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Research Article

Invasion of water hyacinth (*Pontederia crassipes* Mart.) in Jatiluhur Reservoir, West Java, Indonesia and possible impact on dissolved oxygen and water temperature

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Abstract

Water hyacinth is a type of weed that poses a significant global problem in both tropical and subtropical regions. The water hyacinth invasion incident, which occurred in 2021 and continues to be ongoing in the Jatiluhur Reservoir, has caused numerous problems. The purpose of the study was to investigate the impact of water hyacinth invasion on water quality, specifically the dissolved oxygen and temperature. The study was conducted in November 2021, when the water hyacinth invasion occurred, and in October 2012, when an incident of uninvaded water hyacinth. Location was observed in the floating net cage culture area. Dissolved oxygen and temperature were measured at vertical intervals of one meter up to a depth of 10 meters. Observations were carried out bi-hourly, beginning at 10:00 AM and extending until 6:00 AM the next day. Water hyacinth cover conditions in 2012 and 2021 were estimated using Landsat 8 OLI/TIRS Collection 2 Level-2 Surface Reflectance satellite imagery. The analysis approach employed a combination of NDVI and NDWI to more accurately identify and map water hyacinth cover. The results showed an increase in water hyacinth coverage in October 2012 and November 2021, specifically from 147.87 ha to 1,515.96 ha. The invasion of water hyacinth blocked the penetration of sunlight, thus inhibiting photosynthesis and heat absorption. The water hyacinth mats that cover the water's surface disrupt transportation, fishing, and fish farming. The oxic layer and dissolved oxygen values were higher when uninvaded water hyacinth was compared to invaded water hyacinth. The oxic layer, when uninvaded by water hyacinth, could reach a depth of 10 meters. However, during the invasion of water hyacinth, it was only 3 meters at midday to 4:00 PM, and even hypoxic conditions occurred from the surface at other observation times. The surface temperature was higher when the uninvaded water hyacinth reached 33.7 °C, while when the invasion of water hyacinth was only 30.8 °C.

Key words: plant invasion, cover of aquatic plant, oxic layer, diurnal dissolved oxygen, diurnal temperature

Introduction

Water hyacinth (*Pontederia crassipes* or Syn. *Eichhornia crassipes)* is a free-floating aquatic plant known for its swollen petioles (Akinyemiju 1987), terminal inflorescences, numerous roots hanging in the water, showy purple flowers, and abundant seed production (Spencer and Ksander 2005). Water hyacinth is classified as an aquatic weed known for its adaptability to environmental changes and rapid reproduction rate. The distribution of this species is primarily in tropical and subtropical regions, where it thrives in shallow, muddy waters. This plant exhibits a remarkable capacity to adapt to extreme environmental changes, including variations in water level, current, nutrient availability, pH, temperature, and exposure to harmful substances in the water. Its rapid expansion can be attributed mainly to the presence of nutrient-rich water, particularly water rich in nitrogen, phosphorus, and potassium (Tobing and Hayati 2024). *Pontederia crassipes* poses a significant threat to ecological systems if it proliferates unchecked, as the development of dense mats in aquatic environments can severely deplete oxygen levels and devastate biodiversity. The presence of this water hyacinth often leads to the obstruction of waterways, thereby complicating activities such as boating, sport fishing, and other forms of fishing (Abit et al. 2025). The formation of extensive water hyacinth mats leads to alterations in fish communities, which negatively impact the fishing industry and water transportation systems, thereby threatening the livelihoods of residents. Consequently, the invasion of water hyacinth results in both ecological damage and socioeconomic problems (Song et al. 2024).

Water hyacinth was first introduced to Indonesia through the Bogor Botanical Gardens in 1894 by Governor General Thomas Stamford Raffles. Water hyacinth, a native plant of Brazil in South America, was introduced as an ornamental plant in ponds because of its striking and beautiful purple and blue flowers. The rapid proliferation of water hyacinth in the Bogor Botanical Gardens eventually caused it to fill the entire garden's ponds, resulting in its discharge into the local river system. This plant then proliferated in rivers, swamps, and reservoirs in various parts of Indonesia. Water hyacinth is an invasive alien macrophyte species commonly observed in several national priority lake waters in Indonesia, including Lake Sentarum, Tondano, Tempe, Sentani, and Rawa Pening (Kurniawan et al. 2023). The invasion of water hyacinth weeds has emerged as a persistent challenge in Rawa Pening (Tjitrosoedirdjo 2005; Prasetyo et al. 2021; Dewantara et al. 2021; Maulidyna et al. 2021).

Jatiluhur Reservoir functions as a cascade system that holds back the Citrum River and has a maximum area of 8,300 hectares. This reservoir has various functions, including hydroelectric power generation, irrigation, flood control, drinking water supply, supporting industrial needs, facilitating tourism, providing transportation, promoting sports, and supporting

capture fisheries and aquaculture through a floating net cage system. Organic pollution has been detected in the Jatiluhur Reservoir, with elevated total phosphorus concentrations ranging from 56 to 3,253 μg/L. These concentrations are suspected to be the result of floating net cage (FNC) activities and external sources (Astuti et al. 2022). Water hyacinth demands significant amounts of nutrients and phosphorus to achieve optimal growth (Karouach et al. 2022). In 2014, the coverage of water hyacinth in the Jatiluhur Reservoir was approximately 157.92 hectares, increasing to 441.65 hectares by 2019. The presence of water hyacinth is abundant around the reservoir's estuary, especially in the area of the FNC and along the edge of the reservoir's water body. The influx of water into the Jatiluhur Reservoir significantly accelerates the growth of water hyacinth, particularly around the inlet and FNC (Dewantara 2020). In the Saguling Reservoir, located upstream of the Citarum River rapids, the area covered by water hyacinth was recorded during the February 2018 rainy season at 154.3191 hectares. This area decreased to 106.4410 hectares in the dry season of August 2018 (Rosyidy et al. 2019). The presence of water hyacinth is a significant threat to freshwater ecosystems, which has raised public concerns. Villamagna and Murphy (2010) noted that there is a dearth of research focusing on the ecological conditions that existed before the invasion. This study plays an important role in bridging the knowledge gap related to changes in dissolved oxygen concentration and temperature associated with water hyacinth invasion. It is crucial for assessing the effects of water hyacinth invasion, enabling the implementation of control strategies before a significant outbreak occurs. This study aims to assess water quality, specifically focusing on dissolved oxygen and temperature, during the periods when water hyacinth is present and absent in the Jatiluhur Reservoir.

Materials and methods

Site area and time of research

The study was carried out in the Jatiluhur Reservoir, Purwakarta, Indonesia (Figure 1). Water quality observations were conducted at the FNC area (−6.548225 S, 107.389244 E, Figure 1) for 18 hours on October 20, 2012, focusing on areas of uninvaded water hyacinths. Also in October 2012, observations were conducted for vertical water quality monitoring in the FNC area. Subsequently, water quality assessments were performed again at the same site, on November 21, 2021, which coincided with the water hyacinth invasion nine years later. Measurements of temperature and dissolved oxygen were taken vertically to a depth of 10 meters, with intervals of 1 meter, using a Horiba U10 water quality checker equipped with a 10-meter cable. The dynamics of oxygen and temperature influence biochemical reactions, nutrient cycles, and the distribution of biota within the water column (Jones et al. 2011). The consumption rate of oxygen by

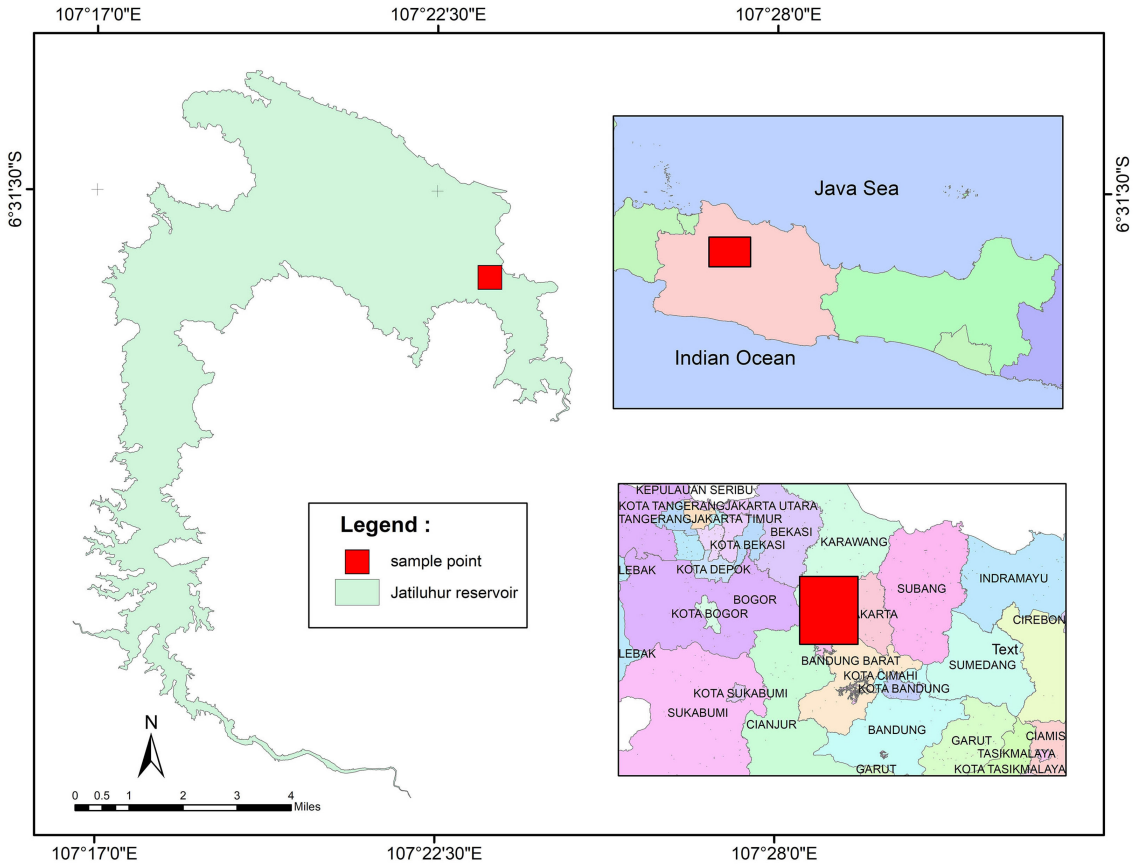


Figure 1. Sampling site in Jatiluhur Reservoir.

biota and microorganisms might lead to an oxygen deficit, which in turn results in a thicker anoxic layer and a thinner oxic layer (Azmudin et al. 2014). The rate of CO_2 fixation through primary productivity was significantly influenced by temperature, which also affected bacterial activity in the decomposition of organic matter (Siriwardana et al. 2019). During our study, observations were conducted bi-hourly from 10:00 AM to 06:00 AM on the next day. The duration of observations was determined by the conditions that allowed boats to navigate through the water hyacinth mats to reach the sampling point in the FNC area, ensuring they did not become trapped within the mats. Moreover, the sun was shining, which promoted photosynthesis.

To enhance the representativeness of invasion dynamics, additional satellite analyses were conducted for intermediate years (2016 and 2019) in addition to 2012 and 2021. These four years collectively represent the temporal progression of the water hyacinth invasion over nearly a decade.

Mapping of water hyacinth

The ecological conditions before the invasion help in describing the subsequent impacts of the water hyacinth invasion. Water hyacinth cover conditions in 2012 and 2021 were estimated using Landsat 8 OLI/TIRS Collection 2 Level-2 Surface Reflectance satellite imagery, obtained from

the USGS Earth Explorer. To strengthen temporal analysis, additional Landsat 7 ETM+ data (for 2012) and Landsat 8 OLI/TIRS data (for 2016, 2019, and 2021) were utilized, all of which were Level-2 Surface Reflectance products that have undergone atmospheric correction. The downloaded image included the spectral bands required for the calculation, namely Band 3 (Green), Band 4 (Red), Band 5 (Near Infrared/NIR), and Band 6 (Shortwave Infrared/SWIR1).

In addition, boundary vector data (Jatiluhur reservoir) in shapefile (SHP) format were used to crop the image to focus on the study area. Before the analysis was carried out, the satellite images went through a pre-processing stage to ensure the accuracy and quality of the data. All images were selected from the dry season period (August–November) to minimize cloud cover and hydrological variability between years. Cloud and shadow masking was applied using the QA_PIXEL band, and for Landsat 7 data, SLC-off gaps were corrected using focal mean interpolation in QGIS 3.22. These steps ensured consistency across sensors and years. For Level-1 imagery, atmospheric correction was performed using the Semi-Automatic Classification Plugin (SCP) in QGIS. However, when using Level-2 Surface Reflectance, this stage could be skipped because the data had already been atmospherically corrected. Next, the study area was clipped using the boundary shapefile to remove areas outside the study's focus. The analysis approach employed a combination of NDVI (Normalized Difference Vegetation Index) and NDWI (Normalized Difference Water Index) to more accurately identify and map water hyacinth cover. NDVI was a commonly used index to detect vegetation based on differences in light reflectance in the Near Infrared (NIR) and Red, while NDWI was used to detect the presence of water by utilizing reflectance in the Green and NIR (Ashok et al. 2021; Chu et al. 2013; Yi et al. 2022). By combining NDVI and NDWI, it removed or corrected NDVI values derived from terrestrial vegetation, leaving only water hyacinth vegetation. After calculating NDVI and NDWI, masking was performed using NDWI as a correction factor. This was done by setting the NDWI Threshold to remove vegetation in the Non-Water Area, with the following correction:

a. If NDWI > 0.3, the area was considered to be clean water (i.e. no vegetation).
b. If NDWI < 0, the area was considered as terrestrial vegetation and removed from the water hyacinth analysis.
c. If the NDWI was between 0 and 0.3, the area potentially contained floating vegetation such as water hyacinth
d. Areas identified as potential floating vegetation ($0 \leq NDWI \leq 0.3$) were further analyzed using NDVI to confirm the presence and density of water hyacinth (Ashok et al. 2021).

Following NDWI masking, NDVI thresholding was applied to identify the density of water hyacinth mats. Pixels with NDVI values between 0.2

and 0.4 were classified as sparse mats, while pixels with NDVI > 0.4 were classified as dense mats. This combination effectively minimized the misclassification between aquatic and terrestrial vegetation.

Four classes were ultimately produced: (1) clear water, (2) water with sediment or minor algae, (3) sparse water hyacinth, and (4) dense water hyacinth mats. This classification scheme was applied consistently to all four years to ensure comparability across time. To ensure the temporal and spatial stability of the observed invasion pattern, each selected image (2012, 2016, 2019, and 2021) was validated using adjacent-month images from the same dry season. This cross-check confirmed that the distribution of water hyacinth mats remained consistent and was not an artifact of short-term drift due to wind or current. The spatial persistence of mats was attributed to the physical interconnection among plants through stolons and the relatively stable hydrodynamic conditions of the reservoir (Rahman et al. 2024).

Furthermore, the images used for each year represent the "average dry-season invasion condition," not a single-day event. This was verified by comparing NDVI and NDWI values from several cloud-free scenes within each year to ensure temporal consistency.

Data analysis

NDWI (Normalized Difference Water Index)

NDWI was used to distinguish water from vegetation and land (Xu 2006). The formula was as follows:

NDWI = (Green − NIR) / (Green + NIR)

where: Green= Band 3

NIR = Band 5

NDVI (Normalized Difference Vegetation Index)

NDVI was used to identify vegetation using NIR and RED reflectance. The NDVI equation was as follows (Tucker 1979):

NDVI = (NIR − Red) / (NIR + Red)

where: NIR = Band 5 (Near Infrared)

Red = Band 4

Table 1 summarizes the NDVI classification used to differentiate water conditions and aquatic vegetation density. Higher NDVI values indicate increasing dominance of floating vegetation, particularly water hyacinth.

The NDVI–NDWI classification results were verified visually using false-color composites and Google Earth imagery to validate the consistency of identified water hyacinth mats. The areal extent of each class was calculated by counting classified pixels (30 × 30 m resolution) and converting them into hectares. The temporal trend of water hyacinth coverage (2012–2021) was then analyzed using linear regression to estimate the rate of invasion and its statistical significance (R^2 and p-value).

Table 1. NDVI classification for aquatic plants cited in line 213.

NDVD Value	Explanation
< 0	Clear water
0–0.2	Water with sediment or small alga
0.2–0.4	Floating vegetation was rare
> 0.4	Dominant water hyacinth



Figure 2. Jatiluhur Reservoir uninvaded by water hyacinth in October 2012 (left plates) and after invasion of water hyacinth in November 2021 (right plates). Photographs by Lismining Pujiyani Astuti.

Results

Visual observation and site conditions

The visual conditions of uninvaded and invaded water hyacinth are presented in Figure 2. Figure 2A indicates that in October 2012, the reservoir surface appeared clear and suitable for navigation. In November 2021 (Figure 2B), extensive invasion by water hyacinth occurred, resulting in large portions of the water surface being covered by dense plant mats. This invasion caused numerous fishing vessels to become inoperable due to obstruction by floating vegetation, negatively affecting local fishermen who depend on the reservoir for their livelihoods. Some fishing boats became trapped within the mats and required assistance to return to port.

To complement field observations and to ensure temporal representativeness, a series of multi-temporal analyses using Landsat surface reflectance imagery was conducted to quantify and visualize the progressive spread of water hyacinth between 2012 and 2021. This approach enabled the identification

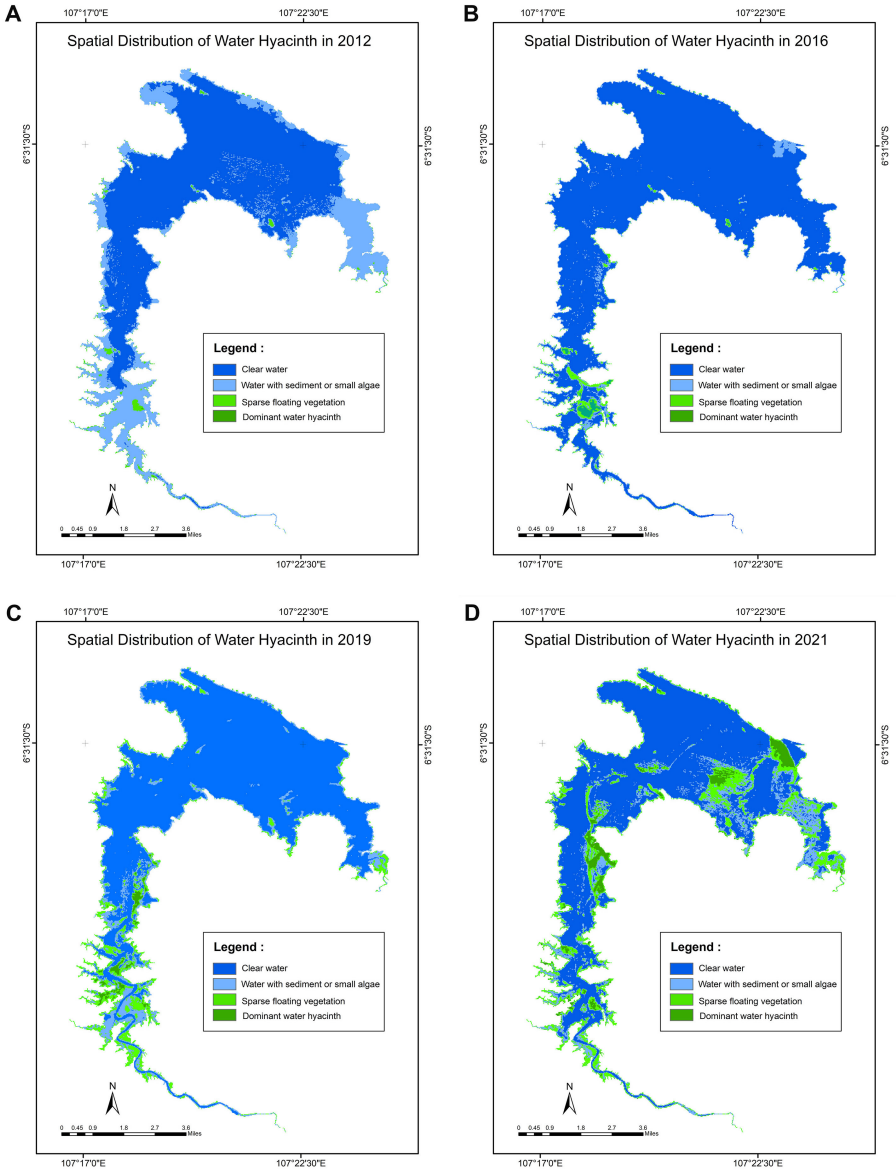


Figure 3. Spatial distribution of water hyacinth (*Pontederia crassipes*) in Jatiluhur Reservoir based on NDVI–NDWI classification using Landsat imagery: (A) 2012, (B) 2016, (C) 2019, and (D) 2021.

of spatial distribution patterns and long-term invasion dynamics across different observation years.

Multi-temporal analysis of water hyacinth expansion (2012–2021)

The analysis of Landsat-based NDVI–NDWI classification across four time points (2012, 2016, 2019, and 2021) revealed a pronounced and continuous expansion of water hyacinth cover in the Jatiluhur Reservoir (Figure 3). To ensure spatial and temporal reliability, each annual classification was validated against cloud-free images from adjacent months within the same dry season, confirming that the observed invasion patterns were consistent and not driven by short-term wind-induced movement of mats.

Spatially, the 2012 imagery indicated that water hyacinth patches were limited to the upstream inlet area near the Citarum River, occupying only

Table 2. Multi-temporal areal extent of water hyacinth (*Pontederia crassipes*) and other surface coverage types in Jatiluhur Reservoir during 2012–2021.

No	Coverage of Water hyacinth	Area (ha)			
		2012	2016	2019	2021
1	Clear water	5,458.59	7,080.39	6,083.64	5,120.46
2	Water sediment or minor algae	2,333.97	581.76	1,035.54	1,304.01
3	Sparse water hyacinth	147.33	228.24	738.18	1,215.54
4	Dense water hyacinth mats	0.54	50.04	83.07	300.42
	Total area	7,940.43	7,940.43	7,940.43	7,940.43

147.87 ha (1.9% of the total surface). By 2016, sparse patches had expanded along the central bays (278.28 ha), suggesting the early stage of establishment under nutrient-enriched conditions. A marked increase occurred between 2016 and 2019, where total hyacinth cover rose to 821.25 ha, and dense mats began to form near floating net cage (FNC) zones, correlating with intensified aquaculture activities. By 2021, total hyacinth coverage reached 1,515.96 ha, indicating an approximately tenfold increase over nine years.

The spatial distribution maps (Figure 3A–D) demonstrate the expansion trend, with the inlet region showing the earliest and most persistent infestation, followed by spread toward the mid-reservoir and nearshore zones. The 2021 map revealed coalesced mats along the northern and eastern margins, forming continuous floating colonies that impeded navigation and water circulation.

The multi-temporal analysis (Table 2) quantitatively supports these findings. Clear water areas declined markedly from 5,458.59 ha in 2012 to 5,120.46 ha in 2021, while sparse and dense water hyacinth collectively increased from 147.87 ha to 1,515.96 ha. Simultaneously, zones with sediment or minor algal proliferation fluctuated, initially decreasing in 2016 (581.76 ha) before increasing again by 2021 (1,304.01 ha), reflecting progressive eutrophication and sediment resuspension processes.

Temporal and ecological interpretation

The multi-temporal trend clearly demonstrates a rapid and consistent increase in *Pontederia crassipes* cover across the 2012–2021 period (Figure 4). The total coverage expanded from 147.87 ha in 2012 to 1,515.96 ha in 2021, indicating a 925% overall increase, equivalent to an average annual expansion rate of approximately 152.9 ha·year^{-1}.

This pattern suggests three distinct ecological phases:

1. Initial colonization (2012–2016)

Water hyacinth coverage remained limited (< 300 ha), with dominance of clear water (> 70%), indicating low nutrient availability and early establishment primarily around the Citarum River inlet.

2. Rapid expansion (2016–2019)

Hyacinth cover tripled (278 → 821 ha), coinciding with intensified aquaculture with floating net cage (FNC) activities and increased nutrient loading (nitrogen, phosphorus) into the reservoir.

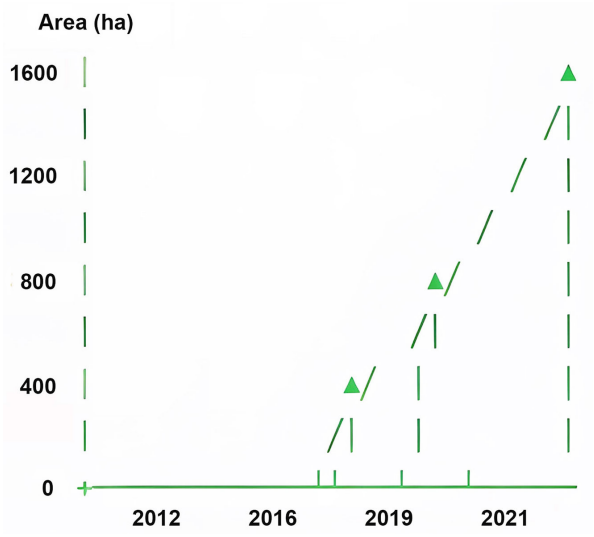


Figure 4. Mini-trend of Water Hyacinth Expansion (2012–2021).

3. Dense mat formation (2019–2021)

Coverage surged to 1,515.96 ha, with dense mats increasing fourfold (83 → 300 ha). This phase reflected eutrophication-driven proliferation and enhanced mat cohesion, possibly supported by hydrodynamic stagnation and limited mechanical control.

Regression analysis yielded the model $y = 151.3x - 303{,}945$ ($R^2 = 0.94$; $p < 0.05$), confirming that the expansion trend was statistically significant and temporally persistent, rather than stochastic or seasonal.

Vertical profile of dissolved oxygen and water temperature

The results of observations of the vertical profile of dissolved oxygen from 10 am to 6 am the following day are presented in Figure 5.

In October 2012 (Figure 5A), when water hyacinth was not invading, oxygen concentrations consistently exceeded 3 mg/L at all depths and observation times. The oxic layer, characterized by oxygen concentrations greater than 3 mg/L, was observed at a depth of 10 meters throughout all observation hours, except at 6:00 PM, when the depth was only six meters. During the water hyacinth invasion in November 2021 (Figure 5B), the oxic layer only reached a depth of 3 meters, as observed between 12:00 PM to 4:00 PM. At other times, oxygen concentrations dropped below 3 mg/L, indicating hypoxic conditions that had begun at the water surface. The presence of water hyacinth mats caused oxygen depletion at the water surface. Oxygen concentrations exceeding 3 mg/L were seen from 12:00 noon to 4:00 PM. In the absence of water hyacinth invasion, the waters showed a deeper oxic layer. This phenomenon was caused by sunlight's ability to penetrate deeper water layers, thereby facilitating the process of photosynthesis in phytoplankton. Phytoplankton photosynthesis produced dissolved oxygen in the water. Water hyacinth mats caused a lack of oxygen on the water surface. This happened when water hyacinth layers block sunlight, thus inhibiting the process of photosynthesis.

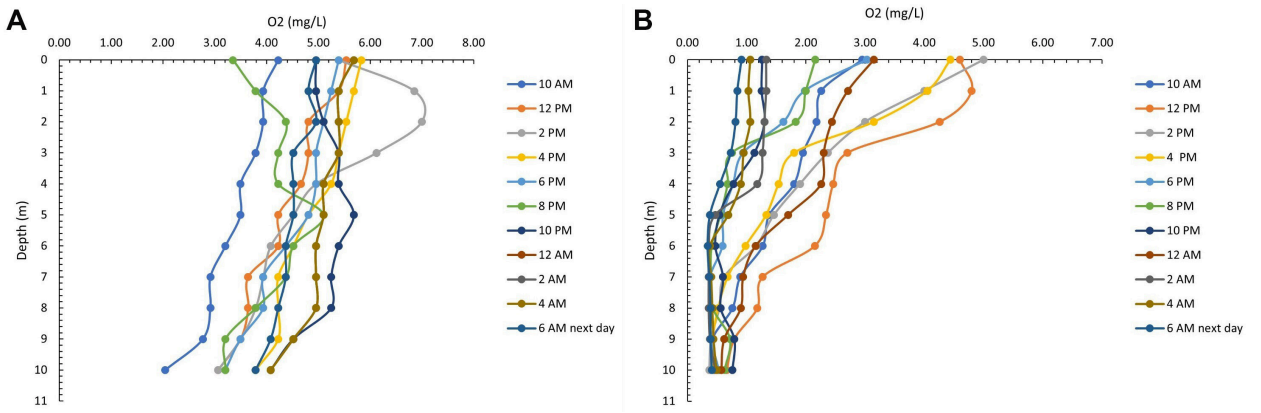


Figure 5. Comparison of the vertical profile of dissolved oxygen in the floating net cage area (a) uninvaded water hyacinth on October 20, 2012, and (b) invasion of water hyacinth on November 21, 2021.

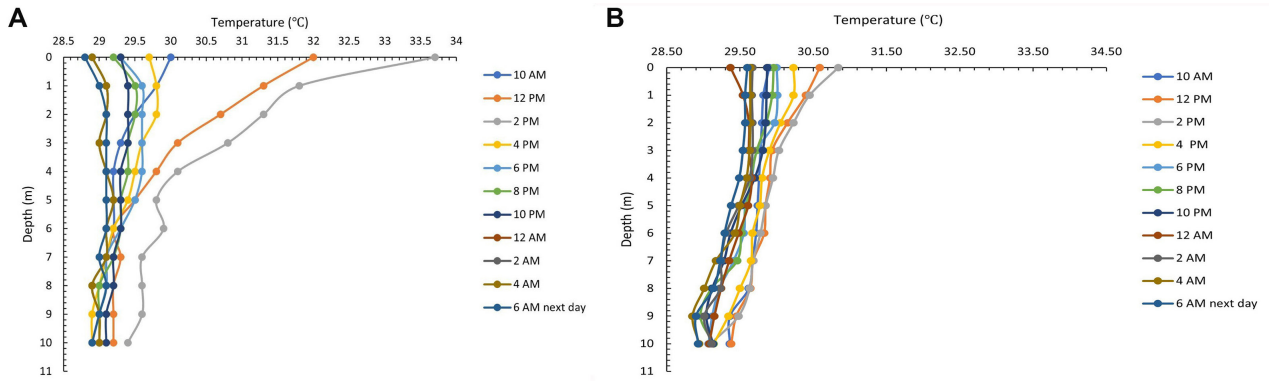


Figure 6. Comparison of the vertical profile of water temperature in the floating net area in (a) uninvaded water hyacinth on October 20, 2012, and (b) invasion of water hyacinth on November 21, 2021.

Figure 6 shows a slight difference between the after- and before-water hyacinth invasion states. The difference lay in the fact that the area before being invaded by water hyacinth produced a higher water surface temperature compared to after being invaded by water hyacinth. The surface temperature that was not invaded reached 33.7 °C at 12:00 PM and 2:00 PM, while the surface temperature invaded by water hyacinth was only 30.8 °C at the exact times. This was believed to be caused by sunlight penetrating the water surface. If there were no water hyacinth, sunlight would directly penetrate the water surface, thereby increasing the water temperature. When water hyacinth invaded, sunlight could not directly penetrate the water surface because the water hyacinth mats obstructed it.

Diurnal of dissolved oxygen

The results of daily observations of dissolved oxygen from 10.00 AM to 06.00 AM the following day at the surface, depths of 5 and 10 meters are presented in Figure 7.

Figure 7 illustrates the difference between the situation before the invasion (in October 2012) and after the invasion by water hyacinth (in November 2021). Surface oxygen concentrations in waters, at depths of 5 and 10 m showed that, in places not yet invaded by water hyacinth, they generally

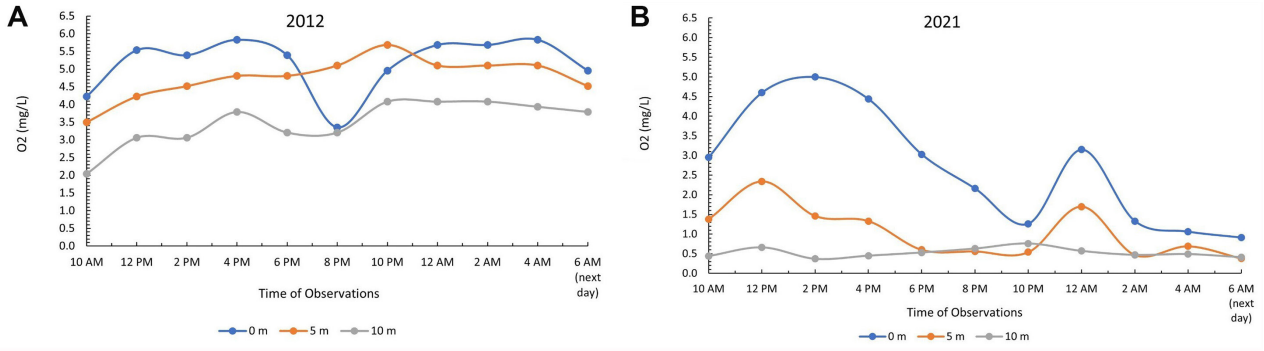


Figure 7. Diurnal of dissolved oxygen in (a) uninvaded water hyacinth on October 20, 2012, and (b) invasion of water hyacinth on November 21, 2021.

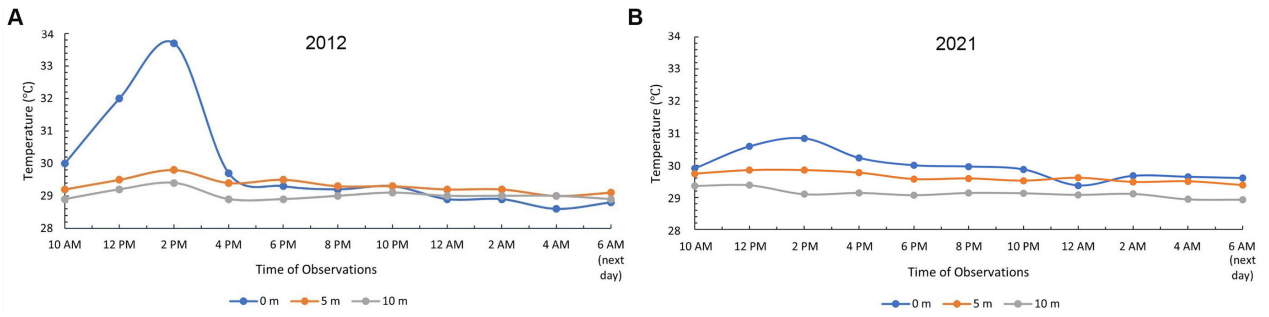


Figure 8. Diurnal temperature (a) uninvaded water hyacinth on October 20, 2012, and (b) invasion of water hyacinth on November 21, 2021.

exceeded 3 mg/L during all observation periods. During water hyacinth invasion, the oxygen content exceeded 3 mg/L at the surface at 12:00 PM, 2:00 PM, and 4:00 PM; however, at depths of 5 and 10 meters, hypoxia (< 1 mg/L) was observed at all observation times. At midnight (12:00 AM), during the water hyacinth invasion, there was an increase in oxygen concentration, which was presumed to be caused by strong winds that increased the diffusion process, thus increasing oxygen levels at the surface and up to a depth of 5 meters.

Diurnal temperature

Daily surface temperatures in areas with uninvaded water hyacinth were often elevated (see Figure 8A), particularly between 10:00 AM and 2:00 PM, ranging from 30 to 33.7 °C. During the invasion of water hyacinth (Figure 8B), the surface temperature decreased, ranging from 29.9 to 30.8 °C. This was believed to be associated with the coverage of water hyacinth mats on the surface, which obstructed sunlight and consequently impeded the heat absorption process in the water. At depths of 5 and 10 meters, the temperature consistently ranged from 29 to 29.9 °C.

Discussion

The rapid growth of water hyacinth can alter ecosystem functions, including physical structures, biogeochemical cycles, and hydrology (Tobias et al.

2019). Water hyacinth that covers water surfaces can interfere with boat navigation, affect water quality, reduce water velocity and provide habitats for non-native predatory biota, disrupt fishing and transportation activities and increase sources of disease in humans, disrupt tourism activities, cause extinction of native aquatic species, and block light penetration into the water column (Tobias et al. 2019; Mitan 2019; Zeleke 2024; Abba and Sankarannair 2024). The invasive capability of water hyacinth is supported by its ability to reproduce sexually through seeds and asexually through vegetative propagation of stolons (Abba and Sankarannair 2024). Water hyacinth reproduces very quickly by producing daughter plants on stolons; 10 plants can produce approximately 650,000 new plants in one growing season (Tobias et al. 2019). Water hyacinth has a high growth rate of approximately 3% per day (Dewantara et al. 2021). Vegetative reproduction can double in 7–10 days (Dewantara et al. 2021). It was also reported that the relative growth rate of water hyacinth in Lake Toba waters is 4.21% (Prasetyo et al. 2021).

According to Dewantara et al. (2021), one of the causes of rapid water hyacinth growth is the presence of organic or inorganic waste. In the Jatiluhur Reservoir, this waste originates from FNC activities, specifically from uneaten feed and fish feces, and also from external sources. The increase in FNC waste can lead to a decline in water quality, specifically an increase in nitrogen and phosphorus nutrients. The estimated phosphorus pollution load attributed to FNC is 2,382.9 tons per year, while external sources contribute roughly 11,091.5 tons per year (Astuti and Tjahjo 2020). The concentration of phosphate in the Jatiluhur Reservoir reached 21 µg/L (Astuti et al. 2022). The findings from an experiment conducted by Xie and Yu (2003) found that the growth of water hyacinth was positively correlated with phosphorus availability, as evidenced by a relative growth rate value that was 3.67 times higher in the high phosphorus treatment compared to the low phosphorus treatment.

The multi-temporal analysis (2012–2021) in this study further confirms that eutrophication and nutrient enrichment have driven a persistent spatial expansion of water hyacinth. Total coverage increased from 147.87 ha in 2012 to 1,515.96 ha in 2021, equivalent to a 925% increase. The expansion trend ($R^2 = 0.94$; $p < 0.05$) reflects a consistent, long-term invasion rather than short-term fluctuation. The highest proliferation occurred between 2016 and 2021, coinciding with increased floating net cage density and agricultural intensification in the upper Citarum watershed.

Spatially, the invasion initially appeared at the reservoir inlet in 2012 and progressively expanded toward the central and southern zones by 2021 (Figure 3). This spatial persistence indicates that water hyacinth mats are not transient features but form semi-stable colonies, supported by interlinked stolons and hydrological stagnation (Rahman et al. 2024). These mats exhibit low mobility due to the large water surface and interwoven

roots, as observed in other large tropical reservoirs (Gezie et al. 2018; Maulidyna et al. 2021).

The proliferation of water hyacinth mats in the Jatiluhur Reservoir from March to October 2021 exhibited consistent growth. Recordings were made at 683, 716, 899, 786, 965, 968, 1212, and 1011 hectares (Rahman et al. 2024), culminating in November 2021 with a total area of 1,515.96 hectares, approximately 300.42 hectares of which were densely covered by a water hyacinth mat. In 2021, the area of water bodies exhibiting sediment and algal proliferation increased from 2012, allegedly due to agricultural runoff and domestic waste, which numerous studies have identified as triggers for eutrophication and excessive growth of water hyacinth (Mukarugwiro et al. 2019). Strong winds or high waves can accelerate the spread of water hyacinth and its colonization in other areas (Karouach et al. 2022). The wind's movement generates water currents, leading to the formation of dense water hyacinth mats (Osumo 2001). This poses significant challenges for fishermen, as it inhibits boat navigation, obstructs fishing operations, and leads to entanglement in nets and damage to equipment (Harun et al. 2021). Between March and November 2021, the population of water hyacinth fluctuated due to mechanical management methods that involved removing mats onto land. Perum Jasa Tirta II, a reservoir management business, has reduced the water hyacinth population through the use of heavy machinery and the processing of water hyacinth as a raw material for handcrafted goods (Harun et al. 2021; Pratama et al. 2024; Poernama et al. 2023). The temporary decline in water hyacinth cover recorded in 2019 likely reflects short-term mechanical control implemented by Perum Jasa Tirta II. However, rapid regrowth by 2021 suggests that mechanical removal alone is insufficient without concurrent nutrient load reduction. The prevalent invasion of water hyacinth in Indonesia is currently a significant issue in Rawa Pening, resulting in a lack of oxygen and nutrients for aquatic biota, which leads to mortality and population declines. Furthermore, it causes sedimentation, which causes shallowing. In 1994, the coverage of water hyacinths in Rawa Pening was 18.45%, which increased to 20–30% in 2002, 70% in 2005, and further climbed to 85% in 2006 (Maulidyna et al. 2021).

The invasion of water hyacinth results in a decline in dissolved oxygen levels (Tobias et al. 2019; Yongo et al. 2017; Shu et al. 2014). Dense and opaque layers of water hyacinth obstruct light penetration into deeper waters, adversely affecting primary productivity (Gezie et al. 2018), while also restricting wind activity and oxygen exchange at the air-water interface (Yongo et al. 2017). Research on water hyacinths in the San Francisco Estuary (SFE; encompassing San Francisco Bay and the Sacramento-San Joaquin Delta) indicated that dissolved oxygen levels were diminished in regions dominated by water hyacinths compared to open water zones. The density of water hyacinth can diminish dissolved oxygen levels and decrease

flow rates (Tobias et al. 2019). The results obtained at Jatiluhur Reservoir indicated that oxygen concentrations were reduced during the invasion of water hyacinth compared to periods when the water hyacinth was not present. At night, during the invasion of water hyacinth, surface oxygen concentrations dropped to below 3 mg/L, indicating hypoxic conditions.

In contrast, areas with uninvaded water hyacinth maintained oxygen levels above 3 mg/L. This was believed to result from the mats inhibiting oxygen production throughout the day. The water hyacinth mats obstruct the movement of oxygen from the atmosphere to the water's surface. Additionally, they inhibit the light necessary for photosynthesis in both phytoplankton and submerged plants, leading to a reduction in oxygen levels. In contrast, water hyacinths do not contribute oxygen to the water column (Villamagna and Murphy 2010).

The findings at the Jatiluhur Reservoir indicated that the oxic layer measured 10 meters in October 2012, when it was not invaded by water hyacinth; however, it diminished to 3 meters in November 2021 under invasive conditions. In an uninvaded area of water hyacinths, the aquatic environment possesses an oxic layer. This is believed to be due to sunlight's ability to penetrate deeper layers of the water column, hence enhancing the photosynthesis process in phytoplankton. Plankton photosynthesis produces dissolved oxygen in the water column. Open water regions generally exhibit elevated dissolved oxygen levels and reduced fluctuation compared to water located under the water hyacinth canopy (Miskella et al. 2021). The invasion of water hyacinth is associated with reduced oxygen concentrations, often resulting in hypoxia, in contrast to waters free of the species (Turner et al. 2010; Yongo et al. 2017). Dissolved oxygen levels can drop significantly, leading to mass fish fatalities result of oxygen depletion in the water column (Osumo 2001).

During nighttime, a respiratory process occurs that decreases oxygen levels, resulting in approximately 2.0–2.5 mg/L of oxygen being lost by the morning (Stansbury et al. 2008). Dissolved oxygen peaks in the afternoon and decreases overnight due to respiration (Balangoda 2017; Bega et al. 2021). The minimum dissolved oxygen values were observed between 6:00 and 7:00 AM (Miranda and Raines 2019), and in Jatiluhur Reservoir occurred at 6:00 AM in November 2021. The DO profile also exhibited pronounced diurnal fluctuations, with oxygen peaking in the afternoon (due to photosynthesis) and declining at night (due to respiration). Minimum DO (< 1 mg/L) was observed at dawn (06:00 AM), consistent with patterns in other eutrophic tropical reservoirs. Dissolved oxygen exhibits diurnal fluctuations related to the photosynthetic and respiratory activities of algae, aquatic flora, aquatic fauna, and microorganisms. Photosynthesis is the primary function that influences daily fluctuations in eutrophic waters (Balangoda 2017). The Jatiluhur Reservoir is characterized by eutrophic to hypertrophic waters (Astuti et al. 2022; Mulyani et al. 2023). At the Heinrich

Martin Dam in Dakota, at a depth of 8 m, diurnal dissolved oxygen (DO) levels consistently reach zero, indicating significant elevated DO consumption for organic matter degradation (Balangoda 2017). However, in the Jatiluhur Reservoir in November 2021, during a water hyacinth invasion at a depth of 10 m, the oxygen content remained below 1 mg/L throughout the day, presumably due to the high DO consumption for organic matter degradation. Water hyacinth invasion produces high levels of organic matter from dead water hyacinths.

The water temperature of the Jatiluhur Reservoir supports the proliferation of water hyacinth, as demonstrated by Madsen and Morgan (2021), who stated that the density of water hyacinth increases with temperatures between 25–30 °C, due to the significant impact of temperature on its biomass and density. In November 2021, during the water hyacinth invasion, the surface temperature recorded was 30.8 °C, which was lower than the 33.7 °C observed during the uninvaded water hyacinth in October 2012. Water hyacinth affects water temperature via two distinct physical mechanisms: (1) it impedes water circulation, potentially elevating temperature by prolonging residence time, and (2) it restricts the sunlight through shading, which may reduce temperature (Tobias et al. 2019). The invasion of water hyacinth can reduce sun radiation and block the exchange of heat between the lake surface and the atmosphere, resulting in lower temperatures and decreased primary productivity in photosynthesis. Sunlight is a fundamental determinant in the functioning of aquatic habitats (Mironga et al. 2012; Miranda and Raines 2019).

Overall, the integration of multi-temporal satellite analysis and in-situ water quality measurements provides strong evidence that water hyacinth expansion in Jatiluhur Reservoir is driven by nutrient enrichment, hydrological stagnation, and insufficient long-term management. These findings emphasize the urgent need for a combined strategy of nutrient control, biological containment, and adaptive mechanical removal to sustain reservoir ecosystem functions.

Conclusion

The extent of water hyacinth coverage during the invasion in November 2021 was significantly greater than in October 2012, reaching 1,515.96 hectares compared to only 147.87 hectares under uninvaded conditions, or equivalent to a 925% increase. Multi-temporal analysis (2012–2021) showed a ninefold increase in water hyacinth area ($R^2 = 0.94$), indicating a persistent and expanding invasion. The spread originated near the Citarum River inlet and expanded toward central and southern zones, driven by nutrient enrichment from aquaculture with floating net cage, agriculture, and domestic sources. This invasion has altered oxygen dynamics, thermal structure, and overall reservoir health. Dissolved oxygen concentrations during the invasion were markedly lower, with values exceeding 3 mg/L

observed only within the upper 3 meters of the water column, whereas under uninvaded conditions, similar oxygen levels extended to depths of up to 10 meters. Surface temperatures were also lower in invaded areas (30.8 °C) than in uninvaded waters (33.7 °C), likely due to the shading effect of dense hyacinth mats that limited sunlight penetration. Integrated management involving nutrient load reduction, periodic mechanical removal, and remote sensing-based monitoring is essential to control further expansion and sustain reservoir functions.

Authors' contribution

LPA: research conceptualization, sample design and methodology, investigation and data collection, data analysis and interpretation, role/writing – original draft; EJ: data analysis and interpretation, role/writing – original draft; ESB: investigation and data collection, data analysis and interpretation, role/writing – original draft; AW: research conceptualization, sample design and methodology, investigation and data collection; SEP: investigation and data collection, GLA: investigation and data collection; H: data analysis and interpretation, writing – review and editing; DWHT: research conceptualization, sample design and methodology, investigation and data collection; TS: research conceptualization, investigation and data collection, writing – review and editing. All authors edited and approved the final manuscript.

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