)

$$E = \sum \left(\frac{ni}{N}\right)^2$$

Where:
C : Species Dominance Index
Ni : Number of individuals of the i-th species on each plot
N : Number of individuals of the i-th species on all plots

The category for species dominance is low (C<0.1), medium (0.5<C<0.75) and high (0.75<C<1).

Evenness Index (Redowan 2015)

$$E = \frac{H'}{LnS}$$

Where:
E : Evenness Index
H' : Shannon Wiener Species Diversity Index
S : Number of all species

The category for evenness is low (E<0.3), medium (0.3<E<0.6) and high (E>0.6).

Margalef Species Richness Index (Margalef 1958)

$$R = \frac{S-1}{Ln\ N}$$

Where:
R : Margalef Species Richness Index
S : Number of all species
N : Number of individuals of the i-th species on all plots

The category for Margalef species richness was low (R<3.5), medium (3.5<R<5.0) and high (R>5.0).

RESULTS AND DISCUSSION

Macrophyte species diversity in Bengawan Solo River

Table 2 shows 23 species of macrophytes documented in Bengawan Solo River with 2,391 individuals spread across 3 observation stations. This species number is higher than the species found in water bodies in Kyiv, Ukraine, with only 3 species. The river in Kyiv is a large river that crosses several countries in Europe (Prokopuk et al. 2023). There were only two growth types of macrophytes in the studied area: free-floating (19 species) and emergent (4 species). Free-floating is a plant that is not attached to the bottom of sediment, or it has leaves that float in the water while its roots are submerged (Lesiv et al. 2020). Water movement influences the free-floating type of growth due to wind blows so that it can easily move from one place to another (Sudipta et al. 2020). In addition, free-floating species can grow in all types of water bodies and are not affected by water depth (Hussner et al. 2021).

Meanwhile, emergent growth type is usually found in submerged soil where groundwater is around 0.5 m below the ground surface. The characteristic of this plant is that its shoots and leaves are above the water, with its roots remaining below the surface (Yuliasni et al. 2023). Emergent growth types were often found at research stations except at the downstream stations such as Karanganyar (ring road bridge) and Sragen. This is because at several research stations, such as upstream, middle, and downstream (Ngabean), several parts of the riverbank are slightly submerged in water. According to Yang et al. (2020), factors that influence emergent plant growth are water levels and competitive interactions between species.

No submerged type was found in the Bengawan Solo River. This is a type of aquatic plant that grows underwater with roots in mud. This type is rarely found because several factors influence its growth, such as the water's depth and color, which is quite murky, so the amount of light entering it and the low gas saturation does not support their living (Lesiv et al. 2020). According to Hussner et al. (2021), the type of submerged growth is influenced by water depth factors because it is related to light requirements. In addition, the submerged growth type is not found in all study sites.

Distribution of aquatic and semi-aquatic species in Bengawan Solo River

Based on their habitat, macrophytes are divided into aquatic and semi-aquatic species (Ali et al. 2020). Table 2 shows that there were 10 species of aquatic plants across 10 observation locations. Aquatic plant species such as *E. crassipes* were found in Wonogiri to Karanganyar. This species was also found in Sragen, but the number was lower than that in Surakarta City. Bengawan Solo River is close to residential areas and subjected to domestic waste, which can lead to eutrophication (Arifianto et al. 2021). Aquatic plant species such as *Limnophyton obtusifolium* (L.). Furthermore, *Ipomoea aquatica* Forssk., *Portulaca oleracea* L., and *Azolla pinnata* R.Br. are found in Sukoharjo and Surakarta; *I. aquatica* was found at Pokohkidul and Giritirto stations, Wonogiri. In comparison, at the downstream station, not too many species of aquatic plants were found; aquatic species were found in downstream locations, such as *E. crassipes, P. stratiotes,* and *A. pinnata*. The distribution of aquatic species at the downstream station was lower than at the upstream and midstream stations, which is due to the large number of industries in the Karanganyar and Sragen areas that do not manage industrial liquid waste properly and are discharged into the Bengawan Solo River (Mustikasari 2019; Hidayad 2020). In addition, the rainy season enlarges water currents, so many aquatic plants are carried away by rainwater at downstream stations (Thiara et al. 2022).

Naturally, semi-aquatic plants can partially live in water (Inelova et al. 2023). Based on Table 2, the number of semi-aquatic plants found was 13 species across 7 observation locations. Semi-aquatic species were not found in Ngabean Karanganyar, Sidokerto, and Proanganom Sragen. This is because many anthropogenic activities around the Bengawan Solo River produce much waste, making semi-aquatic plants rarely found at the downstream stations (Prajoko 2018). In addition, the downstream area of Bengawan Solo River does not have river boundaries, making it difficult to find semi-aquatic species. At the midstream station, semi-aquatic plants were quite diverse, including *Mimosa pudica* L., *Eclipta prostrata* (L.) L., and *Cyperus alternifolius* L. This is due to relatively few anthropogenic activities (Ramadhani 2016). At the upstream station, the distribution of semi-aquatic plant species was also still diverse, including *M. pudica*, *Digitaria nuda* Schumach., *Alternanthera sessilis* (L.) DC., *E. prostrata, Grangea maderaspatana* (L.) Poir. and several other species.

Invasive and non-invasive macrophytes in the Bengawan Solo River

In this study, several invasive alien plants were found along the Bengawan Solo River. A total of 17 invasive alien plant species were identified from the 23 plants documented, and each station had at least one species of invasive alien plant. Invasive alien plant species found along the Bengawan Solo River are caused by several factors, one of which is anthropogenic factors (Li et al. 2022). These anthropogenic factors will significantly influence ecosystem structure and function; for example, river water contaminated with heavy metals will alter water quality, affecting the relationship between species composition and ecological processes (Tokhtar et al. 2020).

At the upstream station, 9 species were found. Invasive alien plants that dominated this station were *I. aquatica* because the flow speed significantly influences the growth rate of this species, where high current speeds will reduce the capability of this plant to absorb nitrates and phosphates (Melani et al. 2020). The *E. crassipes* were also found at the upstream station because the water is contaminated by waste, resulting in eutrophication, especially phosphorus (P) and nitrogen (N) (Maulidyna et al. 2021). The presence of *E. crassipes* reduces dissolved oxygen and blocks sunlight from entering the water, disturbing aquatic ecosystems. The *Pontederia vaginalis* Burm.f. is one of the most invasive plants in the world because this species is perennial and multiplies rapidly in rivers in tropical and subtropical regions (Chen et al. 2017). The *P. vaginalis* is able to cover several hectares of open water because it has a fast reproduction rate and complex root structure (Ghoussein et al. 2023). The *M. pudica* were found on the river banks, reducing the light to penetrate the soil surface so that the plants below *M. pudica* outcompete (Kato-Noguchi 2023). The *L. obtusifolium* was not abundant in the river and is not considered invasive. However, these plants can spread aggressively and affect aquatic ecosystems (Ali and Elhajaz 2021). The *L. flava* is considered invasive because it usually appears when flooded and inhabits shallow swamps. However, this plant can be used for animal feed to control its spread (Chandran and Ramasamy 2015). The *P. oleracea* is also known as one of the most invasive plants worldwide. It can spread very quickly and form dense populations, and it is usually located on river banks with many landfills (Anđelković et al. 2022). The *E. prostrata* is an invasive plant that can grow and multiply rapidly due to the high nutrient content in riverside soils (Liao et al. 2023). The *C. alternifolius* can multiply rapidly in wetlands and form dense stands that can potentially disrupt aquatic ecosystems in the Bengawan Solo River (Verloove 2014).

There were 14 invasive alien plant species found at the midstream station. The highest number of invasive alien species was *E. crassipes*, with 131 individuals. At this station, the water was contaminated by livestock waste and batik dye waste (Hanum et al. 2022). One of the impacts of *E. crassipes* is the reduction of dissolved oxygen and blocking sunlight from entering the water, which ultimately causes aquatic ecosystems to be disturbed (Maulidyna et al. 2021). A large number of *Lemna minor* L. were also found at this station. The calmer water flow is also a factor at this station, where livestock waste is discharged by the surrounding community into the river, resulting in a relatively high nutrient content that triggers excessive growth (Ceschin et al. 2021) and disrupts aquatic ecosystems (Mariani et al. 2020). The *P. stratiotes* can multiply vegetatively rapidly, adversely affecting the environment and biodiversity because of their ability to form a dense layer that blocks the watercourse, hindering fishing and boat transportation and impeding the flow of water in irrigation and flood control canals (Galal et al. 2019).

Table 2. List of macrophytes in Bengawan Solo River, Central Java, Indonesia

Station	Location	Species	Family	Number of Individuals	Growth Type	Habitat Type	Invasiveness
Upstream	Wonogiri (Pokohkidul)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	7	Free-floating	Aquatic	Invasive
		Pontederia vaginalis Burm.f.	Pontederiaceae	95	Emergent	Semi-aquatic	Invasive
		Limnocharis flava (L.) Buchenau	Limnocharitaceae	25	Emergent	Aquatic	Invasive
		Mimosa pudica L.	Fabaceae	89	Emergent	Semi-aquatic	Invasive
		Ipomoea aquatica Forssk.	Convolvulaceae	110	Emergent	Aquatic	Invasive
		Digitaria nuda Schumach	Poaceae	5	Emergent	Semi-aquatic	Non-invasive
		Limnophyton obtusifolium (L.) Miq.	Alismataceae	30	Emergent	Aquatic	Invasive
		Portulaca oleracea L.	Portulacaceae	1	Emergent	Aquatic	Invasive
		Eclipta prostrata (L.) L.	Asteraceae	14	Emergent	Semi-aquatic	Invasive
		Gomphrena celosioides Mart.	Amaranthaceae	5	Emergent	Semi-aquatic	Non-invasive
	Wonogiri (Giritirto)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	5	Free-floating	Aquatic	Invasive
		Ipomoea aquatica Forssk.	Convolvulaceae	4	Emergent	Aquatic	Invasive
		Grangea maderaspatana (L.) Poir	Asteraceae	6	Emergent	Semi-aquatic	Non-invasive
		Mimosa pudica L.	Fabaceae	21	Emergent	Semi-aquatic	Invasive
		Cyperus alternifolius L.	Cyperaceae	5	Emergent	Semi-aquatic	Invasive
Midstream	Sukoharjo (Bacem Bridge, Semanggi)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	325	Free-floating	Aquatic	Invasive
		Lemna minor L.	Lemnaceae	234	Free-floating	Aquatic	Invasive
		Azolla pinnata R.Br.	Salviniaceae	85	Free-floating	Aquatic	Invasive
		Mimosa pudica L.	Fabaceae	3	Emergent	Semi-aquatic	Invasive
	Sukoharjo (Colo Dam, Nguter)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	4	Free-floating	Aquatic	Invasive
		Ipomoea aquatica Forssk.	Convolvulaceae	8	Emergent	Aquatic	Invasive
		Alternanthera philoxeroides (Mart.) Griseb	Amaranthaceae	3	Emergent	Aquatic	Non-invasive
		Digitaria nuda Schumach	Poaceae	6	Emergent	Semi-aquatic	Non-invasive
		Eclipta prostrata (L.) L.	Asteraceae	1	Emergent	Semi-aquatic	Invasive
		Limnophyton obtusifolium (L.) Miq.	Alismataceae	7	Emergent	Aquatic	Invasive
		Azolla pinnata R.Br.	Salviniaceae	15	Free-floating	Aquatic	Invasive
		Impatiens glandulifera Royle	Balsaminaceae	1	Emergent	Semi-aquatic	Invasive
		Portulaca oleracea L.	Portulacaceae	5	Emergent	Aquatic	Invasive
		Pistia stratiotes L.	Araceae	35	Free-floating	Aquatic	Invasive
		Mimosa pudica L.	Fabaceae	3	Emergent	Semi-aquatic	Invasive
		Tridax procumbens L.	Asteraceae	12	Emergent	Semi-aquatic	Invasive

	Surakarta (Jurug Bridge, Jebres)	*Grangea maderaspatana* (L.) Poir	Asteraceae	2	Emergent	Semi-aquatic	Non-invasive
		Eichhornia crassipes (Mart.) Solms	Pontederiaceae	127	Free-floating	Aquatic	Invasive
		Ludwigia adscendens (L.) H.Hara	Onagraceae	86	Emergent	Aquatic	Invasive
		Achyranthes aspera L.	Amaranthaceae	1	Emergent	Semi-aquatic	Non-invasive
		Murdania spirata (L.) G.Brückn.	Commelinaceae	1	Emergent	Semi-aquatic	Non-invasive
		*Limnocharis flava (*L.) Buchenau	Limnocharitaceae	15	Emergent	Aquatic	Invasive
		Pistia stratiotes L.	Araceae	29	Free-floating	Aquatic	Invasive
		Mimosa pudica L.	Fabaceae	5	Emergent	Semi-aquatic	Invasive
		Cyperus alternifolius L.	Cyperaceae	8	Emergent	Semi-aquatic	Invasive
		Alternanthera sessilis (L.) DC.	Amaranthaceae	3	Emergent	Semi-aquatic	Invasive
	Surakarta (Sewu Village)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	190	Free-floating	Aquatic	Invasive
		Azolla pinnata R.Br.	Salviniaceae	15	Free-floating	Aquatic	Invasive
		Pistia stratiotes L.	Araceae	35	Free-floating	Aquatic	Invasive
		Lemna minor L.	Lemnaceae	46	Free-floating	Aquatic	Invasive
		Mimosa pudica L.	Fabaceae	3	Emergent	Semi-aquatic	Invasive
Downstream	Karanganyar (Ringroad Bridge, Dalon)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	154	Free-floating	Aquatic	Invasive
		Hippobroma longiflora (L.) G.Don	Campanulaceae	14	Emergent	Semi-aquatic	Invasive
		Azolla pinnata R.Br.	Salviniaceae	36	Free-floating	Aquatic	Invasive
		Alternanthera sessilis (L.) DC.	Amaranthaceae	16	Emergent	Semi-aquatic	Non-invasive
	Karanganyar (Ngabean, Kebakramat)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	90	Free-floating	Aquatic	Invasive
		Azolla pinnata R.Br.	Salviniaceae	16	Free-floating	Aquatic	Invasive
		Pistia stratiotes L.	Araceae	9	Free-floating	Aquatic	Invasive
	Sragen (Sidokerto, Plupuh)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	178	Free-floating	Aquatic	Invasive
		Azolla pinnata R.Br.	Salviniaceae	6	Free-floating	Aquatic	Invasive
		Pistia stratiotes L.	Araceae	40	Free-floating	Aquatic	Invasive
	Sragen (Pringanom, Masaran)	*Eichhornia crassipes* (Mart.) Solms	Pontederiaceae	56	Free-floating	Aquatic	Invasive
		Azolla pinnata R.Br.	Salviniaceae	25	Free-floating	Aquatic	Invasive
		Pistia stratiotes L.	Araceae	16	Free-floating	Aquatic	Invasive

The *E. prostrata* grows in a humid environment where there is no soil deposit at the midstream and downstream and only water. *Impatiens glandulifera* Royle was only found at this station. This plant usually lives on river banks and is able to displace native vegetation due to its rapid growth and abundant seed production, reducing the richness and diversity of species in aquatic ecosystems by 11-30% (Coakley and Petti 2021). *Tridax procumbens* L. is an invasive plant that can thrive in various habitats due to its ability to tolerate various temperatures and solar radiation (Panda and Behera 2019). This plant can adapt to various types of soil and can spread seeds easily so that they can thrive on river banks (Mecina et al. 2016). *Ludwigia adscendens* (L.) H.Hara can develop rapidly and form a solid layer on the water's surface, blocking light and oxygen. This plant can also release secondary metabolites into the underlying ecosystem, limiting the growth of native plants (Thiébaut et al. 2018). The *A. sessilis* grows quickly in disturbed areas and wetland habitats. It can reproduce in various conditions and has fast growth so that this plant can outcompete native vegetation in aquatic ecosystems (Shen et al. 2021).

At the downstream stations, there were 4 species of invasive alien plants (Table 2). At this station, the river body was contaminated by industries that discharged their waste into the river (Sulistiono et al. 2023). Waste that often contains nutrients and is discharged into river water will feed invasive alien plants, increasing the population of invasive alien plants and damaging aquatic ecosystems (Prabakaran et al. 2019). At this station, there were more than 324 individuals of *E. crassipes* because the river was contaminated by sewage, which allowed it to grow and develop quickly. In addition, many small plants, such as *A. pinnata*, were also found. Because of the slow water flow, this plant can thrive at this station. Excessive growth of *A. pinnata* will result in disturbed ecosystems due to decreased oxygen levels in the water (Bhujel and Rizal 2022). *Hippobroma longiflora* (L.) G.Don was also found at this station due to excessive nutrient levels caused by waste disposal, which accelerates the growth of this plant (Mosyaftiani et al. 2019).

Ecological indices of macrophytes

Shannon-Wiener Species Diversity Index

Table 3 shows that the Shannon-Wiener Species Diversity Index of invasive plant species found at the three research stations was 2.11, or in the medium category. If differentiated based on the station, the upstream had an index of 1.90, the midstream of 2.34, and the downstream with 2.09. In contrast, the diversity index for non-invasive species was only 0.82 (low), with the index upstream being 1.09, midstream was 1.38, and no non-invasive species were found downstream. When the invasive and non-invasive species combined, the Shannon Wiener diversity index of the three stations was 2.17 (moderate), with the index at the upstream being 2.03 (medium), the midstream was 2.38 and downstream was 2.09. The higher diversity index in the midstream is due to fewer industrial and agricultural activities compared to the upstream and downstream areas (Valen et al. 2022). Many factors cause the diversity to be moderate, including weather, water flow, temperature, water discharge, nutrients water and environmental factors (Gao et al. 2022).

The diversity of aquatic plants is one of the indicators of the sustainability of river ecosystems (Biggs et al. 2017). Ceschin et al. (2021) stated that aquatic plants provide abiotic, biotic, and cultural elements in aquatic ecosystems. The diversity index is influenced by the number of species and the number of individuals from each species (Bezaredie et al. 2023). The presence of invasive alien species is an indicator of the suppression of local species in their habitat (Thiemer et al. 2023). Table 4 shows that the Shannon Wiener diversity index for macro aquatic plant species in the Bengawan Solo River is in the moderate category. The moderate diversity in the Bengawan Solo River area is likely influenced by weather (Siddha and Sahu 2022). The reduction in water discharge in the upstream area due to the prolonged dry season causes the water to recede; therefore, the species and number of individuals found were small. In addition, fairly fast current conditions are a factor that causes the diversity of floating-type plant species to be carried faster by the current toward the midstream area (O'Hare et al. 2018). This is almost the same as the condition of Chinese waters, which explains that the condition of macroaquatic plants is influenced by the speed of currents that hit aquatic plants (Zhou et al. 2023).

The low diversity of aquatic plant species downstream is due to high currents and minimal discharge (Gholami et al. 2020). However, in certain seasons, water plants will spread rapidly if stagnant water conditions occur, there is no heavy rain, and the main gate of the dam upstream is not opened, then water plants of certain types, such as *E. crassipes*, *P. stratiotes*, *A. pinnata*, and *L. minor* will be found along the water of Bengawan Solo River. The same study by Numbere et al. (2019) in Nigeria revealed that invasive aquatic plants will find it easier to develop diversity in stagnant and stable water conditions. Invasive species grow and develop very fast and easily dominate and cover the water surface (Weidlich et al. 2020). Stefanidis et al. (2021) explained that the heterogeneity and distribution of aquatic plants influence the diversity of aquatic plants. Furthermore, Zhang et al. (2017) revealed that the stability of aquatic plants in China is influenced by climate change, eutrophication, explosion of invasive species, reclamation, and anthropogenic activities. The activities of households and large-scale industries are also one of the causes of the entry of pollutants into the water, disrupting the continuous diversity. As in South Africa, many aquatic plants are reduced due to pollutants and contamination by industry activities, affecting water quality and species (Edokpayi et al. 2017). The condition of Bengawan Solo River being used for industrial waste has an impact on the diversity of aquatic plants, therefore increasing the dominance of invasive plants.

Simpson Diversity Index

The Simpson Diversity Index of invasive aquatic plants at the tree stations reached 0.73 or moderate (Table 3), where the index upstream was 0.78 (high), midstream was

0.69, and downstream was 0.44 (low). On the other hand, the Simpson Diversity Index of non-invasive aquatic plants at the upstream and midstream was 0.71 and 0.76 or in the high category, and no non-invasive species were found downstream. Table 4 shows that the total Simpson Diversity Index was 0.74 (medium).

The Simpson Diversity Index determines how large a number of species are in a location. Table 3 shows the high Simpson diversity levels obtained from invasive and non-invasive plant species studied. This indicates that the dominance of less varied species will provide high diversity. In comparison, the increased variety of species will provide a low chance of dominance. Based on Table 4, the value of the Simpson Diversity Index is almost close to 1. So, with this value, it can be stated that species of aquatic plants occur at each location in the Bengawan Solo River. The most dominant species were *E. crassipes* and *P. stratiotes.* These plants are very abundant, especially in stations located in Sukoharjo, Surakarta, Karanganyar, and Sragen. The water in Sukoharjo had typical stagnant waters with fairly small currents in the Semanggi area; therefore, a large number of *E. crassipes* and *P. stratiotes* were found in this area. These species have good growth potential if they are in slow water flow (El-Shahawy 2017), swamps, wetlands (Younas et al. 2022), shallow ponds (Kitunda 2017), puddles (Gezie et al. 2018), and large/small rivers that are quite light (Mishra and Maiti 2017). However, some species often coexist with *E. crassipes* and *P. stratiotes,* such as *A. pinnata* and *L. minor*, which have the same habitat and type of roots that float freely on the water's surface. Both species can rapidly cover the water surface if not disturbed by strong water currents.

The species of aquatic plants that dominate the Bengawan Solo River are recognized as very invasive and have high adaptability to a broad range of conditions. Good adaptability is an advantage of invasive plants in reproduction (Van Boheemen et al. 2019). Although the water of the Bengawan Solo River has been contaminated, these aquatic plants are still able to survive (Rizqiyah and Nurina 2021). Special actions are needed to control the dominance of invasive aquatic plant species so that the ecosystem remains stable (Caudill et al. 2019). Controlling the dominance of invasive species is considered important because this phenomenon also occurs in many aquatic ecosystems in South Africa (Hill et al. 2020).

Evenness Index

Based on Table 3, the evenness of invasive aquatic plants in the Bengawan Solo River reached 0.74, which is included in the high category. The upstream and midstream had an index of 0.86 and 0.86 (high), while the downstream had 1.30 (very high). On the other hand, the evenness of non-invasive species had an index of 0.46 (moderate), with an upstream index of 1.00 and a midstream of 0.86. Both are in the high category, and no non-invasive species was found downstream. Table 4 shows the Evenness Index of aquatic plants, which is 0.69 (high), where the upstream had an index of 1.33, the midstream had 1.95, and the downstream had 0.62 (low).

Environmental factors influence the distribution of each species. This resulted in different species distribution for each research station (Tables 3 and 4). The high level of evenness of aquatic plant species in the Bengawan Solo River is caused by the presence of invasive species. One of the causes of high evenness is the dominance of adaptive species in several water areas (Huang et al. 2020). In addition, current speed is also crucial in distributing species from upstream to downstream (McElrone et al. 2013). Currents have become an easy way to free-float aquatic plants such as *E. crassipes*, *P. stratiotes*, *A. pinnata*, and *L. minor* (Datta et al. 2021). On the other hand, aquatic plants attached to the bottom of the soil will spread to other areas through seeds or water-carrying flowers (Rodríguez-Garlito et al. 2022). Therefore, the evenness of aquatic plants in Bengawan Solo River is dominated by free-floating species such as *E. crassipes.*

Table 3. Ecological indices of all macrophytes in Bengawan Solo River, Central Java, Indonesia

Station	Shannon-Wiener Species Diversity Index	Evenness Index	Simpson Diversity	Species Richness (Margaleft)
Upstream	2.03	0.82	0.80	1.82
Middle	2.38	0.79	0.69	2.65
Downstream	2.09	1.30	0.44	0.62
Total	2.17	0.69	0.74	1.69

Table 4. Ecological indices of macrophytes differentiated based on the type of invasiveness in Bengawan Solo River, Central Java, Indonesia

Invasiveness	Station	Shannon-Wiener Species Diversity Index	Evenness Index	Simpson Diversity	Species Richness (Margaleft)
Invasive	Upstream	1.90	0.86	0.78	1.33
	Midstream	2.34	0.86	0.69	1.95
	Downstream	2.09	1.30	0.44	0.62
	Total	2.11	0.74	0.73	1.30
Non-invasive	Upstream	1.09	1.00	0.71	0.72
	Midstream	1.38	0.86	0.76	1.56
	Downstream	-	-	-	-
	Total	0.82	0.46	0.73	0.76

This result is similar to other studies in the Greater Letaba River (Thamaga and Dube 2019), South China (Wu and Ding 2020), Ethiopia (Getnet et al. 2021), and Argentina (Poi et al. 2020). Another factor that can help the dispersal of plant species to other places is animals and humans (Catford and Jansson 2014).

Margalef Species Richness Index

The Margalef index of invasive plants was 1.30 (low), whereas the upstream index was 1.33, the midstream index was 1.95, and the downstream index was 0.62. The index for non-invasive plants was only 0.76, while the upstream had 0.72, the midstream had 1.56, and no non-invasive species were found downstream. Table 4 shows the Margalef index of aquatic plants upstream was 1.82 (moderate), midstream was 2.65 (medium), and downstream was 0.62 (very low), resulting in the combined index for upstream to downstream stations of 1.69 (low).

Although the level of evenness of macrophytes in the Bengawan Solo River was high, Margalef species richness was in the low category. This is because only 23 species were found. Species richness indicates that the greater the number of species found in an area, the richer it is. Poor water and soil quality are also factors that lead to the low number of species (Zhang et al. 2019). The presence of invasive alien species and environmental changes also cause fewer other aquatic plant species to grow and thrive (Hejda et al. 2021). The changing and unstable environment leads to the transformation of local aquatic plant species to decrease (Huang et al. 2020). That way, there is a need for stability, prevention, and control in the Bengawan Solo River against invasive alien aquatic plants and water pollutants to maintain the richness of aquatic plant species.

Controlling invasive alien plants in Bengawan Solo River

Invasive alien species documented in this study need to be managed with certain strategies. Those strategies are focused on the most eminent impacts of invasive plants using different management options adapted to the surrounding environmental conditions (Hess et al. 2019). Identifying areas in the river affected and regularly monitoring invasive plant growth will help determine locations that require necessary measures (Mikulyuk et al. 2020). Location points that require rehabilitation will be taken by two methods: biological techniques, such as using natural enemies and native species, and manual techniques, such as uprooting and removing invasive plants (Sitepu 2020; Weidlich et al. 2020). The government should also play a role by emphasizing and funding universities and organizations to study invasive aquatic plant control (Anifowose and Fagorite 2020). Therefore, controlling invasive alien plants in the Bengawan Solo River can be done based on short-term and long-term scales. Short-term control activities that can be carried out are to identify and recognize invasive types to control and prevent alien species from entering the river. In addition, short-term control can also be done by quickly controlling the population by intensifying the shrubs and weeds pruning in the river area (Sitepu 2020). Long-term control in Bengawan Solo River can be done by conducting an Invasive Plant Risk Assessment (ISPRA). Invasive Plant Risk Assessment is a process to evaluate the invasive potential of a plant species in a particular area, which aims to assess how much risk the plant becomes invasive that is able to spread quickly and disrupt local ecosystems (Bradley et al. 2018).

In conclusion, this study revealed that in Bengawan Solo River, there were 23 species of macrophytes with a total of 2,391 individuals spread across three observation stations. The most common invasive species was *E. crassipes*, and non-invasive is *D. nuda*. The *E. crassipes* was found almost along the Bengawan Solo River since the plant can multiply quickly and easily adapt to changes in extreme conditions such as water currents and nutrient availability. The diversity index of invasive and non-invasive aquatic plant species in the Bengawan Solo River was very low due to the presence of invasive alien species, which suppress local species in their habitat. The Simpson index of invasive and non-invasive plants was quite high, suggesting the dominance of less varied species. The Evenness Index was high due to the presence of several invasive species, while the Margalef Species Richness Index was low.

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