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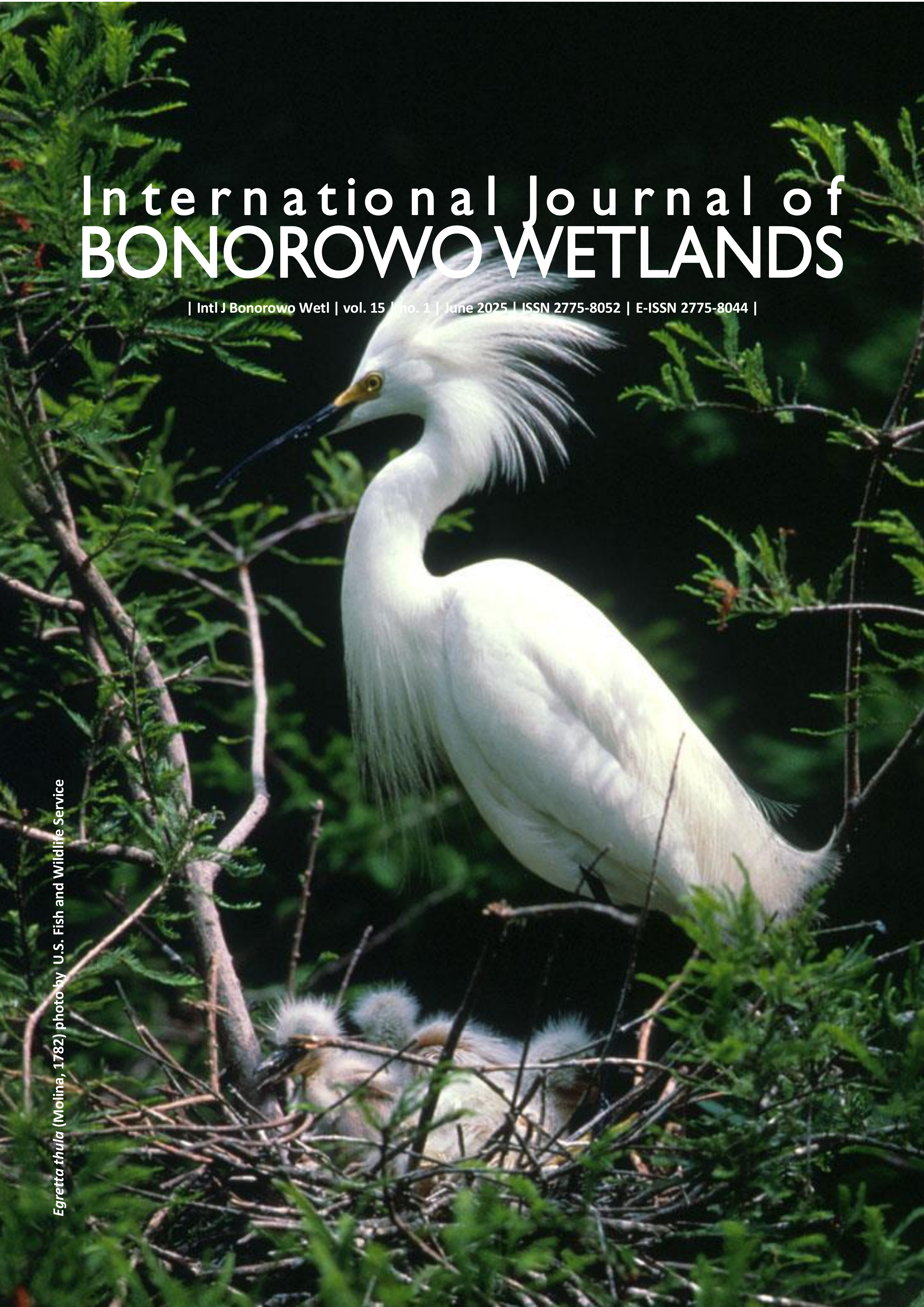

*Egretta thula* (Molina, 1782) photo by U.S. Fish and Wildlife Service

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**Abstract:**

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

**Proceeding:**

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

**Thesis, Dissertation:**

Sugiyarto. 2004. Soil Macro-invertebrates Diversity and Inter-Cropping Plants Productivity in Agroforestry System based on Sengon. [Dissertation]. Universitas Brawijaya, Malang. [Indonesian]

**Information from the internet:**

Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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# Impact of distance from the water body on the point of zero charge of Dutsin-Ma Dam floodplain soils, Katsina State, Nigeria

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Manuscript received: 7 September 2024. Revision accepted: 6 January 2025.

**Abstract.** *Abdulkadir A, Manne IZ, Sani S. 2025. Impact of distance from the water body on the point of zero charge of Dutsin-Ma Dam floodplain soils, Katsina State, Nigeria. Intl J Bonorowo Wetlands 15: 1-6.* This study investigates the point of zero charge (ZPC) and its influence on soil chemical properties in the floodplain around the Dutsin-Ma Dam. The report rigorously examines how proximity to the dam influences critical soil parameters such as pH changes (ΔpH), ZPC, and surface potential (Ψ0) across three zones: Onshore, Mid-shore, and Offshore. Soil samples from these three zones were meticulously analyzed to assess variations in these parameters, which are vital for understanding soil fertility and nutrient availability. The results show that ΔpH decreases with increasing distance from the dam, indicating reduced pH fluctuation in offshore soils. ZPC values increase from onshore to offshore, suggesting that soils farther from the dam reach zero net charge at higher pH levels. Additionally, the surface potential (Ψ0) becomes increasingly negative with distance from the dam, indicating a lower offshore cation exchange capacity (CEC). These findings underscore the significant influence of dam proximity on soil chemical properties, which has practical implications for soil management and agricultural practices. Understanding ZPC and related parameters is essential for optimizing soil fertility and promoting sustainability in floodplain environments. This research provides actionable insights that can empower practitioners to improve agricultural practices and long-term soil health in regions impacted by dam-induced flooding.

**Keywords**: Dutsin-Ma Dam floodplains, electrical conductivity, point of zero charge, soil fertility, soil management, soil pH

## INTRODUCTION

Soil, a complex and dynamic mixture of minerals, organic matter, water, air, and living organisms, has an important role in sustaining life on Earth (Huntley et al. 2023). The composition and characteristics of soil influence various natural processes and human activities, for example, agriculture, forestry, construction, and environmental management. One of the critical parameters in soil chemistry and physics is the determination of the point of zero charge (PZC), a key factor in soil management, nutrient availability, and contaminant retention (Penn and Cambarto 2019; Mohawesh 2020).

Soils in tropical regions, which cover almost 38% of the Earth's surface, are characterized by high mineral and amorphous colloid content, contributing to their amphoteric surface properties (Borrelli et al. 2020). These characteristics have profound implications for agricultural soil management, particularly in relation to the retention and mobility of ionic contaminants (Kome et al. 2019). The soil surface charge, a crucial aspect of soil management, is regulated not only by the activity of potential-determining ions ($H^+$ and $OH^-$) but also by the electrolyte concentrations (ionic strength) in the environment (Wen et al. 2020). The role of electrolyte concentration is significant, as it influences the soil's surface charge, which can be positive, negative, or neutral depending on the pH. The pH value where the net particle charge becomes zero is known as the point of zero charge (PZC), a concept of utmost importance for describing variable-charge surfaces (Parks and de Bruyn 1961; Morais et al. 1976; Appel et al. 2003).

Understanding soils' PZC is critical for determining their anion exchange capacity (AEC) and cation exchange capacity (CEC), which directly affect nutrient retention and contaminant behavior. When a soil's pH exceeds its PZC, the surface carries a net negative charge, leading to increased CEC, where positively charged ions (cations) are exchanged (Mohawesh 2020). Conversely, when the soil's pH falls below its PZC, the surface tends to retain negatively charged ions (anions), exhibiting AEC behavior.

Various methods have been developed to determine the point of zero charge in soils and materials with variable surface charges. Among these, potentiometric titration is commonly used to assess changes in surface potential in response to the activities of $H^+$ and $OH^-$, thereby determining the point of zero salt effect (PZSE) or the point of zero net proton charge (PZNPC) (van Raij and Peech 1972; Parker et al. 1979; Marcano-Martinez and McBride 1989). Another approach, non-specific ion adsorption, measures the electrostatic adsorption of cations and anions to identify the point of zero net charge (PZNC). Some researchers have also utilized methods based on charged particles' mobility in an electric field (O'Brien and Rowlands 1993; Findlay et al. 1996). While these techniques have been effective for studying pure minerals, such as kaolinite and gibbsite, the complexity of soil systems—due to their heterogeneous nature and particle size variation—makes charge mobility more difficult to detect (Barrow 1987; Sposito 1989; Lewis-Russ 1991; Sposito 2016).

This research aims to determine the point of zero charge (PZC) of the Dutsin-Ma Dam floodplain soils and to assess how the PZC varies with distance from the water body. This research has significant practical implications, as it will provide insights into soil chemical properties that are directly relevant to understanding nutrient dynamics, soil fertility, and agricultural practices in the floodplain environment.

## MATERIALS AND METHODS

### Location of sampling sites

The study was carried out in Dutsin-ma, Katsina state, Nigeria. Soil samples were collected from floodplain areas where irrigation farming is carried out throughout the rainy and dry seasons throughout the year. The study site was located between latitude 12° 20.823N and longitude 7°30.455E and 500 m above sea level) in the Sudan Savannah ecological zone of Nigeria. The relative humidity of the study area is moderately high all year-round, and the temperature range is between 21 and 35°C.

### Sampling design

Soil samples were collected from three different sites of the floodplain (onshore, midshore and offshore) based on their proximity to the dam. From each selected site, 10 soil samples were taken using an auger from a depth of 0-30 cm (topsoil) making a total of 30 soil samples.

### General analytical methods

This study used soil-pertinent properties obtained using standard methods as described by Estefan et al. (2013). The pH readings were taken in water at a 1:10 soil/water ratio to model the CEC and AEC values (same soil/ water ratio) measured in the ion adsorption portion of the experiment. Effective CEC was extrapolated from ion adsorption curves at 0.001 M ionic strength (I) at field pH (1:10 soil/ water ratio), as this I was most representative of the soil.

### Determination of point of zero charge

A series of NaCl solutions at concentrations of 0.1, 0.01, and 0.001 M were prepared. 1g of soil was added to beakers containing 10 mL of the electrolyte solutions. pH of each suspension was adjusted to range from 2 to 10 using 0.1 M HCl or NaOH. It was covered and shaken the suspensions, allowing them to equilibrate for 24 hours to 7 days; the final pH after equilibration was measured. The final pH was plotted against the initial pH. The intersection of curves at different electrolyte concentrations indicates the PZC or finds the pH where the net proton charge equals zero.

### Estimating change in pH

The ΔpH of the soil samples was calculated using the following formula:

$\Delta pH = pH(KCl) - pH(H_2O)$ (Kome et al. 2018).

### The surface electrical potential

The surface electrical potential (Ψ0) in mV was estimated using the Nernst equation, which Chaves et al. (2016) reduced as follows:

$\Psi_0 = 59.1(PZC - pH(H_2O))$

### Data analysis

With SPSS software version 23 for Windows, soil properties of different sites of cultivated soil were analyzed using Analysis of Variance (ANOVA). The ANOVA test was also used for significant differences of C and N associated with each of the particle-size fractions. Mean values of soil properties and C and N concentrations in the particle size fraction were compared using Fisher's Protected Least Significant of Difference (LSD) at a 5% level of significance.

## RESULTS AND DISCUSSIONS

### Chemical characteristics of the experimental soil

Table 1 presents the descriptive statistics of the chemical properties of the experimental soil in the floodplain of the Dutsin-ma dam, which includes key parameters such as pH (in both $H_2O$ and KCl), electrical conductivity (EC), point of zero charge (ZPC), and exchangeable cations (Ca, Mg, K, Na), among others. The statistics include the minimum, maximum, mean, standard deviation, variance, skewness, and kurtosis for each parameter, offering insights into their distribution and variability, which is similar to the findings of Aki and Isong (2018).

The mean pH in $H_2O$ is 5.69, ranging from 4.8 to 6.7, with a moderate variability (standard deviation of 0.63). The pH in KCl is slightly lower, with a mean of 5.28. The positive skewness and kurtosis indicate that the distribution of pH values is left-skewed with relatively few high values, suggesting that most soil samples are more acidic (Abdulkadir et al. 2022). The variance is slightly higher in pH (KCl), implying greater variability in this measurement compared to pH ($H_2O$). The EC values have a wide range from 0.19 to 2.90, with a mean of 0.70, and exhibit high variability (standard deviation of 0.85), which is in agreement with the findings of Sani et al. (2019; 2022). The positive skewness (2.18) indicates a long tail with higher EC values, while the high kurtosis (4.08) suggests a sharp peak, implying a few extremely high values in the dataset.

The ΔpH (difference between pH in $H_2O$ and KCl) ranges from -0.80 to -0.10, with a mean of -0.41. The relatively low standard deviation (0.24) shows moderate variability in the differences. Negative skewness (-0.48) and kurtosis (-1.24) suggest a fairly uniform distribution with fewer extreme values. The ZPC values vary from 3.50 to 6.30, with a mean of 4.88. This variability is reflected in the standard deviation of 1.01, suggesting that ZPC differs considerably across soil samples. The slight negative skewness (-0.13) and kurtosis (-1.52) imply a left-skewed distribution with relatively fewer extreme values. The surface potential ranges from -94.56 to -11.82 mV, with a mean of -48.27 mV. The high standard deviation (27.82) and variance (773.71) indicate significant variability in surface potential across different samples. This wide range reflects the influence of various factors on soil cation exchange capacity (Habib et al. 2024).

Calcium (Ca) shows a range from 1.72 to 4.66 cmol/kg, with a mean of 3.40 cmol/kg, indicating moderate variability. Similar trends are observed for magnesium (Mg) and potassium (K), with means of 1.73 cmol/kg and 3.71 cmol/kg, respectively, which is in accordance with the findings of Abdulkadir et al. (2020). Sodium (Na) exhibits the least variability, with a narrow range (0.68 to 0.97 cmol/kg) and a mean of 0.83 cmol/kg. The exchangeable cations generally show low skewness and kurtosis, suggesting relatively normal distributions with moderate variability. The TEB ranges from 5.72 to 12.92 cmol/kg, with a mean of 9.66 cmol/kg, showing a moderate standard deviation of 2.36. The distribution of TEB is slightly left-skewed (-0.15), with fewer extreme values. Available phosphorus shows a mean of 22.65 mg/kg, ranging from 15.41 to 32.44 mg/kg. The positive skewness (0.41) and slightly negative kurtosis (-1.22) suggest that most samples have phosphorus levels around the mean, with a few high values. The ECEC ranges from 5.89 to 13.59 cmol/kg, with a mean of 10.02 cmol/kg, indicating moderate variability. The slight negative skewness (-0.12) and kurtosis (-1.07) reflect a relatively even distribution of ECEC values across samples.

The variability of experimental soil chemical properties, a novel aspect of our research, highlights the influence of the floodplain environment on soil characteristics. The wide range in pH values, both in $H_2O$ and KCl, a unique finding, indicates differences in acidity across sample locations, which can significantly influence nutrient availability and microbial activity (Habib et al. 2024). The variation in ZPC values, another novel discovery of soil's capacity to adsorb cations and anions, varies considerably across the samples. This suggests that soils closer to or farther from the water body may differ in their ability to retain nutrients or contaminants. Electrical conductivity, a measure of the soil's salinity, shows a highly skewed distribution with a few outliers, indicating localized areas with significantly higher salt concentrations. This could be due to variations in soil moisture content or the influence of floodwaters from the dam (Loneragan 1975)

The exchangeable cations, particularly calcium, magnesium, and potassium, exhibit moderate variability, reflecting differences in soil fertility across the floodplain. Sodium, with its low variability, indicates that it is less affected by the proximity to the water body. The results provide valuable insights into the floodplain soil's chemical properties, which are crucial for understanding soil fertility, nutrient retention, and potential agricultural productivity in the region. Understanding these variations can inform better soil management practices tailored to the specific needs of different zones within the floodplain.

### Influence of distance from the water on some selected chemical properties of the experimental soil

Table 2 provides data on some selected chemical properties of soil at different distances from a dam: onshore, mid-shore, and offshore. The properties measured are pH in water (pH ($H_2O$)), pH in potassium chloride (pH(KCl)), electrical conductivity (EC), total exchangeable bases (TEB), exchangeable acidity (EA), and effective cation exchange capacity (ECEC).

**Table 1.** Descriptive statistics of the chemical properties of the experimental soil

| | Minimum | Maximum | Mean | Standard Deviation | Variance | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|
| pH($H_2O$) | 4.8 | 6.7 | 5.69 | 0.63 | 0.403 | 0.41 | -1.234 |
| pH(KCl) | 4.2 | 6.5 | 5.28 | 0.81 | 0.652 | 0.09 | -1.466 |
| EC | 0.19 | 2.90 | 0.70 | 0.85 | 0.718 | 2.18 | 4.078 |
| ΔPH | -0.80 | -0.10 | -0.41 | 0.24 | 0.055 | -0.48 | -1.242 |
| ZPC | 3.50 | 6.30 | 4.88 | 1.01 | 1.01 | -0.13 | -1.522 |
| $\Psi_0$ | -94.56 | -11.82 | -48.27 | 27.82 | 773.71 | -0.48 | -1.242 |
| Ca | 1.72 | 4.66 | 3.40 | 0.93 | 0.86 | -0.33 | -0.760 |
| Mg | 1.08 | 2.36 | 1.73 | 0.44 | 0.20 | 0.07 | -1.282 |
| K | 1.64 | 5.12 | 3.71 | 1.04 | 1.09 | -0.48 | -0.272 |
| Na | 0.68 | 0.97 | 0.83 | 0.10 | 0.01 | -0.18 | -1.506 |
| EA | 0.17 | 0.67 | 0.36 | 0.17 | 0.03 | 0.87 | 0.040 |
| TEB | 5.72 | 12.92 | 9.66 | 2.36 | 5.58 | -0.15 | -1.067 |
| Av. P | 15.41 | 32.44 | 22.65 | 5.83 | 34.04 | 0.41 | -1.225 |
| ECEC | 5.89 | 13.59 | 10.02 | 2.51 | 6.31 | -0.12 | -1.073 |

Note: EA: Exchangeable Acidity, EC: Electrical Conductivity, TEB: Total Exchangeable Bases, Av. P: Available Phosphorus, ECEC: Effective Cation Exchange Capacity, ZPC: Zero Point of Charge, $\Psi_0$: Surface electrical potential

**Table 2.** Selected chemical properties of soil at different distances from a dam

| Position | pH($H_2O$) | pH(KCl) | EC | TEB | EA | ECEC | OC |
|---|---|---|---|---|---|---|---|
| Onshore | 5.075c | 4.500c | 0.9025 | 12.357a | 0.5425a | 12.90a | 1.0950a |
| Midshore | 5.525b | 5.250b | 0.8150 | 9.592a | 0.3300b | 9.92b | 0.7650b |
| Offshore | 6.475a | 6.225a | 0.3675 | 7.040c | 0.2100b | 7.25c | 0.4000c |
| SED | 0.1379 | 0.1728 | 0.634 | 0.518 | 0.0740 | 0.551 | 0.0742 |

**Table 3.** The influence of distance from the dam on some selected soil chemical properties

| Position | ΔpH | ZPC | $\Psi_0$ |
|---|---|---|---|
| Onshore | -0.5750b | 3.925c | -82.74b |
| Midshore | -0.2750a | 4.975b | -32.51a |
| Offshore | -0.2500a | 5.975a | -29.55a |
| SED | 0.1258 | 0.269 | 8.70 |

Soil pH increases significantly from onshore to offshore, with offshore soils being more alkaline; similar to pH ($H_2O$), pH (KCl) increases significantly with distance from the dam, indicating a decrease in soil acidity offshore. EC decreases with distance from the dam, suggesting lower salinity levels offshore; TEB is highest onshore and decreases with increasing distance from the dam. Higher TEB onshore indicates more nutrient availability close to the dam; ECEC follows a similar trend to TEB, being highest onshore and decreasing offshore, indicating a higher nutrient-holding capacity near the dam.

### Influence of distance from the dam on some selected soil chemical properties

ΔpH decreases with distance from the dam, suggesting that soil pH stabilizes further away from the water source, ZPC increases with distance from the dam, indicating a higher pH at which the soil surface has zero net charge offshore, Ψ0 decreases (becomes less negative) with distance from the dam, suggesting that the soil's ability to retain cations decreases further away from the dam.

In this study, we investigated the correlations between pH in water and various soil properties. Table 3 presents our findings. We found that pH ($H_2O$) and pH(KCl) have a very strong positive correlation of 0.968, indicating that pH measured in water and salt solution are highly related and tend to increase or decrease together. pH ($H_2O$) and EC have a Weak negative correlation of -0.252, suggesting a slight inverse relationship between soil pH in water and electrical conductivity, though not significant. pH ($H_2O$) and ΔpH have a Moderate positive correlation: 0.497, indicating a relationship where higher pH in water tends to be associated with higher differences in pH, though not significant. pH ($H_2O$) and ZPC have a Strong positive correlation of 0.911, suggesting that as pH in water increases, the zero point of charge also increases significantly. pH ($H_2O$) and $\Psi_0$ have a Moderate positive correlation, the same as with ΔPH, indicating a relationship, though not significant. pH ($H_2O$) and EA have a Strong negative correlation: - 0.715, indicating that as pH in water increases, exchangeable acidity decreases significantly. pH ($H_2O$) and ECEC have a Very strong negative correlation of -0.871, indicating that as pH in water increases, effective cation exchange capacity decreases significantly (Dawaki et al. 2020).

In Table 2, the increase in soil pH (both pH ($H_2O$) and pH(KCl)) from onshore to offshore indicates a significant reduction in soil acidity as the distance from the dam increases. This trend could be due to the leaching of acidic components away from the shoreline or differences in soil management practices and vegetation cover. Higher pH levels offshore suggest better soil conditions for many crops, which prefer neutral to slightly alkaline soils. The decreasing trend in EC with distance from the dam suggests that soils closer to the dam have higher salinity levels. This could be attributed to the accumulation of salts through irrigation or floodwater from the dam. Lower salinity levels offshore are beneficial for plant growth, as high salinity can hinder water uptake by plants and affect soil structure. The higher TEB and EA values onshore indicate greater availability of exchangeable cations and higher soil acidity near the dam. These trends reflect the influence of water movement and deposition of minerals from the dam's waters. Managing these properties is crucial, as high exchangeable acidity can lead to aluminum toxicity, which adversely affects plant growth. Recent studies corroborate these findings, highlighting the impact of water bodies on surrounding soil properties. For instance, research has shown that proximity to water sources like dams can significantly influence soil pH, salinity, and nutrient availability (Lal 2011). Changes in soil properties with distance from water bodies are crucial for understanding soil management needs and optimizing agricultural practices (Doran and Zeiss 2000). In Table 3, The higher change in pH (ΔpH) onshore indicates greater variability in soil pH closer to the dam, likely due to the influence of water flux and mineral deposition. The reduced ΔpH offshore suggests more stable soil conditions, which is beneficial for plant growth as extreme pH fluctuations can adversely affect nutrient availability. The increase in ZPC from onshore to offshore indicates that the soil surface's net charge at a higher pH level increases with distance from the dam. This trend suggests that soils further from the dam are more capable of maintaining a stable charge environment, which can influence nutrient retention and soil structure. The significant negative surface potential ($\Psi_0$) onshore suggests a higher cation exchange capacity (CEC) closer to the dam, which could be beneficial for nutrient retention. However, this can also lead to higher soil acidity and potential toxicity issues. The less negative Ψ0 offshore indicates a decrease in CEC, potentially reducing nutrient retention but also reducing the risk of soil acidity and toxicity. Recent studies have highlighted the significant impact of proximity to water bodies on soil chemical properties. The variability in soil pH, ZPC, and surface potential is influenced by factors such as water movement, mineral deposition, and organic matter content (Lal 2011). Research also indicates that managing these properties is crucial for optimizing soil health and fertility, particularly in agricultural settings (Doran and Zeiss 2000). It is therefore important to understand the spatial variation of these properties can help in developing targeted soil management practices to improve crop productivity and sustainability (Bot and Benites 2005).

**Table 4.** Correlation analysis of the electrochemical properties of Dutsin-Ma Dam flood plain soil

| | **pH($H_2O$)** | **pH(KCl)** | **EC** | **ΔpH** | **ZPC** | **$\Psi_0$** | **EA** | **ECEC** |
|---|---|---|---|---|---|---|---|---|
| pH($H_2O$) | 1 | | | | | | | |
| pH(KCl) | 0.968$^{**}$ | 1 | | | | | | |
| EC | -0.252 | -0.096 | 1 | | | | | |
| ΔpH | 0.497 | 0.699$^{*}$ | 0.386 | 1 | | | | |
| ZPC | 0.911$^{**}$ | 0.985$^{**}$ | 0.013 | .810$^{**}$ | 1 | | | |
| $\Psi_0$ | 0.497 | 0.699$^{*}$ | 0.386 | 1.000$^{**}$ | 0.810$^{**}$ | 1 | | |
| EA | -0.715$^{**}$ | -0.850$^{**}$ | -0.147 | -0.902$^{**}$ | -0.910$^{**}$ | -0.902$^{**}$ | 1 | |
| ECEC | -0.871$^{**}$ | -0.912$^{**}$ | 0.190 | -0.669$^{*}$ | -0.906$^{**}$ | -0.669$^{*}$ | 0.872$^{**}$ | 1 |

Note: **: Correlation is significant at the 0.01 level, *: Correlation is significant at the 0.05 level

Table 4 shows the very strong correlation between pH($H_2O$)and pH(Salt), which implies that these measurements are highly consistent and reliable indicators of soil acidity. This relationship is crucial for soil management practices, as it helps in determining the soil's buffering capacity and potential response to amendments. The weak and non-significant correlations of EC with other parameters suggest that soil salinity, as measured by EC, does not strongly influence or influence the other soil properties measured in this study. This may indicate that the salinity levels are relatively stable or independent of pH and other chemical properties. The strong positive correlation between ZPC and both pH measurements (pH(H2O) and pH (salt)) suggests that higher soil pH is associated with higher ZPC. This relationship is critical for understanding soil's surface charge properties, which influence nutrient availability and retention. The perfect correlation between ΔpH and $\Psi_0$ (0.699*) indicates that these measurements are essentially identical, reflecting the same soil property. The relationship between $\Psi_0$ and other properties follows similar patterns to ΔpH. The strong negative correlations of EA and ECEC with pH measurements indicate that as soil pH increases, both EA and ECEC decrease. This suggests that more acidic soils have higher exchangeable acidity and cation exchange capacity, which could impact nutrient availability and soil structure. Managing soil pH could thus be essential for optimizing these properties.

The study concludes that proximity to the dam significantly affects soil chemical properties, impacting soil acidity, salinity, nutrient availability, and cation exchange capacity. Soils closer to the dam are more acidic and saline, with higher nutrient availability, but also higher exchangeable acidity, which can pose challenges for plant growth. In contrast, soils further from the dam exhibit more stable pH levels, lower salinity, and reduced acidity, creating more favorable conditions for plant growth and soil health.

## REFERENCES

Abdulkadir A, Dawaki MU, Sani M. 2019. Effect of organic soil amendments on soil chemical properties in Sudan Savannah of Nigeria. Niger J Soil Sci 30 (2): 122-132. DOI: 10.36265/njss.2020.300215.

Abdulkadir A, Halilu Y, Sani S. 2022. Evaluation of physical and chemical properties of soils at Bichi Local Government Area, Kano State, Nigeria. IRE J 5 (9): 556-562.

Aki EE, Isong IA. 2018. Characterization of physico-chemical properties and micronutrients status of soil developed on Anantigha coastal marine sediment in Calabar. Glob J Agric Sci 17 (1): 1-12. DOI: 10.4314/gjass.v17i1.1.

Appel C, Ma LQ, Dean Rhue R, Kennelley E. 2003. Point of zero charge determination in soils and minerals via traditional methods and detection of electroacoustic mobility. Geoderma 113 (1-2): 77-93. DOI: 10.1016/s0016-7061(02)00316-6.

Barrow NJ. 1987. Variable charge oxides as soil constituents and as models of soil constituents. Reactions with Variable-Charge Soils 6-15. DOI: 10.1007/978-94-009-3667-6_2.

Borrelli P, Robinson DA, Panagos P, Lugato E, Yang JE, Alewell C, Wuepper D, Montanarella L, Ballabio C. 2020. Land use and climate change impacts on global soil erosion by water (2015-2070). Proc Natl Acad Sci 117 (36): 21994-22001. DOI: 10.1073/pnas.2001403117.

Bot A, Benites J. 2005. The importance of soil organic matter: Key to drought-resistant soil and sustained food production. FAO Soils Bull 80: 1-78.

Chaves LHG, Mendes JS, Chaves IDB. 2016. Effects of poultry biochar on electrochemical properties of electronegative soils. Intl J Curr Res 8 (11): 40834-40837.

Dawaki MU, Abdulkadir A, Abdulrahman BL. 2020. Comparative potential effects of biochar, compost and inorganic fertilizer on major nutrient ions mobility and stability in screen - house irrigated maize in the drier savannas of Nigeria. Niger J Soil Sci 29 (2): 122-132. DOI: 10.36265/njss.2020.290215.

Doran JW, Zeiss MR. 2000. Soil health and sustainability: Managing the biotic component of soil quality. Appl Soil Ecol 15 (1): 3-11. DOI: 10.1016/S0929-1393(00)00067-6.

Estefan G, Sommer R, Ryan J. 2013. Methods of Soil, Plant, and Water Analysis: A manual for the West Asia and North Africa region. International Center for Agricultural Research in the Dry Areas (ICARDA), Beirut, Lebanon.

Findlay AD, Thompson DW, Tipping E. 1996. Electrokinetic properties of oxide particles in natural waters. Colloids Surfaces A: Physicochem Eng Asp 111 (3): 203-212. DOI: 10.1016/0927-7757(95)03510-9.

Habib D, Bashir MB, Dawaki MU, Onokebhagbe V, Umar AM, Sharif U, Abubakar AU. 2024. Effects of organic amendments on tomato yield and electrochemical properties of soilless growing media. Intl J Agric Environ Food Sci 8 (2): 392-400. DOI: 10.31015/jaefs.2024.2.14.

Huntley BJ. 2023. Ecology of Angola. Springer International Publishing. DOI: 10.1007/978-3-031-18923-4.

Kome GK, Enang RK, Yerima BPK, Lontsi MGR. 2018. Models relating soil pH measurements in $H_2O$, KCl and $CaCl_2$ for volcanic ash soils of Cameroon. Geoderma Reg 14: e00185. DOI: 10.1016/j.geodrs.2018.e00185.

Lal R. 2011. Soil health and climate change: An overview. In: Singh BP, Cowie AL, Chan KY (eds.). Soil Health and Climate Change. Springer Berlin, Heidelberg. DOI: 10.1007/978-3-642-20256-8_1.

Lewis-Russ A. 1991. Measurement of Surface Charge of Inorganic Geologic Materials: Techniques and Their Consequences. Adv Agron 46: 199-243. DOI: 10.1016/s0065-2113(08)60581-7.

Loneragan JF. 1975. The availability and absorption of trace elements in soil-plant systems and their relation to movement and concentrations of trace elements in plants. In: Nicholas DJD, Egan AH (eds.). Trace Elements in Soil-Plant-Animal Systems. Academic Press, New York. DOI: 10.1016/b978-0-12-518150-1.50013-6.

Marcano-Martinez E, McBride MB. 1989. Comparison of the titration and ion adsorption methods for surface charge measurement in oxisols. Soil Sci Soc Am J 53 (4): 1040-1045. DOI: 10.2136/sssaj1989.03615995005300040009x.

Mohawesh O, Albalasmeh A, Al-Hamaiedeh H, Qaraleh S, Maaitah O., Bawalize A, Almajali D. 2020. Controlled land application of Olive Mill Wastewater (OMW): Enhance soil indices and barley growth performance in arid environments. Water Air Soil Pollut 231: 1-12. DOI: 10.1007/s11270-020-04612-z.

Morais FI, Page AL, Lund LJ. 1976. The effect of pH, salt concentration, and nature of electrolytes on the charge characteristics of Brazilian tropical soils. Soil Sci Soc Am J 40: 521 - 527.

O'Brien RW, Rowlands WN. 1993. Measuring the surface conductance of kaolinite particles. J Colloid Interface Sci 159 (2): 471-476. DOI: 10.1006/jcis.1993.1348.

Parker JC, Zelazny LW, Sampath S, Harris WG. 1979. A critical evaluation of the extension of zero point of charge (ZPC) theory to soil systems. Soil Sci Soc Am J 43 (4): 668-674. DOI: 10.2136/sssaj1979.03615995004300040008x.

Parks GA, de Bruyn PL. 1961. The zero point of charge of oxides. J Phys Chem 66: 967-973.

Penn C, Camberato J. 2019. A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. Agriculture 9 (6): 120. DOI: 10.3390/agriculture9060120.

Sani S, Pantami SA, Sani M. 2019. Evaluation of soil physical properties at Jibia Irrigation Project, Katsina State, Nigeria. Fudma J Agric Agric Techol 5 (1): 231-24.

Sufiyanu S, Mahmud S, Pantami SA, Abdulkadir A, Abdullahi YM, Harisu GN, Jazuli BL. 2022. Spatial variability of soil hydraulic properties in Jibia Irrigation Project, Katsina State, Nigeria. Nat Resour Sustain Dev 12 (2): 245-254. DOI: 10.31924/nrsd.v12i2.103.

Sposito G. 1981. The operational definition of the zero point of charge in soils. Soil Sci Soc Am J 45 (2): 292-297. DOI: 10.2136/sssaj1981.03615995004500020013x.

Sposito G. 2016. The Chemistry of Soils. Oxford University Press. DOI: 10.1093/oso/9780190630881.001.0001.

Van Raij B, Peech M. 1972. Electrochemical properties of some oxisols and alfisols of the tropics. Soil Sci Soc Am J 36 (4): 587-593. DOI: 10.2136/sssaj1972.03615995003600040027x.

Wen X, Wang Y, Cheng P, Liu D, Ma S, Zhang C, Liu T, Tao L. 2020. Surface charge properties of variable charge soils influenced by environmental factors. Appl Clay Sci 189: 105522. DOI: 10.1016/j.clay.2020.105522:

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# Spatial assessment of ecotourism potential in the mangrove area of Ujungalang Village, Cilacap District, Central Java, Indonesia

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**Abstract.** *Santika YE, Arlysia V, Astuti AR, Putri DS, Puspitosari A, Budiharta S, Yap CK, Setyawan AD. 2025. Spatial assessment of ecotourism potential in the mangrove area of Ujungalang Village, Cilacap District, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 7-19.* Mangrove ecosystem, with its diverse ecological and economic functions, is a vital provider of ecosystem services that benefit coastal communities, including the potential for ecotourism development, which is considered as win-win solution for conservation and sustainable utilization of natural resources. Ujungalang Village, located in Kampung Laut Sub-district, Cilacap District, Central Java, is one area with significant mangrove potential that can be developed as an ecotourism destination. This study aims to identify potential mangrove ecotourism locations in Ujungalang Village and analyze the physical and social conditions that support the development of mangrove ecotourism in the region. The research was conducted using a quantitative method with a spatial approach, employing Geographic Information System tools and remote sensing data. The spatial analysis technique utilized is overlay, involving scoring and weighting several factors influencing ecotourism potential including slope, temperature, land use, conservation status, population density, elevation, as well as facilities and infrastructure. The study results show that the Ecotourism Potential Index of Ujungalang Village ranges from 3.03 to 156.16, which can be divided into three categories: non-potential, with values of 3.03-33.66 (174.02 ha); low potential, with values of 33.67-64.30 (1,292.52 ha); and highly potential, with values of 125.59-156.16 (5,290.43 ha). The findings of this study can assist tourism planners and government authorities in identifying appropriate locations for ecotourism development, instilling a sense of optimism and hope.

**Keywords:** Ecotourism, GIS, mangrove, overlay, potential mapping

## INTRODUCTION

Ecotourism is a form of nature-based tourism where economic activities can be aligned with the conservation of species and habitats, both directly and indirectly, benefiting local communities through empowerment as well as protecting biodiversity (Saeroji 2020). In many cases, ecotourism aims to promote environmental conservation practices in protected natural areas, which involves local communities as a form of sustainable tourism (Çetinkaya et al. 2018). This is achieved by educating visitors and local communities to protect nature while enjoying the ecosystem services the nature provided as well as gaining economic benefits for regional development (Gigović et al. 2016).

In Indonesia, ecotourism has been increasing and developing in various regions, attracting international and domestic tourists. There are several well-known ecotourism destinations in Indonesia, for example Kuala Langsa Mangrove Forest Ecotourism in Aceh, Tangkahan Ecotourism and Gunung Leuser National Park in North Sumatra, Way Kambas National Park in Lampung, Bunaken National Park in North Sulawesi, Komodo National Park in East Nusa Tenggara, Raja Ampat in West Papua and others (Yusnikusumah and Sulystiawati 2016; Safuridar and Andiny 2020; Mu'tashim and Indahsari 2021; Yunanda and Chair 2022).

Mangrove areas have a great potential to be developed into environmentally-based tourism destinations (Erlinda et al. 2022). The presence of mangroves in coastal areas offers natural beauty and unique experiences to visitors, for example through bird watching. Additionally, educational activities focused on biodiversity, ecological functions, and conservation efforts also have the potential to attract tourists (Mulyadi et al. 2021).

Indonesia has the largest mangrove area in the world, covering 3,112,989 ha, which is equivalent to 22.6% of the world's mangrove area (Febrianto et al. 2024). One of the mangrove areas in Java Island that is still in its natural state is located in Segara Anakan, Cilacap District, Central Java Province. Kampung Laut Sub-district, one of the sub-districts located in the Segara Anakan lagoon, is situated on the edge of the lagoon and is surrounded by water, making its location relatively isolated (Qomariyah and Kiat 2024).

Kampung Laut Sub-district has the potential to be developed for mangrove ecotourism. Various species of mangroves grow in this area might be used for education purposes as well as research activities. Kampung Laut Sub-district has a tourist attraction called Kolak Sekancil, a mangrove arboretum area that was abandoned during the COVID-19 pandemic. The main issues in developing this area to be attractive as tourism spot are the lack of supporting infrastructure and limited education of the local community. This has resulted in suboptimal management, which hinders the development of ecotourism and educational activities (Dian et al. 2024).

Suboptimal management of mangrove ecotourism can lead to a decline in the value of resources, including mangroves (Liu et al. 2021). Therefore, it is important to study on the potential of mangroves, one of which can be done using remote sensing methods (Abidin et al. 2023). The combination of remote sensing and Geographic Information Systems (GIS) is considered an efficient method for tourism planning, development and management by handling the large volume of spatial data, and analyzing the relationship between spatial data and various tourism aspects, such as location (Sahani 2019; Pathmanandakumar et al. 2023).

Literature analysis reveals that various spatial variables (factors and criteria) have been employed to determine potential ecotourism locations using GIS. Chaudhary et al. (2022) used GIS and remote sensing to identify potential ecotourism locations in Garhwal, Uttarakhand, India, based on vegetation, biodiversity, slope, and elevation. Pathmanandakumar et al. (2023) used Analytical Hierarchy Process (AHP) and GIS to identify suitable zones for ecotourism development in Batticaloa District, Sri Lanka, based on landscape, conservation areas, elevation, accessibility, and population density. This study aims to identify potential locations for ecotourism development in Ujungalang Village by systematically integrating approaches used in the three previous studies in term of geographical aspects (slope, elevation, and land use), ecological aspects (conservation status), physical aspects (temperature), and socio-economic aspects (population density and infrastructure). The scoring and weighting were applied to factors such as slope, temperature, land use, conservation status, population density, elevation, and infrastructure to achieve the GIS combination. Therefore, the findings of this study can assist tourism planners and the government in determining appropriate locations and further developing ecotourism activities.

## MATERIALS AND METHODS

### Study area and period

This research was conducted in the mangrove ecosystem area in Ujungalang Village in October 2024. The mangrove ecosystem is within the Segara Anakan Lagoon area, which is administratively part of Kampung Laut Sub-district, Cilacap District. Ujungalang Village covers an area of 6,756.97 ha and consists of four hamlets: Lempong Pucung, Motean, Paniten, and Bondan (Figure 1).

Ujungalang Village is located at an elevation of 1-40 meters above sea level (masl), with a slopes ranging from less than 5° (very gentle) to more than 35° (very steep). The temperature in Ujungalang Village ranges from 22-30.6°C, predominantly falling within temperature factor class IV (28-30°C). The area of Ujungalang Village is primarily dominated by mangrove forests, covering 5,474.59 ha or 81.02% of the total land cover. The mangrove vegetation in Ujungalang Village includes species such as *Avicennia alba*, *Ceriops tagal*, *Ceriops decandra*, *Aegiceras floridum*, *Aegiceras corniculatum*, *Sonneratia caseolaris*, *Bruguiera sexangula*, nipa palm, and various minor mangroves and associated species (Hariyadi 2018).

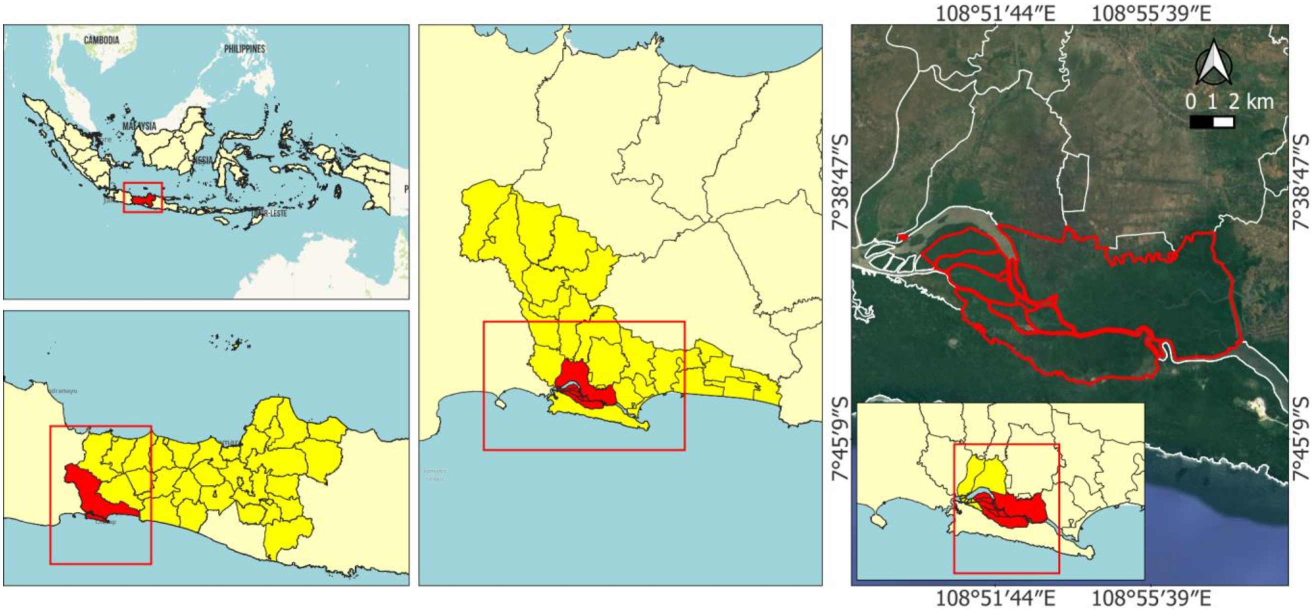

**Figure 1.** Location of Ujungalang Village, Kampung Laut Sub-district, Cilacap District, Central Java, Indonesia

According to data from the BPS-Statistics of Kampung Laut Sub-district (2024), the population of Ujungalang Village is 4,265 people, with a population density of 65.87 people/km². The male population consists of 2,271 people, or 53.25%, while the female population consists of 1,994 people or 46.75%. Based on the data from the BPS-Statistics of Kampung Laut Sub-district (2020), the residents of Ujungalang Village include 900 fishermen and 458 farmers.

### Data collection

This research used both primary and secondary data. Primary data was obtained through field observations at the research site, including information about the facilities and infrastructure supporting tourism activities. Information about these facilities and infrastructure was also verified through map analysis sourced from Google Maps. Meanwhile, the secondary data used in this study is presented in Table 1.

#### *Land use*

In addition to vegetation cover, various natural landscapes and areas with cultural value are also key factors in the development of ecotourism (Chaudhary et al. 2022). Land use information was obtained using Google Earth imagery. The Google Earth imagery, adjusted for coordinates and administrative boundaries, was manually delineated for land use classification. The boundary data was obtained from the Geospatial Information Agency website (https://tanahair.indonesia.go.id/), which contains the boundary of Ujungalang Village. In this study, land use is categorized into five types: agriculture, open land (unused vacant land), settlement, mangrove forest, and water bodies.

#### *Slope*

The Digital Elevation Model Shuttle Radar Topographic Mission (DEM SRTM) was used to determine the slope. After calculating the slope from the DEM, the slope values were then reclassified into categories that are suitable for supporting the development of ecotourism. Chaudhary et al. (2022) classified the slopes as follows: very suitable (<5.0°), suitable (5.1°-15.0°), moderate (15.1°-25.0°), low suitable (25.1°-35.0°), and unsuitable (>35.0°).

#### *Elevation*

DEM SRTM can be used to extract topographic features, such as slope, and generate surface elevation maps. For this purpose, the DEM was reclassified to represent elevation zones ranging from unsuitable to very suitable based on accessibility levels and climate feasibility. Fu et al. (2018) classified suitable elevations as follows: very suitable (<100 masl), suitable (100-500 masl), moderate (500-1,000 masl), low suitable (1,000-1,500 masl), and unsuitable (>1,500 masl).

#### *Temperature*

The temperature data used in this study were extracted from the spatial (raster) Land Surface Temperature (LST) data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD11A2 V6.1 imagery. The imagery was downloaded and processed using the Google Earth Engine (GEE) platform. Data processing techniques included image composition, data extraction based on the study area, and area calculation based on temperature factor classes. The temperature related to ecotourism activities were categorized into five classes: very suitable (20-21°C), suitable (22-24°C/17-19°C), moderate (25-27°C/14-16°C), low suitable (28-30°C/11-13°C), and unsuitable (>30°C/<10°C) (Department of Forestry Republic of Indonesia 2003).

#### *Population*

Demographic data were obtained from the publication of BPS-Statistics of Kampung Laut Sub-district. The demographic data used in this study include total population, population distribution by gender, population density, and primary occupations.

#### *Facilities and infrastructure*

Information about facilities and infrastructure was obtained through field observations and interpretation of Google Maps. Facilities included various amenities and infrastructure needed by tourists in a destination area, such as accommodations, restaurants, transportation, and travel agency services (Amerta et al. 2024).

**Table 1.** Secondary data and data sources used in this study in Ujungalang Village, Kampung Laut Sub-district, Cilacap District, Central Java, Indonesia

| Data | Years | Type of data | Sources |
|---|---|---|---|
| Administrative boundary | 2024 | Vector | Shapefile of Administrative Boundary (https://tanahair.indonesia.go.id/) |
| Land use | 2024 | Raster (30m resolution) | Image from Google Earth (https://earth.google.com/) |
| Slope | 2024 | Raster (30m resolution) | DEM SRTM 30m (https://earthexplorer.usgs.gov/) |
| Elevation | 2024 | Raster (30m resolution) | DEM SRTM 30m (https://earthexplorer.usgs.gov/) |
| Temperature | 2024 | Raster (30m resolution) | MODIS Imagery from Google Earth Engine (https://earthengine.google.com/) |
| Population | 2024 | Vector | BPS-Statistics Cilacap District (https://cilacapkab.bps.go.id/id) |
| Facilities and infrastructure | 2024 | Vector | Map from Google Maps (https://www.google.com/maps) |
| Road network | 2024 | Vector | Shapefile of Road Network (https://tanahair.indonesia.go.id/) |
| Conservation | - | Vector | Peraturan Daerah Kabupaten Cilacap Nomor 17 Tahun 2001 (Regulation of Cilacap District Number 17 of 2001) (https://jdih.cilacapkab.go.id/v2/) |

*Road network*

The road network data was obtained from the Geospatial Information Agency website (https://tanahair.indonesia.go.id/) and adjusted to the study area. Road network information was used to evaluate the accessibility of the study area, which is planned to be developed into an ecotourism destination. Tourism destinations should be easily accessible, with necessary facilities readily available for tourists, such as transportation to the destination, as well as safe and comfortable roads.

*Conservation*

To preserve the beauty of nature, nature reserves and protected areas play a crucial role in supporting the development of ecotourism activities (Gigović et al. 2016). In this study, conservation status is ranked based on the opportunities available for ecotourism activities. Conservation forests are ranked as having a high potential for ecotourism. Coastal buffer zones are categorized as having fair potential for ecotourism. Wildlife sanctuaries, nature reserves, and national parks are categorized as having moderate potential for ecotourism, while other conservation areas are considered to have low potential for ecotourism. However, areas outside protected zones, or unprotected areas, are considered to be non-potential for ecotourism. According to Regional Regulation of Cilacap District Number 17 of 2001, the mangrove forest in the Segara Anakan area is a protected forest area.

## Data analysis

The analysis method used in this study is a quantitative method with a spatial approach through the use of Remote Sensing (RS) and Geographic Information System (GIS). The spatial analysis technique employed was overlay, which involved the process of assigning scores and weights to each factor affecting ecotourism (Waspodo et al. 2024). The overlay is a spatial analysis technique that involves combining multiple spatial elements or geographic layers to generate new elements or information (Hafidz et al. 2023). The spatial data in this study was analyzed and processed using ArcGIS 10.8 software. Figure 2 presents a flowchart that systematically depicts the stages and methods of this research.

*Scoring*

The first step in analyzing the potential of ecotourism is to assign scores to each criterion of the factors used. The factors considered in this study include slope, temperature, land use, conservation status, population density, elevation, and facilities and infrastructure. The determination of factors and criteria is based on a literature review, taking into account the physical conditions of the research location (Table 2).

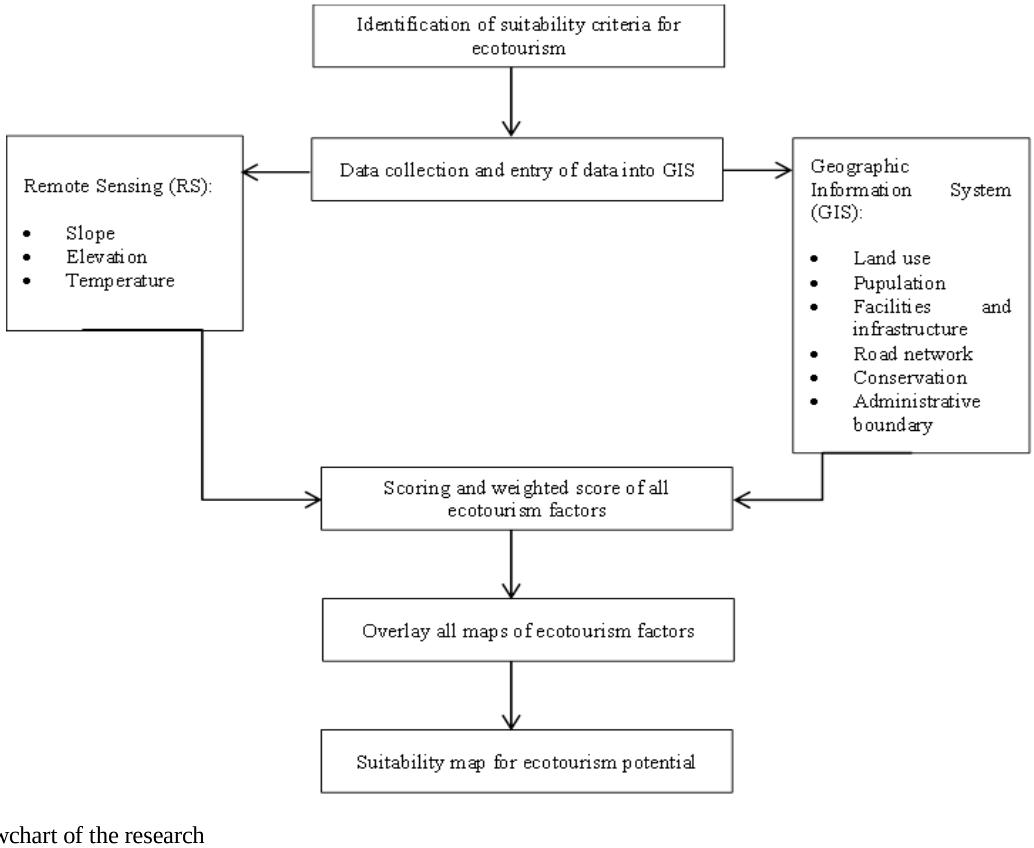

**Figure 2.** Flowchart of the research

**Table 2.** Factors and criteria scores used in the research and related references

| Factors | Criteria scores/factor class | | | | | References |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| Land use | Mangrove forest | Water bodies (lakes, swamps, rivers, etc.) | Agricultural areas (rice fields, farms, gardens) | Open land | Settlement | Pathmanandakumar et al. (2023) |
| Slope (°) | <5 | 5.1-15 | 15.1-25 | 25.1-35 | >35 | Chaudhary et al. (2022); Yasin and Woldemariam (2023) |
| Elevation (meters above sea level/masl) | <100 | 100-500 | 500-1000 | 1000-1500 | >1500 | Fu et al. (2018) |
| Temperature (°C) | 20-21 | 22-24/17-19 | 25-27/14-16 | 28-30/11-13 | >30/<10 | Department of Forestry Republic of Indonesia (2003) |
| Population density (people/km$^2$) | 0-50 | 51-150 | 151-250 | 251-400 | >400 | National Standardization Agency of Indonesia (2004); Samanta and Baitalik (2015) |
| Facilities and infrastructure | ≥4 types | 3 types | 2 types | 1 type | None | Department of Forestry Republic of Indonesia (2003); Sisriany (2021) |
| Conservation status | Conservation forest/protected forest | Coastal buffer zone | Wildlife sanctuary, nature reserve, national park | Other conservation areas | Unprotected | Gigović et al. (2016); Sahani (2019) |

**Table 3.** Position of the factor ranking

| Data | Ranking |
|---|---|
| Land use | 1 |
| Conservation status | 2 |
| Elevation (meters above sea level/masl) | 3 |
| Facilities and infrastructure | 4 |
| Slope (°) | 5 |
| Temperature (°C) | 6 |
| Population density (people/km$^2$) | 7 |

*Weighted score*

Scores are used to differentiate the extent of the influence of each assessment criterion for each factor used, while the weight values serve to distinguish the impact between factors. Weighting for each factor is used to measure the development of natural tourism potential, a practical application of our methodology. Factors with high carrying capacity are given high weights. In contrast, factors with low carrying capacity are given low weights (Selamat 2015). Weighting is performed using the ranking method from Selamat (2015), with the rankings shown in Table 3 and the following formula:

$$Wj = n - rj + 1 / \Sigma(n - rp + 1)$$

Where: Wj = Normal weight of factor j (j = 1,2,3,.....n); n = Number of factors being studied; rj = Position of the factor ranking; rp = Factor (p = 1,2,3,.....n).

*Ecotourism potential index*

The ecotourism potential index was obtained by overlaying all the maps that have been weighted. The weight value of each factor is multiplied by the amount of spatial data or the number of polygons representing land availability in each map to produce the final value. This final value is then used to determine the classification of ecotourism potential using the following formula:

$$I : \frac{a-b}{n}$$

Where: I: Class interval; a: Highest score; b: Lowest score; n (number of classes): 5.

## RESULTS AND DISCUSSION

### Potential index of ecotourism based on remote sensing and GIS

*Land use*

Land uses in Ujungalang Village are classified into mangrove forests, water bodies (rivers), rice fields, and settlements (Figure 3.A). The largest extent of land use is mangrove forest with 5,474.59 ha, followed by rice fields with 929.42 ha. Meanwhile, settlements, which serve as residential areas and spaces for community activities, cover an area of 57.4 ha. Other land uses include rivers, covering 295.56 ha. Based on these land uses, Ujungalang Village falls into land use factor classes I, II, III, and V (Table 2).

*Conservation status*

According to the Regional Regulation of Cilacap District Number 17 of 2001, the mangrove forest in the Segara Anakan area is designated as a protected forest area (Figure 3.B). Kampung Laut Sub-district is located in the middle of the Segara Anakan area, which consists of four villages: Klaces, Panikel, Ujungalang, and Ujunggagak. Therefore, the mangrove forest in Ujungalang Village is part of the Segara Anakan conservation area. Protected areas play a crucial role in supporting ecotourism due to their function in conservation and the preservation of natural beauty that can serve as tourist attractions (Chaudhary et al. 2022). Implementing ecotourism activities in protected areas ensures that conservation involves not only the preservation of biodiversity but also the overall environment (Ahmadi et al. 2017). The ideal areas for ecotourism development are those located closest to protected areas (Chaudhary et al. 2022).

Conservation efforts through mangrove reforestation have also been carried out in Ujungalang Village. The concern of a local resident regarding mangrove degradation that occurred in 1998 marked the beginning of attention to this issue, as that year saw a significant conversion of mangrove land into shrimp ponds. This land conversion disrupted the breeding and spawning cycles of fish, leading to a decline in fish production (Gustami et al. 2023). The wastewater produced by the shrimp ponds also impacted the quality of the mangrove ecosystem. After the shrimp ponds went bankrupt and were abandoned by investors, the deforestation that occurred caused significant damage to the mangrove forest in Kampung Laut Sub-district, as well as a considerable reduction in land area.

In 2005, Patra Krida Wana Lestari Group was formed, focusing on mangrove conservation, under the guidance of Pertamina and DKP2SKSA (Ratini et al. 2016). This group focuses on developing nurseries to produce seedlings and the restoration of mangrove forest to recover its functions as a coastal protector. Since 2009, Patra Krida Wana Lestari Group and Pertamina have successfully planted over 1.5 million mangrove trees, covering an area of approximately 160 ha in the Segara Anakan conservation area (Environmental Agency of Cilacap District 2019). This mangrove conservation area was later named Kolak Sekancil, and it was established in 2016 with support from Pertamina.

### *Elevation*

Ujungalang Village is located at an elevation of 1-40 meters above sea level (masl), which falls into factor class I (Figure 3.C). The analysis results show that the village has the potential to be developed as a water tourism destination. Still, efforts to mitigate potential disasters, such as floods and tsunamis, must be considered.

### *Facilities and infrastructure*

Ujungalang Village has various facilities and infrastructure that support the community's needs (Table 4), although there are still some deficiencies that need to be addressed for further development. Based on this table, the availability of facilities and infrastructure is classified as "very good" because more than four types of facilities are available (Figure 3.D). Basic facilities such as clean water are available through wells and the Regional Drinking Water Company (PDAM) network, ensuring that the community's water needs are met. Religious facilities are also adequate, with a mosque, prayer room, and church. In terms of electricity, the village is served by a Hybrid Power Plant (HPT), which provides energy needs in the area. However, the communication and internet network in the village is only available through the support of two providers, which offer communication access to the residents.

Several other important facilities in Ujungalang Village have yet to be available or are still limited. Parking areas and public sanitation facilities are completely absent, which poses a barrier to the development of the tourism sector as well as to activities that require high mobility from the community. Trash bins and accommodations are also very limited, and the village does not have an adequate waste management system, so environmental cleanliness issues need to be addressed promptly. Facilities such as food stalls are still limited to small convenience stores, while souvenir shops are already available to support visiting tourists. Souvenirs are made by the local community, such as the Women's Farmer Group, which demonstrates community initiative, although further support is still needed.

In terms of tourism management, there is an information board that serves as a tourist guide, but a management office still needs to be made available. The local government primarily carries out tourism management, but it is not yet optimal and still lacks involvement from the local community. Additionally, a security post is also unavailable, which is a concern to ensure the comfort and safety of both residents and visitors.

### *Slope*

The slope is one of the main criteria for identifying potential ecotourism locations (Yasin and Woldemariam 2023). Landscape with flat topography or gentle slope is preferable for developing an ecotourism site, while steeper slopes reduce the potential for developing the site (Sahani 2019). Extremely steep slopes can increase the risk of erosion, excessive sedimentation, and potential hazards for tourists. Ujungalang Village has a relatively safe slope, with the majority of the area, approximately 5,290 ha or 79.50%, classified as having gentle slopes (5-15°) (Figure 3.E). Therefore, the slope in Ujungalang Village indicates good safety factors and potential for ecotourism development.

**Table 4.** Facilities and infrastructure in Ujungalang Village, Cilacap District, Central Java, Indonesia

| Facilities and infrastructure | Availability | Description |
|---|---|---|
| Clean water | Available | Water spring cave and *Perusahaan Daerah Air Minum* (PDAM) or regional drinking water company |
| Places of worship | Available | Mosque/prayer room, church |
| Electricity | Available | Hybrid Power Plant (HPT) |
| Communication network | Available | 2 providers |
| Parking area | Not available/ None | - |
| Public sanitation facilities | Not available/ None | - |
| Trash bins | Rarely | No waste collection |
| Food stalls or restaurants | Rarely | Convenience store |
| Accommodation | Rarely | Homestay |
| Souvenir shop | Available | Made by women's farming group (kelompok tani wanita) |
| Management office | Not available/ None | - |
| Information boards | Available | Tourist signage |
| Tourism management | Available | The local government manages it, but it is not yet optimal |
| Security post | Not available/ None | - |

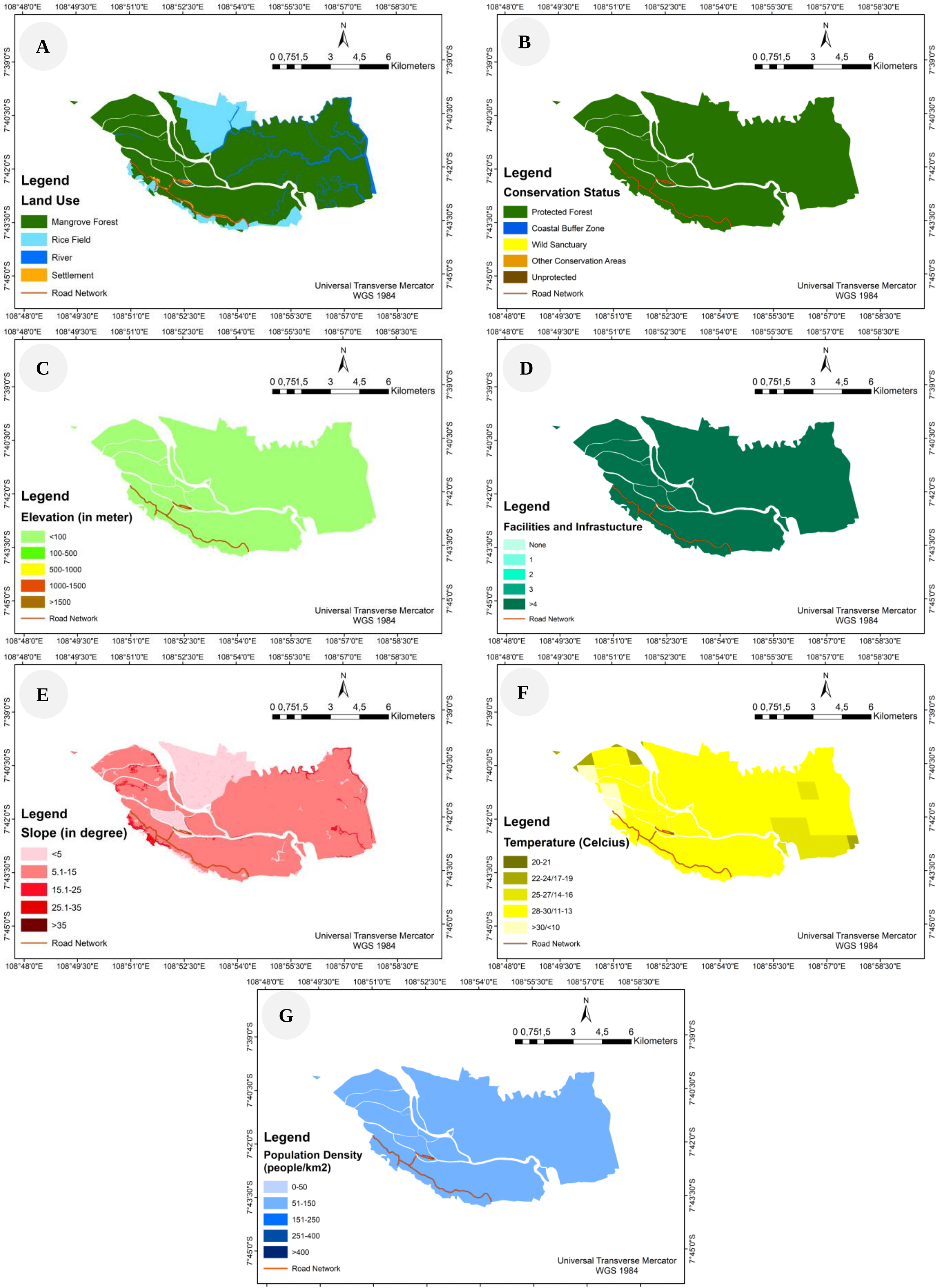

**Figure 3.** Spatial classification of each factor related to ecotourism in Ujungalang Village, Cilacap District, Central Java, Indonesia: A. Land use; B. Conservation status; C. Elevation; D. Facilities and infrastructure; E. Slope; F. Temperature; G. Population density

*Temperature*

The temperature in Ujungalang Village ranges from 22-30.6°C. This indicates that the village falls into factor classes II (110.25 ha), III (602.29 ha), IV (5,817.03 ha), and V (219.39 ha) for mangrove ecotourism development based on its temperature range. According to Figure 3.F, Ujungalang Village is dominated by factor class IV, with a temperature range of 28-30°C. This relatively high temperature is due to the village's location in the coastal area, which tends to have hotter or higher temperatures. In terms of temperature, Ujungalang Village is less suitable for tourism because of its hot climate. According to Yasin and Woldemariam (2023), lower temperature ranges are recommended for tourism, as most people tend to be more comfortable in cooler environments when vacationing.

*Population density*

Ujungalang Village is one of the villages with a relatively large population in the Kampung Laut Sub-district; data from the BPS-Statistics of Kampung Laut Sub-district (2024), the population of Ujungalang Village is 4,265 people, which occupy an area of 67.56 km². Therefore, the population density in this village is 65.87 people/km². According to the Analysis of Operational Areas of Natural Tourism Objects and Attractions book (*Analisis Daerah Operasi Objek dan Daya Tarik Wisata Alam/ADO-ODTWA)* by the Department of Forestry Republic of Indonesia (2003), this population density is categorized as low (Figure 3.G). However, the population and population density are expected to increase over time, which will result in a growing demand for land for housing. This increase in population density has the potential to cause negative impacts, as it could lead to a reduction in the area of mangrove forests (Ernawati 2016). In line with the findings of Ismail et al. (2019), the reduction in the mangrove area can decrease economic activities in the Segara Anakan area, which will ultimately have a negative impact on the local community's livelihood.

*Accessibility*

The journey to reach Ujungalang Village is approximately 8 km from the city center of Kampung Laut Sub-district, Klaces Village, or about 23 km from the city center of Cilacap District. This area can be accessed by both land and sea routes, using either a ship or a boat, with a travel time of 1.5 to 2 hours from the port in Cilacap, depending on the condition of the boat and the currents in Segara Anakan. Along the way, visitors can see the Cilacap port, the coastline of Nusakambangan, and the vast mangrove forests. According to data from the BPS-Statistics of Kampung Laut Sub-district (2024), public transportation is available in Ujungalang Village, though it only follows a fixed route.

Accessibility to Ujungalang Village can be categorized as limited, as the frequency of public boat transportation from Sleko Port is very restricted, with departures only available at 09:00 and 16:00 WIB. In addition, the cost of renting a boat is relatively high. For land access, the journey can be made via Tanjung Intan Ferry Port or Batre Port to Nusakambangan Island, with a travel time of about 1 hour. This land route can be traveled by motorcycle, although the road conditions are still unpaved (Sanjatmiko 2016).

**Ecotourism potential index**

The ecotourism potential index assesses an area's suitability for development as an ecotourism destination (Manurung et al. 2022). Table 5 presents the assessment results for each ecotourism potential factor in Ujungalang Village, while Table 7 and Figure 4 show the ecotourism potential classification.

The final values in Table 5 are used as the final weights for each factor. Then, the maps of each factor, which have been weighted, are overlaid, and the summed weights of each factor are used to obtain the ecotourism potential value (Table 6).

The analysis results show that the mangrove ecotourism potential in Ujungalang Village falls into three categories: non-potential (174.02 ha), low potential (1,292.52 ha), and high potential (5,290.43 ha). This indicates that most of Ujungalang Village has a very high potential to be developed as a mangrove ecotourism destination. Ujungalang Village is located in Kampung Laut Sub-district, which is known for its vast and fertile mangrove areas. The existence of mangroves is due to their location at the mouth of several rivers, such as the Citanduy, Cimeneng, Cibeureum, Sapu Regel, and Donan rivers. The meeting of fresh water from these rivers with the salty water from the Indian Ocean creates brackish water areas that support the growth of mangrove vegetation and the formation of mangrove forests (Ratnasari and Romansyah 2022).

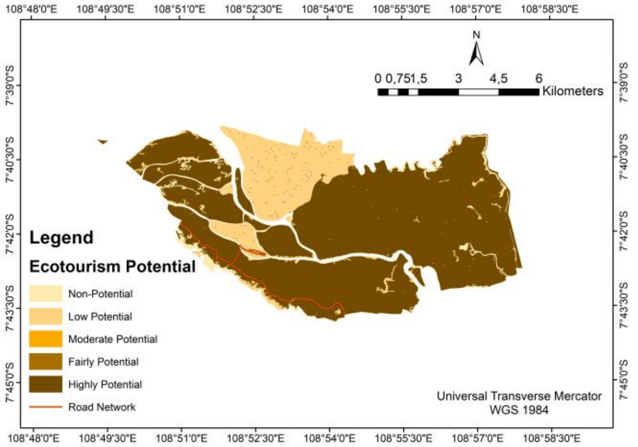

**Figure 4.** Ecotourism potential map in Ujungalang Village, Cilacap District, Central Java, Indonesia

**Table 5.** Assessment result of each ecotourism potential factor in Ujungalang Village, Cilacap District, Central Java, Indonesia

| Factors | Description | Amount of availability | n$^{*)}$ | rj$^{*)}$ | wj$^{*)}$ | Final value |
|---|---|---|---|---|---|---|
| Land use | Rice fields | 29 | 7 | 1 | 0.25 | 7.25 |
| | Mangrove forest | 7 | | | | 1.75 |
| | Settlement | 8 | | | | 2.00 |
| | Rivers | 13 | | | | 3.25 |
| Conservation status | Conservation forest | 1 | 7 | 2 | 0.21 | 0.21 |
| Elevation (masl) | <100 | 1 | 7 | 3 | 0.18 | 0.18 |
| Facilities and infrastructure | >4 types | 1 | 7 | 4 | 0.14 | 0.14 |
| Slope (°) | <5 | 421 | 7 | 5 | 0.11 | 45.11 |
| | 5.1-15 | 1,384 | | | | 148.29 |
| | 15.1-25 | 166 | | | | 17.79 |
| | 25.1-35 | 35 | | | | 3.75 |
| | >35 | 5 | | | | 0.54 |
| Temperature (°C) | 22-24/17-19 | 2 | 7 | 6 | 0.07 | 0.14 |
| | 25-27/16-16 | 2 | | | | 0.14 |
| | 28-30/11-13 | 1 | | | | 0.07 |
| | >30/<10 | 2 | | | | 0.14 |
| Population density (people/km$^2$) | 65.87 | 1 | 7 | 7 | 0.11 | 0.11 |

Note: $^{*)}$n = Number of factors being studied; rj = Position of the factor ranking; rp = Factor (p=1,2,3,.....n)

**Table 6.** Index value of ecotourism potential in Ujungalang Village, Cilacap District, Central Java, Indonesia

| Land use | Conservation status | Elevation | Facilities and infrastructure | Slope | Temperature | Population density | Index value |
|---|---|---|---|---|---|---|---|
| 1.75 | 0.21 | 0.18 | 0.14 | 0.54 | 0.14 | 0.11 | 3.03 |
| 2.00 | 0.21 | 0.18 | 0.14 | 0.54 | 0.07 | 0.11 | 3.21 |
| 2.00 | 0.21 | 0.18 | 0.14 | 0.54 | 0.14 | 0.11 | 3.28 |
| 1.75 | 0.21 | 0.18 | 0.14 | 3.75 | 0.14 | 0.11 | 6.23 |
| 2.00 | 0.21 | 0.18 | 0.14 | 3.75 | 0.07 | 0.11 | 6.41 |
| 3.25 | 0.21 | 0.18 | 0.14 | 3.75 | 0.07 | 0.11 | 7.66 |
| 3.25 | 0.21 | 0.18 | 0.14 | 3.75 | 0.14 | 0.11 | 7.73 |
| 7.25 | 0.21 | 0.18 | 0.14 | 0.54 | 0.07 | 0.11 | 8.46 |
| 7.25 | 0.21 | 0.18 | 0.14 | 3.75 | 0.07 | 0.11 | 11.66 |
| 1.75 | 0.21 | 0.18 | 0.14 | 17.79 | 0.07 | 0.11 | 20.16 |
| 1.75 | 0.21 | 0.18 | 0.14 | 17.79 | 0.14 | 0.11 | 20.23 |
| 2.0 | 0.21 | 0.18 | 0.14 | 17.79 | 0.07 | 0.11 | 20.41 |
| 2.0 | 0.21 | 0.18 | 0.14 | 17.79 | 0.14 | 0.11 | 20.48 |
| 3.25 | 0.21 | 0.18 | 0.14 | 17.79 | 0.07 | 0.11 | 21.66 |
| 3.25 | 0.21 | 0.18 | 0.14 | 17.79 | 0.14 | 0.11 | 21.73 |
| 7.25 | 0.21 | 0.18 | 0.14 | 17.79 | 0.07 | 0.11 | 25.66 |
| 7.25 | 0.21 | 0.18 | 0.14 | 17.79 | 0.14 | 0.11 | 25.73 |
| 1.75 | 0.21 | 0.18 | 0.14 | 45.11 | 0.07 | 0.11 | 47.56 |
| 1.75 | 0.21 | 0.18 | 0.14 | 45.11 | 0.14 | 0.11 | 47.63 |
| 2.00 | 0.21 | 0,18 | 0.14 | 45.11 | 0.07 | 0.11 | 47.81 |
| 2.00 | 0.21 | 0.18 | 0.14 | 45.11 | 0.14 | 0.11 | 47.88 |
| 3.25 | 0.21 | 0.18 | 0.14 | 45.11 | 0.07 | 0.11 | 49.06 |
| 3.25 | 0.21 | 0.18 | 0.14 | 45.11 | 0.14 | 0.11 | 49.13 |
| 7.25 | 0.21 | 0.18 | 0.14 | 45.11 | 0.07 | 0.11 | 53.06 |
| 7.25 | 0.21 | 0.18 | 0.14 | 45.11 | 0.14 | 0.11 | 53.13 |
| 1.75 | 0.21 | 0.18 | 0.14 | 148.29 | 0.07 | 0.11 | 150.66 |
| 1.75 | 0.21 | 0.18 | 0.14 | 148.29 | 0.14 | 0.11 | 150.73 |
| 2.00 | 0.21 | 0.18 | 0.14 | 148.29 | 0.07 | 0.11 | 150.91 |
| 2.00 | 0.21 | 0.18 | 0.14 | 148.29 | 0.14 | 0.11 | 150.98 |
| 3.25 | 0.21 | 0.18 | 0.14 | 148.29 | 0.07 | 0.11 | 152.16 |
| 3.25 | 0.21 | 0.18 | 0.14 | 148.29 | 0.14 | 0.11 | 152.23 |
| 7.25 | 0.21 | 0.18 | 0.14 | 148.29 | 0.07 | 0.11 | 156.16 |

**Table 7.** Ecotourism potential classification in Ujungalang Village, Cilacap District, Central Java, Indonesia

| Index value | Potential ecotourism class | Total area (Ha) |
|---|---|---|
| 3.03-33.66 | Non-potential | 174.02 |
| 33.67-64.30 | Low potential | 1,292.52 |
| 64.31-94.94 | Moderate potential | - |
| 94.95-125.59 | Fairly potential | - |
| 125.59-156.16 | Highly potential | 5,290.43 |

Ujungalang Village is a place of immense potential, with a diverse ecotourism index that ranges from high (125.59-156.16) to non-potential (3.03-33.66). Several factors, including land use, conservation status, elevation, facilities and infrastructure, slope, temperature, and population density, influence this variation and contribute to this potential. The primary factor influencing ecotourism potential is land use change, as it significantly impacts the determination of ecotourism potential, particularly in the case of the Mangrove Forest in Ujungalang Village. The conservation status of Ujungalang Village as a Conservation Forest enhances its protected status, thereby increasing its ecotourism potential. Facilities and infrastructure are also key to boosting ecotourism potential. The variety of facilities and infrastructure, with more than four types of infrastructure, have positively influenced its ecotourism development. However, the low population density in the Ujungalang Village limits community involvement in environmental preservation efforts, a challenge that can be overcome with the right strategies.

## Discussion

The mangrove ecotourism potential in Ujungalang Village is classified into three categories: non-potential, covering 174.02 ha; low potential, covering 1,292.52 ha; and high potential, covering 5,290.43 ha. Of the total area, approximately 78.29% in Ujungalang Village has a very high potential for the development of mangrove ecotourism. This potential is supported by the presence of thriving mangrove forests in the area. As an ecosystem, mangrove forests offer natural beauty and environmental value, including vegetation, marine life, wildlife, and the surrounding environment, all of which can support the development of ecotourism activities (Joandani et al. 2019).

Most of the mangrove area in Ujungalang Village is classified as having high ecotourism potential with extent of 5290.43 ha and an index range of 125.59-156.16. The condition of the mangrove forest in Ujungalang Village is considered good, making it highly potential to be developed as an ecotourism destination. Additionally, the availability of supporting facilities and infrastructure is also an important factor. The location already has facilities such as clean water, places of worship, information boards, and souvenir shops, which further enhance the potential of Ujungalang Village as a mangrove ecotourism destination. According to Joandani et al. (2019), the presence of local souvenirs not only attracts tourists but also contributes to the improvement of the local economy. Moreover, the area's status as a conservation zone further supports the development of ecotourism activities.

The locations with low ecotourism potential index typically have limited natural attractions or are not yet optimal for sustainable tourism development. Ecotourism is a concept that integrates environmental conservation, sustainable tourism development, and local community empowerment (Afif and Aisyianita 2023). Approximately 21.71% of the total area in Ujungalang Village is considered less suitable for ecotourism due to its geographical conditions, which require many adjustments to ensure the safety and comfort of tourists. These geographical conditions include agricultural areas, residential zones, and regions prone to disasters such as tsunamis and floods. According to Chaudhary et al. (2022), areas classified as unsuitable for ecotourism development include lowland regions, which are predominantly used for intensive agriculture and densely populated urban centers. The development of this area requires additional infrastructure, such as flood-resistant drainage systems, observation posts, information boards, and an early warning system. Furthermore, disaster mitigation training for the management team needs to be conducted before the ecotourism area is opened to the public. In the development plan, inclusivity in tourism development is a key consideration, ensuring that all visitors, including those with disabilities, feel valued and considered. This is in line with the ecotourism potential of Ujungalang Village, which focuses on conservation and water activities. According to Sica et al. (2021), responsible and inclusive tourism management not only supports sustainability but also opens up new opportunities in areas previously considered less suitable through innovative attractions that can attract tourists' interest.

Mangrove-based ecotourism is a form of ecotourism that can preserve the environment. Mangroves have great potential to be developed as ecotourism destinations due to their unique characteristics and the ability of these areas to be used as tourist locations while maintaining the originality of the forest and the preservation of the organisms that live within it (Pellokila and Sagala 2019). Utilizing the mangrove ecosystem for ecotourism is also a strategic step in improving the welfare of local communities. The distinctiveness of mangroves, such as their root structures and the diversity of fauna associated with this ecosystem, makes them highly potential for development as an alternative tourism destination (Hadinata et al. 2020). Sustainable mangrove ecotourism development can be carried out with an integrated approach involving the active participation of coastal communities around the mangrove areas. This approach not only raises awareness about the importance of mangrove conservation for the sustainability of local communities but also ensures that development strategies align with the needs and interests of local people. Intensive consultation and coordination with coastal communities are key to achieving sustainable and inclusive management.

Furthermore, Qomariah (2009) stated that community involvement in ecotourism management includes two main aspects: the ability to be a good host and openness to visitors. The principles of ecotourism are not only focused on economic benefits but also aim to raise tourists awareness and sensitivity about the local social and cultural aspects, which can be gained through interactions with local communities (Dian et al. 2024). Therefore, education and socialization about the importance of mangrove conservation for the sustainability of coastal communities livelihoods are essential.

Sustainable mangrove ecotourism development also requires awareness of conservation aspects, mangrove preservation, and the enhancement of supporting tourism infrastructure (Dian et al. 2024). One step that can be taken is the development of supporting facilities such as public sanitation facilities and proper waste management. In Ujungalang Village, the lack of such facilities poses an obstacle to realizing sustainable mangrove ecotourism. According to Joandani (2019), the availability of facilities and infrastructure plays a crucial role in the success of ecotourism, as it supports the comfort and convenience of visitors. Furthermore, improving these facilities can stimulate economic growth within the community by increasing the number of tourists (Handayani and Harlina 2021).

One important form of collaboration is with local government institutions, such as the Cilacap District Tourism Office (*Dinas Pariwisata Kabupaten Cilacap*). This collaboration can cover various aspects, including the development of tourism infrastructure, promotion of tourist destinations, environmental management, and the formulation of regulations that support sustainable tourism development (Amerta et al. 2024). Government institutions can also provide support in the form of funding and supervision to ensure that tourism activities comply with established standards. Collaboration with the private sector also plays a crucial role in supporting the development of mangrove ecotourism in Ujungalang Village. Local and national companies can contribute by investing in tourism infrastructure, developing tour packages, conducting promotional and marketing activities, and providing accommodation services and other supporting facilities (Sartika et al. 2024). Collaboration with the private sector can also bring innovation and valuable expertise to enhance the tourist experience and strengthen competitiveness.

Collaboration with academics and mangrove experts is also necessary for ecotourism management, both for managing mangrove areas, utilizing mangroves to create value-added products, and ensuring the sustainability of mangrove ecotourism by considering the carrying capacity of the area (Millenia et al. 2021). Assessment of environmental carrying capacity assessment is crucial in determining the area of mangroves that can be utilized for tourism, as well as the safe and comfortable duration of visits for tourists (Hadinata et al. 2020). This aspect is a key factor in ensuring the sustainability of mangrove ecotourism management.

In conclusion, around 78.29% of the area in Ujungalang Village has a great potential to be developed as mangrove ecotourism, mainly due to the lush mangrove forest in the area. Meanwhile, 21.71% of the area is considered unsuitable for ecotourism due to its geographic conditions, which require significant modifications to meet safety and comfort standards for tourists. These geographic conditions include agricultural areas, settlements, and areas that are prone to natural disasters such as tsunamis and floods. Therefore, it is necessary to build flood-resistant infrastructure development, as well as the provision of observation posts, informational boards, and an early warning system. The development of sustainable mangrove ecotourism can be more integrated by involving the local coastal community, which in turn will raise their awareness of the importance of mangrove conservation for the community's livelihood. Additionally, mangrove ecotourism development can be carried out through collaboration with local government institutions, the private sector, academics, and mangrove experts for the management and development of mangrove ecotourism. This research contributes to identifying ecotourism indicators and helps develop a methodology for analyzing ecotourism potential. Mapping potential ecotourism locations is a valuable tool for policymakers and decision-makers in planning sustainable tourism development that benefits local communities while protecting biodiversity. The findings of this study provide information that can guide regional investments by identifying suitable areas for ecotourism development. Ultimately, this can encourage job creation opportunities, improve the economic welfare of local communities, and preserve natural resources.

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## REFERENCES

Abidin Z, Nuryani FE, Saputra DK, Fattah M, Harahab N, Kusumawati A. 2023. Mangrove potential assessment for determining ecotourism attraction and strengthening destination branding and marketing: "Gunung Pithing Mangrove Conservation", Indonesia. Geoj Tourism Geosites 47 (2): 388-396. DOI: 10.30892/gtg.47204-1036.

Afif F, Aisyianita RA. 2023. Ecotourism in Jatimulyo Village, Kulonprogo, a common thread of bird conservation and tourism. Jurnal Pariwisata 10 (2): 107-116. DOI: 10.31294/par.v10i2.15662. [Indonesian]

Ahmadi M, Khodadadi M, Shahabi H. 2017. Planning for ecotourism in the protected area of Manesht and Ghelarang, Ilam Province, Iran. J Qual Assurance Hospitality Tourism 19 (2): 243-268. DOI: 10.1080/1528008X.2017.1394956.

Amerta IMS, Putra IBU, Artana IWS, Darmawan AAR. 2024. Identification of the “4A” potential in developing the tourist attraction of Jaga Satru Waterfall in East Duda Village, Karangasem District. Intl J Environ Sustain Soc Sci 5 (2): 441-455. DOI: 10.38142/ijesss.v5i2.1034.

BPS-Statistics Cilacap District. 2020. Kampung Laut Sub-district in Figures 2020. BPS-Statistics Cilacap District, Cilacap. [Indonesian]

BPS-Statistics Cilacap District. 2024. Kampung Laut Sub-district in Figures 2024. BPS-Statistics Cilacap District, Cilacap. [Indonesian]

Çetinkaya C, Kabak M, Erbaş M, Özceylan E. 2018. Evaluation of ecotourism sites: A GIS-based multi-criteria decision analysis. Kybernetes 47 (8): 1664-1686. DOI: 10.1108/K-10-2017-0392.

Chaudhary S, Kumar A, Pramanik M, Negi MS. 2022. Land evaluation and sustainable development of ecotourism in the Garhwal Himalayan region using geospatial technology and analytical hierarchy process. Environ Dev Sustain 24: 2225-2266. DOI: 10.1007/s10668-021-01528-4.

Department of Forestry Republic of Indonesia. 2003. Analysis of Operational Areas of Natural Tourism Objects and Attractions. Department of Forestry, Jakarta. [Indonesian]

Dian R, Purba BM, Rumapea NHY, Pinem DE. 2024. Sustainable mangrove ecotourism development strategy in Belawan Sicanang, Medan Belawan Sub-district, Medan City. Jurnal Darma Agung 32 (3): 246-258. DOI: 10.46930/ojsuda.v32i3.4437. [Indonesian]

Director of Natural Tourism and Environmental Services Utilization. 2003. Guidelines for Analysis of Area of Operation of Natural Tourism Objects and Attractions (ADO-ODTWA). Department of Forestry: Directorate General of Forest Protection and Nature Conservation, Bogor. [Indonesian]

Environmental Agency of Cilacap District. 2019. Mangrove Planting in Sagara Anakan Area in Commemoration of Environment Day. Environmental Agency of Cilacap District, Cilacap. [Indonesian]

Erlinda S, Mulyadi A, Zulkarnain, Suwondo. 2022. Policy strategy for sustainable management of mangrove ecotourism in Siak Regency, Riau Province, Indonesia. Intl J Sustain Dev Plan 17 (1): 173-183. DOI: 10.18280/ijsdp.170117.

Febrianto S, Rahman A, Jati OE, Wirasatriya A, Muskananfola MR, Latifah N. 2024. Machine learning for mangrove species distribution using Sentinel 2 satellite image in Segara Anakan, Cilacap Region, Indonesia. Reg Stud Mar Sci 81: 103984. DOI: 10.1016/j.rsma.2024.103984.

Fu J, Xia N, Zhang G. 2018. Research on landform classification of Beijing-Tianjin-Hebei Region based on SRTM remote sensing image data. ESMA: IOP Conf Ser: Earth Environ Sci 252: 052006. DOI: 10.1088/1755-1315/252/5/052006.

Gigović L, Pamučar D, Lukić D, Marković S. 2016. GIS-Fuzzy DEMATEL MCDA model for the evaluation of the sites for ecotourism development: A case study of "Dunavski kljuc" region, Serbia. Land Use Policy 58: 348-365. DOI: 10.1016/j.landusepol.2016.07.030.

Gustami E, Marganof M, Indra G. 2023. The threat of mangrove ecosystem deforestation and its impact on the community of Nagari Kataping, Batang Anai Sub-district, Padang Pariaman District. Sumatra Trop For Res J 7 (1): 167-176. [Indonesian]

Hadinata FW, Khayani DN, Tria H, Zurba N. 2020. Development of conservation-based mangrove ecotourism in coastal Kubu Raya District, West Kalimantan. J Aceh Aquat Sci 4 (1): 25-33. DOI: 10.35308/.v4i1.2720. [Indonesian]

Hafidz, Susetyo B, Erwin H. 2023. Analysis of potential leading tourist attractions in the Webgis-Based Pongkor Geopark Area. Infotech J 9 (1): 167-174. DOI: 10.31949/infotech.v9i1.5241. [Indonesian]

Handayani E, Harlina T. 2021. The effect of Osing Traditional Village tourism on increasing family income in Kemiren Banyuwangi community. Relasi: Jurnal Ekonomi 17 (2): 294-307. [Indonesian]

Hariyadi. 2018. The role of communities in mangrove ecosystem management for disaster mitigation: A study in Segara Anakan, Cilacap District. Kajian 23 (1): 43-61. [Indonesian]

Ismail, Sulistiono, Hariyadi S, Madduppa H. 2019. Relationship between Segara Anakan mangroves and declining mangrove crab (*Scylla* sp.) catch in Cilacap District, Central Java Province. Jurnal Ilmu Pertanian Indonesia 24 (3): 179-187. DOI: 10.18343/jipi.24.3.179. [Indonesian]

Joandani GK, Pribadi R, Suryono CA. 2019. Assessment of the potential for ecotourism development as a mangrove conservation effort in Pasar Banggi Village, Rembang District. J Mar Res 8 (1): 117-126. DOI: 10.14710/jmr.v8i1.24337. [Indonesian]

Liu C, Liu G, Yang Q, Luo T, He P, Franzese PP, Lombardi GV. 2021. Emergy-based evaluation of world coastal ecosystem services. Water Res 204: 117656. DOI: 10.1016/j.watres.2021.117656.

Manurung WA, Restu IW, Kartika GRA. 2022. Feasibility analysis of ecotourism potential of Pandan Beach, Pandan District, Central Tapanuli, North Sumatra. Bumi Lestari 22 (1): 1-11. DOI: 10.24843/blje.2022.v22.i01.p01. [Indonesian]

Millenia J, Sulivinio, S, Rahmanita M, Emier Osman I. 2021. Sedari Village mangrove tourism development strategy based on 4A analysis (attraction, accessibility, amenities, ancillary services). Jurnal Ilmiah Pariwisata 26 (3): 284-293. DOI: 10.30647/jip.v26i3.1584. [Indonesian]

Mu'tashim MR, Indahsari K. 2021. Ecotourism development in Indonesia. Senriabdi 1 (1): 295-308. [Indonesian]

Mulyadi A, Efriyeldi E, Marbun B. 2021. Mangrove ecotourism development strategy BBD, Riau. Dinamika Lingkungan Indonesia 8 (1): 48-56. DOI: 10.31258/dli.8.1.p.48-56. [Indonesian]

National Standardization Agency of Indonesia. 2004. Guidelines for Urban Residential Environmental Planning. National Standardization Agency of Indonesia, Jakarta. [Indonesian]

Pathmanandakumar V, Goh HC, Chenoli SN. 2023. Identifying potential zones for ecotourism development in Batticaloa District of Sri Lanka using the GIS-based AHP spatial analysis. Geoj Tourism Geosites 46 (1): 252-261. DOI: 10.30892/gtg.46128-1022.

Pellokila IR, Sagala N. 2019. Mangrove forest ecotourism development strategy in Oesapa Beach Area. Tourism: Jurnal Pariwisata 2 (1): 47-63. DOI: 10.32511/tourism.v2i1.319. [Indonesian]

Qomariah L. 2009. Development of Community-Based Ecotourism in Meru Betiri National Park (Case Study of Rajegwesi Block SPTN 1 Srogan). [Thesis]. Institute Pertanian Bogor, Bogor. [Indonesian]

Qomariyah RN, Kiat UEI. 2024. Vegetation density analysis for mangrove health level in Kampung Laut Sub-district, Cilacap District using NDVI (Normalized Difference Vegetation Index) method. Universitas Muhammadiyah Surakarta, Surakarta. [Indonesian]

Peraturan Daerah Kabupaten Cilacap Nomor 17 Tahun 2001 tentang Pengelolaan Hutan Mangrove di Kawasan Segara Anakan. [Indonesian]

Ratini, Sulistyantara B, Budiarti T. 2016. Mangrove conservation planning of Ujung Alang Village, Kampung Laut Sub-district, Cilacap District. Jurnal Silvikultur Tropika 7 (2): 108-114. [Indonesian]

Ratnasari D, Romansyah R. 2022. Analisis kerapatan lenti sel pada tumbuhan di ekosistem mangrove Kecamatan Kampung Laut. Bioed: Jurnal Pendidikan Biologi 10 (1): 40-44. DOI: 10.25157/jpb.v10i1.7169. [Indonesian]

Saeroji A. 2020. Penggunaan istilah 'wisata alam'dan 'ekowisata': sebuah telaah singkat. J Tourism Destination Attraction 8 (2): 147-154. DOI: 10.35814/tourism.v8i2.1664. [Indonesian]

Safuridar, Andiny P. 2020. The impact of mangrove forest ecotourism development on the social and economic aspects of the community in Kuala Langsa Village, Aceh. Jurnal Samudra Ekonomi dan Bisnis 11 (1): 43-52. DOI: 10.33059/jseb.v11i1.1882. [Indonesian]

Sahani N. 2019. Application of analytical hierarchy process and GIS for ecotourism potentiality mapping in Kulu District, Himachal Pradesh, India. Environ Dev Sustain 22: 6187-6211. DOI: 10.1007/s10668-019-00470-w.

Samanta S, Baitalik A. 2015. Potential site selection for ecotourism: A case study of four blocks in Bankura District using remote sensing and GIS technology, West Bengal. Intl J Adv Res 3 (4): 978-989.

Sanjatmiko P. 2016. Common Property di Tengah Perubahan Bentang Alam Kawasan Segara Anakan. Departemen Antropologi FISIP Universitas Indonesia, Depok. [Indonesian]

Sartika, Abbas B, Supriaddin N, Nur M, Tambunan R. 2024. Analisis promosi pariwisata dan budaya masyarakat lokal dalam meningkatkan kunjungan wisatawan di Kota Baubau Provinsi Sulawesi Tenggara. Syntax Idea 6 (7): 3164-3180. DOI: 10.46799/syntax-idea.v6i7.4087. [Indonesian]

Selamat BM. 2015. Parameter weighting and decision making. Jurusan Ilmu Kelautan dan Perikanan, Universitas Hasanuddin, Makasar. [Indonesian]

Sica E, Sisto R, Bianchi P, Cappelletti G. 2021. Inclusivity and responsible tourism: Designing a trademark for a National Park Area. Sustainability 13 (1): 13. DOI: 10.3390/su13010013.

Sisriany S, Sulistyantara B, Budiarti T. 2021. Multicriteria potential mapping for mangrove ecotourism in Batu Ampar, West Kalimantan. IOP Conf Ser: Earth Environ Sci 879: 012023. DOI: 10.1088/1755-1315/879/1/012023.

Waspodo S, Amir S, Hilyana S, Gigentika S, Wahyudi R. 2024. Analisis daya dukung ekosistem dan konservasi mangrove dalam meningkatkan potensi ekowisata di Desa Cendi Manik, Sekotong Tengah, Lombok Barat. J Mar Res 13 (3): 511-521. DOI: 10.14710/jmr.v13i3.41922. [Indonesian]

Widyastuti E. 2016. Crabs diversity at mangrove ecosystem in Lingga Waters and adjacent area, Riau Island. Zoo Indonesia 25 (1): 22-32. [Indonesian]

Yasin KH, Woldemariam GW. 2023. GIS-based ecotourism potentiality mapping in the East Hararghe Zone, Ethiopia. Heliyon 9 (8): e18567. DOI: 10.1016/j.heliyon.2023.e18567.

Yunanda KL, Chair IM. 2022. Strategi Pengembangan Fasilitas Daya Tarik Wisata Danau Nibung Kabupaten Mukomuko. Jurnal Pendidikan Tambusai 6 (2): 15846-15854. DOI: 10.31004/jptam.v6i2.4885. [Indonesian]

Yusnikusumah TR, Sulystiawati E. 2016. Evaluation of ecotourism management in the Tangkahan Ecotourism Area of Gunung Leuser National Park, North Sumatra. J Reg City Plann 27 (3): 173-189. DOI: 10.5614/jrcp.2016.27.3.1.

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# Diversity and morphometry of mangrove species and it's relation to environmental factors in Tagum City, Davao del Norte, Philippines

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**Abstract.** *Punong A, Pentason J, Amores A. 2025. Diversity and morphometry of mangrove species and it's relation to environmental factors in Tagum City, Davao del Norte, Philippines. Intl J Bonorowo Wetlands 15: 20-27.* Mangroves are a vital component of sustainable marine ecosystems, providing numerous ecosystem services that promote coastal protection, biodiversity conservation, carbon sequestration, and water quality improvement. This study focuses on the mangrove species found in Sitio Cabugan, Barangay Busaon, Tagum City, Davao del Norte, Philippines. Result shows that there were seven species in the studied area namely, *Avicennia marina, Nypa fruticans, Bruguiera gymnorhiza, Rhizophora mucronata, Rhizophora apiculata, Sonneratia alba,* and *Avicennia rumphiana*. *Avicennia marina* had the highest population, with a total of 567, a relative abundance of 70.79% and a cumulative distribution of 74.51, while *A. rumphiana* had the lowest number with only two individuals and a relative abundance of 0.25% with a cumulative distribution of 74.77. Moreover, it revealed poor species diversity and uneven distribution across the sampling stations. Environmental factors such as water temperature, salinity, and pH were within the normal range for growth and development, with station-specific variations influencing species distribution. Trunk size plays a significant role in structuring site-species interactions, indicating favorable environmental conditions to particular species. *Sonneratia alba*, *R. mucronata*, and *A. marina* showed a preference for stable environments, while *B. gymnorhiza* and *N. fruticans* demonstrate adaptability to contrasting conditions. This research underscores the need for conservation strategies and ongoing monitoring to ensure mangrove ecosystem stability and biodiversity preservation.

**Keywords:** Community structure, mangrove species vegetation, morphometry, sustainable marine ecosystem, Tagum City

**Abbreviations:** IUCN: International Union for Conservation of Nature, PCA: Principal Component Analysis

## INTRODUCTION

Mangrove forests are located in coastal areas of tropical and subtropical regions, and considered as one of the most biologically important ecosystems with diverse flora. They contribute to energy flow between land and sea and provide vital ecosystem services like coastal protection, biodiversity habitat, food production and recreation (Nehru and Balasubramanian 2018). Globally, there is a total of 54 true mangrove species and 60 species of mangrove associates. At the species level, mangrove plays a unique function in the ecosystem. For example, the study conducted by Govindhan (2024) reveal the critical role of mangroves like *Avicennia marina* (Forssk.) Vierh. in environmental stability and pollution mitigations as it has specific responses to pollutants, including trace metal. Previous studies in Pichavaram coastal areas highlighted *A. marina's* antioxidant capacity amidst heavy metal contamination and identified bioactive compounds with promising therapeutic potential.

Despite their importance, global population of mangroves has been experiencing a worrisome decline primarily because of human activities. These actions present a significant peril to the mangrove ecosystem and the rich variety of life within these areas. As a response, considerable efforts have been undertaken to restore large areas of mangrove forests, primarily for the purposes of obtaining timber and safeguarding coastal regions (Rovai et al. 2018). Many studies have revealed that adverse environmental conditions led to a decline in the population of mangrove species. Noor et al. (2015) conducted research in Pakistan that investigated the impact of various environmental factors on two mangrove species. The study revealed that factors such as temperature fluctuations, salt stress, and water and oxygen stress caused by siltation negatively affected the survival of mangroves in the Pakistan mangrove forest. The same study conducted by Ghanbarzad Dashti et al. (2021) on the impact of salinity and temperature stress on survival and responses of mangrove and it results negatively and correlatedly affect the mangrove productivity and diversity. The study of Chen et al. (2017) in China investigated extreme water temperature in mangrove response. The findings revealed significant differences in how mangroves respond to extreme temperatures across different geographic locations and species. During this event, it was observed that certain species, including *Bruguiera sexangula* (Lour.) Poir., *Sonneratia alba* Sm., and *Rhizophora mucronata* Lam., displayed a high susceptibility to cold temperatures. Conversely, species such as *Kandelia obovata* Sheue, H.Y.Liu & J.W.H.Yong, *Aegiceras corniculatum* (L.) Blanco, *A. marina*, and *Bruguiera gymnorhiza* (L.) Lam. remained unaffected by the temperature changes (Sippo et al. 2017). This lack of impact can be attributed to the fact that the temperature did not reach a low enough level to significantly affect these particular species. Additionally, in Sri Lanka most mangrove species showed reduced performance, measured by stand basal area and biomass, as soil salinity increased (Cooray et al. 2021).

The Philippines has been perpetually recorded as one of the top biodiversity hot spots of the world (Marchese 2015). This is due to its archipelagic nature and tropical climate within the country. According to Primavera et al. (2004) and Ono et al. (2016), it is estimated that mangroves in the Philippines span approximately 36,000 km, encompassing over 7,000 islands in total. According to Hogarth (2015), the Philippines is home to approximately 44 true mangrove species. Despite the favorable temperature conditions for mangroves in the country, there remains a threat to these species due to recorded water pollution in coastal areas, especially in proximity to chemical factories, as stated by Mialhe et al. (2016). It is crucial to identify the species present and determine the abundance, richness, and evenness of the population. However, the understanding of the relationship between mangrove physicochemical parameters has been limited.

Despite numerous ecological studies of mangrove ecosystems in the Philippines, a comprehensive assessment of the mangroves in Tagum City, particularly in Sitio Cabugan, Barangay Busaon, remains unexplored. This research fills that gap by offering a detailed taxonomic profile, analyzing the diversity and morphometry of local mangroves, and investigating their relationship with physicochemical parameters. On that note, this would be the first study in the area that aims to provide essential insights into the ecological dynamics of mangrove populations and how environmental parameters influence the diversity of mangrove species and lay the groundwork for sustainable conservation practices in the region. The declining mangrove population highlighted the urgency of this study, and the potential understanding of the species response to stimuli or the outside environment is in need, and what certain tolerable conditions these mangroves need to sustain biodiversity.

## MATERIALS AND METHODS

### Study area

This study was conducted in Sitio Cabugan, Barangay Busaon, Tagum City, Davao del Norte, Philippines, which has a total land area of 19,580 hectares (Figure 1). Land uses are dominated by agriculture, which produces various crops. Tagum City becomes a wonderful destination for tourist because of their mesmerizing water banks with the presence of mangroves. The Barangay Libuganon is geographically located at 7°10’ N and 125°20’ E. The intertidal zone is located on the coast which borders the terrestrial ecosystems (Nordlund et al. 2018; Wang et al. 2019). The intertidal zone is the narrowest because that zone is strongly influenced by tides.

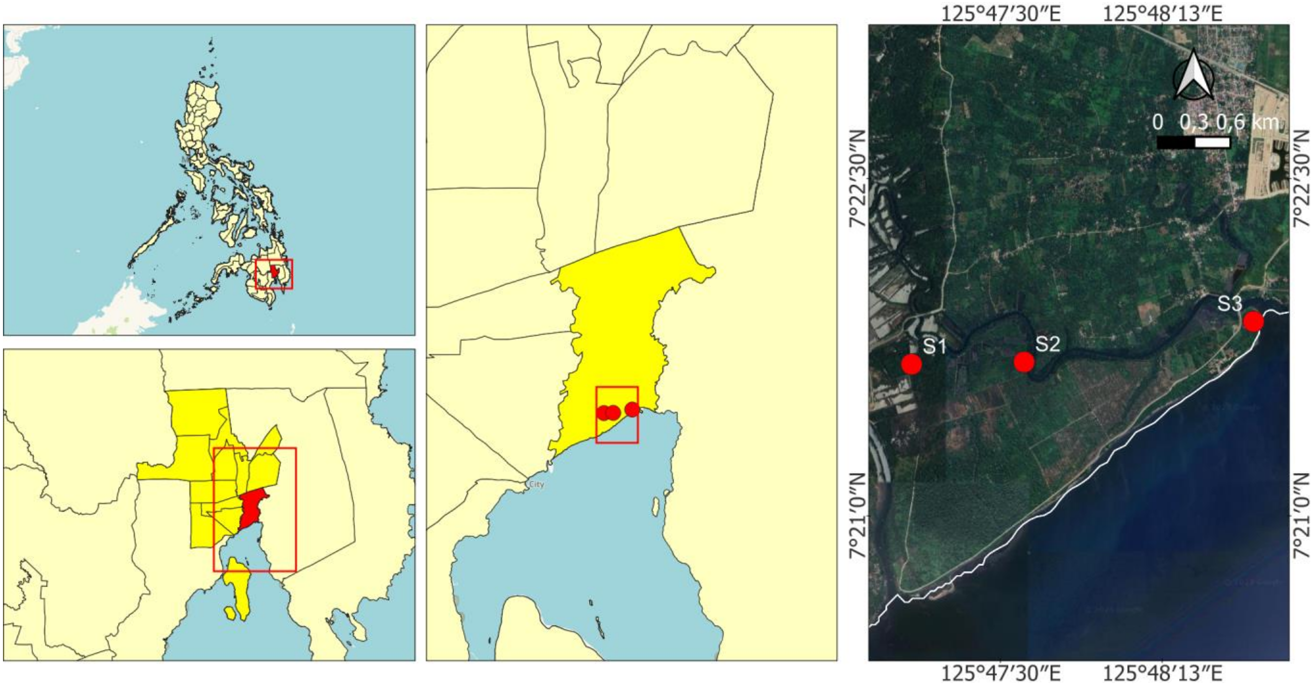


**Figure 1.** Map of study location in Sitio Cabugan, Barangay Busaon, Tagum City, Davao del Norte, Philippines

## Procedures

This study used a quantitative approach using the descriptive design since the researchers intend to identify and establish the taxonomic profiles of the mangrove species present in Tagum City. Using this method, the data gathered was recorded and analyzed quantitatively to obtain an accurate result. Primavera et al. (2004) suggest that quantitative research design provides an effective approach for reaching conclusive results and either validating or refuting a hypothesis. This design is favored due to its longstanding use and consistency across various scientific fields and disciplines. Since the mangrove species present in Tagum City was observed and analyzed according to their taxonomic profiles, indices and physicochemical parameters, descriptive research design is a valid method for research and a precursor to more quantitative studies regarding this subject.

The materials and instruments used in this study were the transect lines approximately 100 m long, a 10 × 10 m quadrant, refractometer, pH meter, digital thermometer, camera for documentation, Field Guide Manual to Philippine Mangroves by Primavera et al. (2016) for the identification of mangroves species present in the area. Figure 2 represents the layout of transect established at each station. The transect line was a 100-meter rope laid perpendicular to the shore. A 10 × 10 m steel quadrant was laid along the transect line. There were four quadrants laid in one transect line in three different stations. A 10 m x 10 m quadrant was used to account the mangroves present in the area. In the study area, salinity of the water was measured using a refractometer. A small sample of water was placed in the refractometer's glass prism. The pH level or acidity of the water was measured using a pH meter. Additionally, a digital thermometer was utilized to determine the water temperature. The camera was used for the documentation of the mangrove species and the field guide manual for the identification of mangrove species.

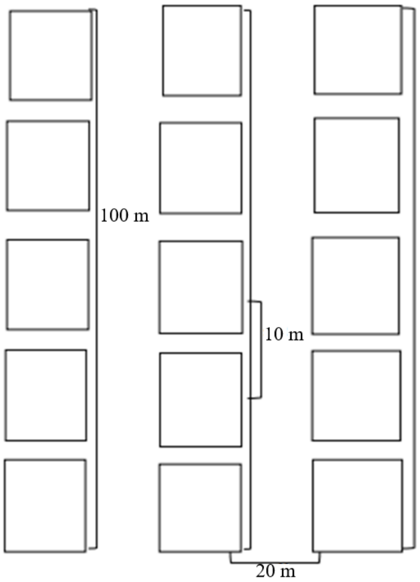


**Figure 2.** Layout of transect was established in each station for vegetation sampling

*Determination of the quadrant*

The researchers checked the parcel of mangroves in the area and established the quadrant with size of 10 × 10 m based on English et al. (1994) as cited in JC et al. (2016). The adaptation of the use of quadrants was instructed by the local scientist/personnel since this is commonly used for most of their flora assessments. The researchers are using a meter tape to measure the indicated quadrant in one station in the mangrove. The researchers divided the identified quadrant into four.

*Collection of data for mangrove morphometry*

In collecting data on mangrove species, the researchers employed a combination of opportunistic and direct observational methods to accurately document the diversity and characteristics of mangroves within the study site. Opportunistic observations allowed the researchers to adapt their data collection based on the availability and accessibility of specific mangrove species in the area, ensuring comprehensive documentation. Upon locating mangrove stands, the researchers systematically recorded the observable morphological characteristics of the mangroves within designated quadrants. These characteristics included attributes such as trunk diameter, leaf size and shape, bark texture, and color variations of leaves and stems. This detailed documentation provided essential data for accurate species identification and ecological analysis. To ensure coherence in data collection and maintain consistency across the study site, a quadrant division system was applied. Each station was subdivided into 1 × 1 m quadrants, where the presence of mangrove species was recorded. For each quadrant, the researchers listed the species present and counted the number of individual mangrove trees or seedlings. This structured approach ensured that data were systematically gathered and comparable across different stations within the study area.

Photographic documentation was also an essential aspect of data collection. The researchers captured high-quality images of the identified mangrove species, focusing on key distinguishing features such as leaves, stems, roots, and reproductive structures. These photographs served as a visual reference for subsequent species identification and verification. To measure the physical attributes of the mangroves, the researchers employed standard field measurement techniques. The trunk diameter of each mangrove tree was measured by wrapping a measuring tape around the tree at breast height (approximately 1.3 meters above the ground) to obtain the Diameter at Breast Height (DBH). The height of each mangrove tree was measured using a steel tape, extending from the base of the trunk at ground level to the highest point of the tree canopy. These measurements provided valuable data for understanding the growth patterns and biomass distribution of the mangrove species in the area.

Species identification and taxonomic classification were conducted up to the species level. The researchers referred to the Field Guide Manual to Philippine Mangroves authored by Primavera et al. (2004) as the primary reference for identifying and classifying the mangrove species. The identification process was further verified by consultation with a local scientist familiar with the flora of the region to ensure the accuracy and reliability of the findings. In compiling the taxonomic profiles of the mangrove species, the researchers adhered to established principles of taxonomy. The study drew upon the foundational concepts outlined in Ohl's (2014) book, Principles of Taxonomy and Classification: Current Procedures for Naming and Classifying Organisms. This resource provided guidance on the systematic classification of mangroves, facilitating a comprehensive understanding of their taxonomy. Additionally, related scientific studies were reviewed and incorporated as supporting references to strengthen the taxonomic framework.

*Data collection for biodiversity indices*

Species richness and evenness were determined by listing and counting the number of species found at the specific site of area. Counting plants within clearly defined sample units is a longstanding technique employed to assess vegetation density. To determine the number of plant species, the researchers individually counted mangroves of the same species using the stick method and recorded the data in a notebook. Documentation was facilitated through the use of a camera, which captured photographs of suitable specimens to record their morphological and diagnostic characteristics.

*Data collection of physicochemical parameters*

The physicochemical parameters were measured to obtain the average of each quadrant and to get the value per station and the average per station as the final value. Water temperature (°C) was obtained per station during the field sampling using the thermometer. The average temperature of coastal surface waters is about 17°C (62.6° Fahrenheit). The water salinity (ppt) was obtained every station using the refractometer. To measure the salinity of the water in the study area, a small amount of water was placed in the glass prism of the refractometer. Then the refractometer gave the measurement by looking through the eyepiece. The pH meter was utilized at each station to determine the pH level of the water. Pure water has a pH of 7, and if the pH is below 7, the water is considered acidic, while a pH above 7 indicates basic properties. In the case of groundwater systems, the typical pH range falls between 6 and 8.5.

### Data analysis

For taxonomic classification, the study documented all collected plant species and classified through taxonomic nomenclature following Brooks et al. (2019). The mangroves were identified and classified taxonomically up to the species level using the Field Guide Manual to Philippine Mangroves by Primavera et al. (2004). It was initially identified using the morphological structure and was validated and verified by a local scientist using photographs and the documented measurement.

This study used Shannon-Wiener's diversity index (H') and Simpson's index to assess and interpret mangrove species diversity and composition. Individuals were counted for each species. The Shannon diversity index (H) is a widely used metric to describe species diversity within a community. This index takes into account the abundance, richness, and evenness of species present. On the other hand, the Simpson index is considered a dominance index as it places greater emphasis on common or dominant species. In this context, the presence of a few rare species with limited representation does not significantly impact the overall diversity (Battaglia 2017). Moreover, result shown from the field experiment of five different sample in three stations using various instruments. Data was recorded from the result of pH meter for water pH, refractometer for water salinity and digital thermometer for water temperature. The analysis was anchored on the study of Imamsyah et al. (2020).

Descriptive statistics were used to summarize species composition, abundance, indices, and morphometric variables such as tree height and trunk diameter. To detect significant variations in morphometric traits among study sites, Pearson's linear correlation (r) with Bonferroni correction was performed for normally distributed data. More so, Principal Component Analysis (PCA) was employed to visualize patterns and relationships among environmental factors, species diversity, and morphometric variables. PCA, in particular, helped identify the most influential environmental variables affecting mangrove growth and structural characteristics, transforming complex data into interpretable principal components. Correlation and regression analyses further explored the relationships between morphometric traits and environmental factors, such as temperature, salinity, and water pH, providing predictive insights. These statistical approaches collectively enabled a comprehensive evaluation of the ecological dynamics within the mangrove ecosystem, supporting conservation and sustainable management efforts.

## RESULTS AND DISCUSSION

There were seven species of four family of mangroves found in the study area. Family Avicenniaceae consisted of *A. marina* with local name of *Miapi,* and *Avicennia rumphiana* locally known as *Piapi*; family Arecaceae included *Nypa fruticans* Wurmb with local name of *Nipa*; family Rhizophoraceae included *B. gymnorhiza* locally called *Putotan-Pula, R. mucronata* locally known as of *Bakhaw-babae* and *Rhizophora apiculata* Blume with local name of *Bakhaw-lalaki*; and family Lithraceae consisted of *S. alba* locally called *Pagatpat*. Malik et al. (2015) conducted a study on mangrove biodiversity and identification in South Sulawesi, Indonesia. The study identified ten mangrove species belonging to six families (Avicenniaceae, Rhizophoraceae, Euphorbiaceae, Combretaceae, Arecaceae, and Sonneratiaceae).

### Morphometric characteristics of mangrove species

The morphometric characteristics of mangrove species in the study area are presented in Table 1 with description detailed below.

**Table 1.** Morphometric characteristics of mangrove species in Tagum City, Davao del Norte, Philippines

| Mangrove species | Max. height (m) | Max. trunk size (cm) | Trunk color | Roots system | Leaves shape and texture | Leaves color | Flowers or buds colors |
|---|---|---|---|---|---|---|---|
| *Avicennia marina* (Forssk.) Vierh. | 28 | 50 | Grey | Broad lateral system with pneumatophores | Oblong | Light green | Light green |
| *Avicennia rumphiana* Hallier fil. | 30 | 40 | Grey | Broad lateral system with pneumatophores | Elliptic | Dark green | Light brown |
| *Nypa fruticans* Wurmb | 6 | 2 | Light green | Adventitious roots | Long blade | Green | Red-like and yellow |
| *Bruguiera gymnorhiza* (L.) Lam. | 5 | 2 | Brown | Short prop roots | Ovate | Green | Reddish brown |
| *Rhizophora apiculate* Bl. | 25 | 52 | Green | Aerial and stilt | Oblong | Green | Light yellow |
| *Rhizophora mucronata* Lam. | 28 | 45 | Dark green | Aerial and stilt | Oblong | Dark green | Cream and yellow |
| *Sonneratia alba* Sm. | 26 | 60 | Cream and brown | Presence of pneumatophores | Elliptic | Light green | Light green |

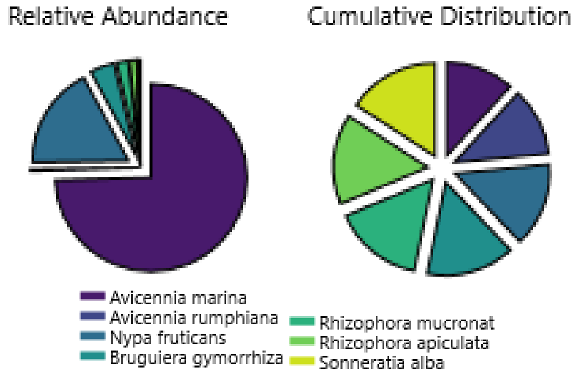


**Figure 3.** Species composition and relative abundance of mangrove species in Tagum City, Davao del Norte, Philippines

*Avicennia marina*, the species can reach a height of 28 meters. With a diameter of up to 50 cm, the trunk is a combination of grey in color. The roots have a wide lateral system that is surrounded by pneumatophores (breathing roots) and can grow up to 20 cm tall. Leaves are oblong with a round tip and can be up to 8 by 5 cm in size. The leaves are a light green color. The leaves are arranged in a diagonal pattern. Buds are light green in color and have an oval curve with a pointed apical beak.

*Avicennia rumphiana*, the species grows up to 30 m tall. It is grey in color and mostly grows straight. The trunk has a diameter of up to 40 cm. It also has a broad lateral root system with breathing roots or the pneumatophores. The leaves are elliptic in shape that measures 9 by 6 cm. The leaves are dark green in color with powdery hair underneath. The buds are color light brown, oval shape with a pointed apical beak.

*Nypa fruticans*, the species grows up to 6 m. It is a light green color. It has a cluster arrangement on a single stalk. The trunk has a diameter of up to 2 cm. The roots have additional adventitious roots arise from the lower part of the stem. The leaves are green in a long blade in shape and can grow up to 15 cm. It is arranged spirally. Flowers are in color red-like and yellow in a globular cluster.

*Bruguiera gymnorhiza*, the tree grows up to 3.5 to 5 m tall. The trunk is up to 2 cm in diameter. The trunk is glabrous with color brown and a reddish brown bark with stipules on young branches. The roots are a short prop root. The leaves are color green and ovate and lathery. Flowers's axillary, solitary, drooping and is reddish brown in colors.

*Rhizophora mucronata*, the tree grows up to 25 m tall. The trunk measures up to 52 cm. Evergreen tree with horizontally fissured dark brown bark. The roots are composed of aerial and stilt roots emerging from the lower branches of the roots. Leaves are green, leathery, slightly oblong and arranged oppositely. Flowers are light yellow; buds have 2 lobed leaflets near the base.

*Rhizophora apiculata*, the tree grown up to 28 m tall. Trunk diameter is up to 45 cm. Dark green smooth oblong leaves with reddish leaf stalks. Flowers are composed of cream-colored petals that are linear in a cross-shaped pattern. It has a read stipules and a yellow sepal. Buds are elliptical in shape and finely fissured.

*Sonneratia alba*, the tree grows up to 26 m. The trunk is diameter is up to 60 cm. It is having a smooth longitudinal fissure that is a combination of cream and brown in color. It has a pneumatophore or breathing roots that develop from the main roots. Leaves are light green, elliptic in shape with a broad leaf tip. Buds are oblong and green in color.

### Species composition and abundance

Figure 3 shows the species composition and abundance on the study area. *Avicennia marina* had the highest number of individuals with a total of 567 with a relative abundance of 70.79% and a cumulative distribution of 74.51, followed by *N. fruticans* with a total number of 173 with a relative abundance of 21.60% and a cumulative distribution of 92.25; *B. gymnorhiza* with a total number of 31 and a relative abundance of 2.87% and a cumulative distribution of 96.32; *R. mucronata* with a total of 15 and a relative abundance of 1.87% and a cumulative distribution of 98.29; *R. apiculata* with a total number of 9 and a relative abundance of 1.12% and a cumulative distribution of 99.48; *S. alba* with a total number of 4 and a relative abundance of 0.50% and a cumulative distribution of 100; and *A. rumphiana* was the lowest with with a total number of 2 is and a relative abundance of 0.25% and a cumulative distribution of 74.77.

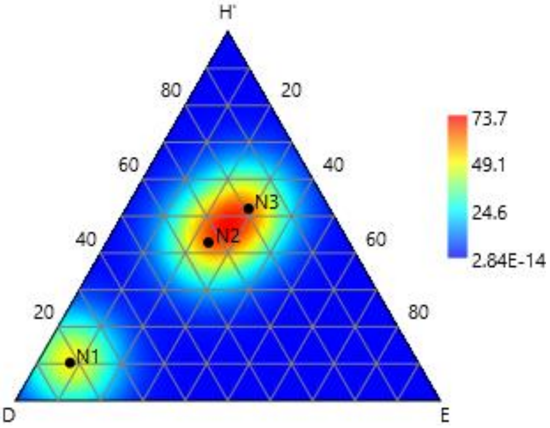


**Figure 4.** Ternary plot of biodiversity indices of mangrove species in Tagum City, Davao del Norte, Philippines. Note: H': Shannon-Wiener diversity index; D: Simpson index; E: Evenness index

The dominant species found in the study sites, *A. marina* and *N. fruticans*, is in line with the study by Baleta and Casalamitao Jr (2016) which revealed the most abundant species in Puerto Princesa, Palawan were *N. fruticans, B. sexangula, A. marina, A. lanata* and *Xylocarpus granatum* J.Koenig. The dominance of the two species is due to their suitability to live in muddy-sandy substrate (Malik et al. 2015). On the other hand, species with the lowest number of individuals was *A. rumphiana* and is listed as vulnerable, which aligns with the study of Pototan et al. (2021). The species *A. rumphiana* is facing a threat from the loss of its mangrove habitat across its distribution range. This loss is mainly attributed to activities such as extraction and coastal development. Additionally, the effects of global warming and climate change are expected to have further impacts on these areas (Rovai et al. 2018).

Figure 4 shows the ternary plot of biodiversity indices of mangrove species in terms of richness and evenness. At station 1, there were four species found with a total number of 146 individuals and a Shannon-Wiener diversity index of 0.12 (low), Simpson index of 0.96 (high) and Evenness index of 1.044 (less even). The low diversity index was because there were only four species found in the study area with only one individual for each of the three species while the majority belonged to one species, i.e., *A. marina*. At Station 2, there were six species with a total number of 345 individuals, the highest of the three stations. Station 2 had a Shannon-Wiener's diversity index of 0.75 (low), Simpson's index of 0.96 (moderate) and Evenness index of 0.43 (less even). At station 3, there were six species of mangroves with a total number of 270 individuals and a Shannon-Wiener diversity index of 1.17 (medium) and Simpson index of 0.43 (moderate) and Evenness index of 0.65 (more even).

The diversity of mangrove species is influenced by the substrate type and salt intrusion. The presence and distribution of mangrove species in the study area are influenced by the physical characteristics of the area and the type of substratum where these species thrive (Baleta and Casalamitao Jr 2016). Physiological adaptations, such as substrate type and salt extrusion, also play a role (Naskar and Palit 2015). Station 2, which exhibited the highest diversity index, was characterized by a sandy-muddy substrate that is rich in organic matter and supports the growth of various fauna and flora, contributing to the diversity and abundance of mangrove species in the area. Smoothly distributed substrate particles in certain areas contain higher levels of organic matter, creating a favorable environment for diverse and robust mangrove growth (Windusari et al. 2014). *Avicennia marina* is commonly found in areas with clay mud or muddy substrates (Ono et al. 2016). Research conducted by Islam et al. (2016) indicates that *A. marina* and *S. alba* thrive in regions with high salinity, particularly coastal areas.

### Physicochemical parameters

The physicochemical parameters in the sampled area indicated a normal range for mangrove ecosystem. The pH at station 1 was 8.16, while that at stations 2 and 3 was 8.11 and 8.13, respectively. The salinity ranged from 17.9 to 18.6 ppt in the three stations, indicating normal condition in tropical area, while water temperature ranged from 32 to 32.3°C. In the investigation conducted by Sippo et al. (2017) on the impact of alkalinity output from mangrove tidal creek in Australia, it was observed that water in close proximity to the mangroves exhibited a higher pH level (8.1) compared to seawater farther away from the coastal mangroves (pH 7.3). This variation in pH was attributed to the presence of fallen leaves, stems, and roots on the ground, which undergo decomposition and contribute to the acidity of the water. A similar study conducted by Islam et al. (2016) demonstrated an average salinity of 18.2 ppt. The salinity levels are influenced by factors such as evaporation, runoff, and rainfall (Ono et al. 2016). Increased sunlight penetration into the water column intensifies evaporation, leading to higher salinity levels, whereas higher rainfall contributes to lower salinity levels.

Water temperature is one factor that can affect the condition of mangrove vegetation. The difference in temperature is also affected by the high and low density of mangroves. The temperature will increase if the mangrove density is low because of the high intensity of sunlight received by waters, otherwise, the temperature will decrease if the density of mangroves is high. Biswas and Biswas (2020) stated that lack of light penetration is the main limiting factor in growth for mangroves. Water temperature reading in the study area were in the range for the survival of aquatic organisms (Osland et al. 2020).

### Relationship between mangrove species morphometry and environmental factors

Figure 5 shows the Principal Component Analysis (PCA) biplot that illustrates the relationships between environmental variables, mangrove species, and sampling sites, providing insights into the factors influencing community structure and morphometric traits. In this study, the PC1 eigenvalue has 15179 while PC2 has an eigenvalue of 817.91, meaning that PC1 represents 93.71% of the variance among variables while PC2 significantly represents 5.05% of the variance among variables with the cumulative correlation of more than 98.76%, implying that the cluster of samples is highly explained by the variables measured.

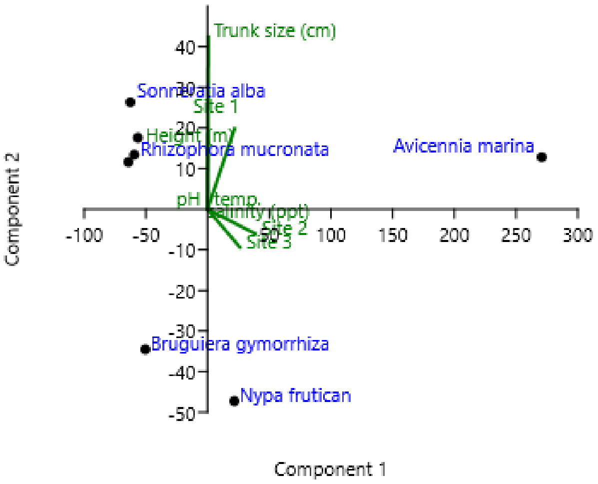
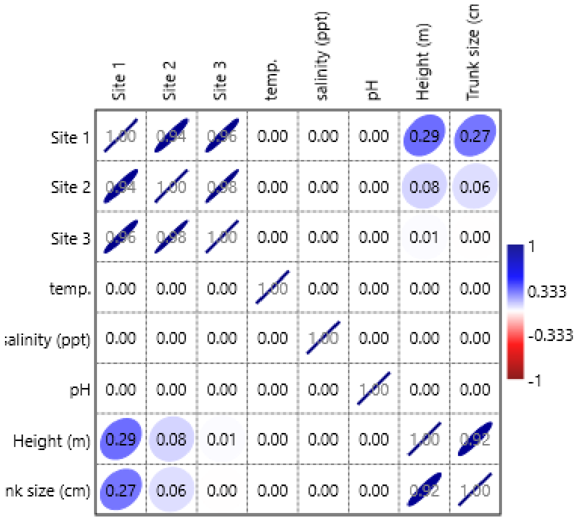


**Figure 5.** Principal component analysis showing the relationship between environmental variables and mangrove morphometry



| | Site 1 | Site 2 | Site 3 | temp. | salinity (ppt) | pH | Height (m) | Trunk size (cn |
|---|---|---|---|---|---|---|---|---|
| Site 1 | 1.00 | 0.94 | 0.96 | 0.00 | 0.00 | 0.00 | 0.29 | 0.27 |
| Site 2 | 0.94 | 1.00 | 0.98 | 0.00 | 0.00 | 0.00 | 0.08 | 0.06 |
| Site 3 | 0.96 | 0.98 | 1.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 |
| temp. | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| alinity (ppt) | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 |
| pH | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| Height (m) | 0.29 | 0.08 | 0.01 | 0.00 | 0.00 | 0.00 | 1.00 | 0.92 |
| nk size (cm) | 0.27 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.92 | 1.00 |

**Figure 6.** Linear Pearson r with Bonferroni correction showing the relationship between mangrove species morphometry and study sites

To specify, from the three stations of the study, station 1 had the close relative influence of the abundance of *S. alba*, considering the environmental parameters measured, where water temperature, salinity, and pH with 32.4°C, 18 ppt, and 8.11 ppt, respectively. The length and direction of these vectors indicate the strength and relationship of variable such as trunk size, temperature, pH, and salinity. Trunk size exhibits a strong association along component 2, suggesting its importance in structuring certain species and site interactions. This explains the study of Srivastava and Mehta (2023) that trunk size often has more extensive contribution to specific mangrove species growth and development.

The positions of mangrove species reveal their distinct ecological preferences. *Sonneratia alba*, *R. mucronata*, and *A. marina* are associated with environmental gradients positively, indicating their potential preference for larger trunk sizes and favorable environmental conditions. Conversely, *B. gymnorhiza* and *N. fruticans* are positioned negatively, suggesting their adaptability to contrasting environmental conditions. *R. apiculata* and *R. mucronata* thrive best in site 3 considering the bearable environmental conditions present. However, station 2 had the least accumulative pH compared to the other stations in this study. Alsumaiti and Shahid (2018) mentioned a possible contribution of pH to the abundance of mangrove and Kida and Fujitake (2020) emphasized that neutral pH 7 considered to be the suitable measurement for mangrove growth and development.

Figure 6 illustrates the relationship between mangrove species morphometry and environmental factors across three study sites, using Pearson's correlation coefficients with Bonferroni correction for statistical significance. Positive correlations are depicted in blue, with stronger relationships indicated by deeper shades and larger circles. Station 1 demonstrates positive correlations with mangrove height with the r value of 0.29 and trunk size with the r value of 0.27, suggesting that mangroves in this site tend to grow taller and develop thicker trunks compared to other locations. In contrast, stations 2 and 3 show negligible or no meaningful correlations with morphometric features, indicating less favorable conditions or less pronounced growth patterns.

Environmental parameters such as temperature, salinity, and pH exhibit no strong correlations with mangrove morphometry, implying that these factors may be stable or uniformly distributed across the study sites. Notably, there is a strong positive correlation between height and trunk size with the r value of 0.92, indicating that taller mangroves tend to have thicker trunks. Overall, station 1 appears to offer more favorable conditions for mangrove growth, while environmental factors remain consistent across the locations, showing limited influence on morphometric variations.

In conclusion, seven mangrove species were identified in the study: *A. marina*, *A. rumphiana*, *N. fruticans*, *B. gymnorhiza*, *R. mucronata*, *R. apiculata*, and *S. alba*, with *A. marina* being the most dominant and *A. rumphiana* the least abundant. Station 1 had four species with low diversity but high dominance by *A. marina*; Station 2 supported six species with similarly low diversity and moderate evenness; and Station 3 had the highest diversity and evenness among six species. Moreover, environmental conditions were stable across stations, with minor differences favorable to mangrove survival, though lower pH at station 2 may explain *A. marina*'s abundance. PCA analysis revealed that trunk size significantly influenced species distribution, with *S. alba*, *R. mucronata*, and *A. marina* preferring stable environments, while *B. gymnorhiza* and *N. fruticans* adapted to variable conditions. The findings highlight the need for targeted conservation and environmental monitoring to maintain mangrove ecosystem health. Future research should incorporate more ecological variables, and explore mangrove taxonomy at the cellular level to deepen understanding of species traits and vulnerabilities. Lastly, comprehensive educational materials and community engagement, combined with robust conservation efforts and ecological monitoring, are essential for ensuring the long-term resilience and sustainability of the mangrove ecosystem.

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## REFERENCES

Alsumaiti T, Shahid S. 2018. A comprehensive analysis of mangrove soil in Eastern Lagoon National Park of Abu Dhabi Emirate. Intl J Business Appl Soc Sci (IJBASS) 4 (5): 39-56.

Baleta FN, Casalamitao Jr RS. 2016. Species composition, diversity and abundance of mangroves along the estuarine area of Maligaya, Palanan, Isabela, Philippines. Intl J Fish Aquat Stud 4 (2): 303-307.

Battaglia D. 2017. Aeroponic gardens and their magic: Plants/persons/ethics in suspension. Hist Anthropol 28 (3): 263-292. DOI: 10.1080/02757206.2017.1289935.

Biswas PL, Biswas SR. 2020. Mangrove forests: Ecology, management, and threats. In: Leal Filho W, Azul AM, Brandli L, Lange Salvia A, Wall T (eds.). Life on Land. Encyclopedia of the UN Sustainable Development Goals. Springer, Cham. DOI: 10.1007/978-3-319-95981-8_26.

Brooks W, Manz A, Woolston C. 2019. Evidence Mapping: Investigating the Social and Ecological Impacts of Conservation in Mangrove Ecosystems. [Master's Project]. Duke University, Durham.

Chen L, Wang W, Li QQ, Zhang Y, Yang S, Osland MJ, Huang J, Peng C. 2017. Mangrove species' responses to winter air temperature extremes in China. Ecosphere 8 (6): e01865. DOI: 10.1002/ecs2.1865.

Cooray PLIGM, Jayawardana DT, Gunathilake BM, Pupulewatte PGH. 2021. Characteristics of tropical mangrove soils and relationships with forest structural attributes in the northern coast of Sri Lanka. Reg Stud Mar Sci 44: 101741. DOI: 10.1016/j.rsma.2021.101741.

English S, Wilkinson C, Baker V. 1994. Survey Manual for Tropical Marine Resource. Autralian Institute of Marin Science, Townsville.

Ghanbarzad Dashti S, Farzingohar M, Souri A. 2021. Temperature and salinity effects in sensitive area of Qeshm Island: Mangrove forests. Intl J Coast Offshore Environ Eng 6 (4): 13-18. DOI: 10.22034/ijcoe.2021.150792.

Govindhan P. 2024. Phytochemical analysis of the methanolic extract from the mangrove species *Avicennia marina* plant species inhabited in coastal water. Nat Prod Res 2024: 1-11. DOI: 10.1080/14786419.2024.2402474.

Hogarth PJ. 2015. The Biology of Mangroves And Seagrasses. Oxford Univ Press, Oxford. DOI: 10.1093/acprof:oso/9780198568704.001.0001.

Imamsyah A, Arthana IW, Astarini IA. 2020. The influence of physicochemical environment on the distribution and abundance of mangrove gastropods in Ngurah Rai Forest Park Bali, Indonesia. Biodiversitas 21 (7): 3178-3188. DOI: 10.13057/biodiv/d210740.

Islam S, Feroz SM, Ahmed ZU, Chowdhury AH, Khan RI, Al-Mamun A. 2016. Species richness and diversity of the floristic composition of the Sundarbans Mangrove Reserve Forest, Bangladesh in relation to spatial habitats and salinity. Malays For 79 (1&2): 7-38.

JC EHP, Dewiyanti I, Karina S. 2016. Importance value index of mangrove vegetation in the Kuala Idi Area, East Aceh District. Jurnal Ilmiah Mahasiswa Kelautan dan Perikanan Unsyiah 1 (1): 82-95. [Indonesian]

Kida M, Fujitake N. 2020. Organic carbon stabilization mechanisms in mangrove soils: A review. Forests 11 (9): 981. DOI: 10.3390/f11090981.

Malik A, Fensholt R, Mertz O. 2015. Mangrove exploitation effects on biodiversity and ecosystem services. Biodivers Conserv 24: 3543-3557. DOI: 10.1007/s10531-015-1015-4.

Marchese C. 2015. Biodiversity hotspots: A shortcut for a more complicated concept. Glob Ecol Conserv 3: 297-309. DOI: 10.1016/j.gecco.2014.12.008.

Mialhe F, Gunnell Y, Mering C, Gaillard JC, Coloma JG, Dabbadie L. 2016. The development of aquaculture on the northern coast of Manila Bay (Philippines): An analysis of long-term land-use changes and their causes. J Land Use Sci 11 (2): 236-256. DOI: 10.1080/1747423X.2015.1057245.

Naskar S, Palit PK. 2015. Anatomical and physiological adaptations of mangroves. Wetl Ecol Manag 23: 357-370. DOI: 10.1007/s11273-014-9385-z.

Nehru P, Balasubramanian P. 2018. Mangrove species diversity and composition in the successional habitats of Nicobar Islands, India: A post-tsunami and subsidence scenario. For Ecol Manag 427: 70-77. DOI: 10.1016/j.foreco.2018.05.063.

Noor T, Batool N, Mazhar R, Ilyas N. 2015. Effects of siltation, temperature and salinity on mangrove plants. Eur Acad Res 2 (11): 14172-14179.

Nordlund LM, Jackson EL, Nakaoka M, Samper-Villarreal J, Beca-Carretero P, Creed JC. 2018. Seagrass ecosystem services–What's next? Mar Pollut Bull 134: 145-151. DOI: 10.1016/j.marpolbul.2017.09.014.

Ohl M. 2014. Principles of Taxonomy and Classification: Current Procedures for Naming and Classifying Organisms. In: Henke W, Tattersall I (eds.). Handbook of Paleoanthropology. Springer, Berlin, Heidelberg. DOI: 10.1007/978-3-642-39979-4_4.

Ono J, Yong JW, Takayama K, Saleh MN, Wee AK, Asakawa T, Yllano OB, Salmo SG, Suleiman M, Tung NX, Soe KK. 2016. *Bruguiera hainesii*, a critically endangered mangrove species, is a hybrid between *B. cylindrica* and *B. gymnorhiza* (Rhizophoraceae). Conserv Genet 17: 1137-1144. DOI: 10.1007/s10592-016-0849-y.

Osland MJ, Day RH, Hall CT, Feher LC, Armitage AR, Cebrian J, Dunton KH, Hughes AR, Kaplan DA, Langston AK, Macy A, Weaver CA, Anderson GH, Cummins K, Feller IC, Snyder CM. 2020. Temperature thresholds for black mangrove (*Avicennia germinans*) freeze damage, mortality and recovery in North America: Refining tipping points for range expansion in a warming climate. J Ecol 108 (2): 654-665. DOI: 10.1111/1365-2745.13285.

Pototan BL, Capin NC, Delima AG, Novero AU. 2021. Assessment of mangrove species diversity in Banaybanay, Davao Oriental, Philippines. Biodiversitas 22 (1): 144-153. DOI: 10.13057/biodiv/d220120.

Primavera JH, Dela Cruz M, Montilijao C, Consunji H, Dela Paz M, Rollon RN, Maranan K, Samson MS, Blanco A. 2016. Preliminary assessment of post-Haiyan mangrove damage and short-term recovery in Eastern Samar, central Philippines. Mar Pollut Bull 109 (2): 744-750. DOI: 10.1016/j.marpolbul.2016.05.050.

Primavera JH, Sadaba RB, Lebata MJHL, Altamirano JP. 2004. Handbook of mangroves in the Philippines-Panay. SEAFDEC, Tigbauan, Iloilo, Philippines.

Rovai AS, Twilley RR, Castañeda-Moya E, Riul P, Cifuentes-Jara M, Manrow-Villalobos M, Pagliosa PR. 2018. Global controls on carbon storage in mangrove soils. Nat Clim Change 8: 534-538. DOI: 10.1038/s41558-018-0162-5.

Sippo JZ, Maher DT, Tait DR, Ruiz-Halpern S, Sanders CJ, Santos IR. 2017. Mangrove outwelling is a significant source of oceanic exchangeable organic carbon. Limnol Oceanogr Lett 2 (1): 1-8. DOI: 10.1002/lol2.10031.

Srivastava S, Mehta L. 2023. The social life of mangroves: Neoliberal development and mangrove conservation in the changing landscape of Kutch. Environ Plan E: Nat Space 6 (4): 2229-2248. DOI: 10.1177/25148486211045360.

Wang Q, Cao Z, Liu Q, Zhang J, Hu Y, Zhang J, Xu W, Kong Q, Yuan X, Chen Q. 2019. Enhancement of COD removal in constructed wetlands treating saline wastewater: intertidal wetland sediment as a novel inoculation. J Environ Manag 249: 109398. DOI: 10.1016/j.jenvman.2019.109398.

Windusari Y, Sarno S, Saleh E, Hanum L. 2014. Substrate characteristics and its impact on distribution of mangrove species: A case study in Sungai Barong Kecil in the Sembillang National Park at Banyuasin, South Sumatra. Berkala Penelitian Hayati 20 (1): 82-86. DOI 10.23869/108.

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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.

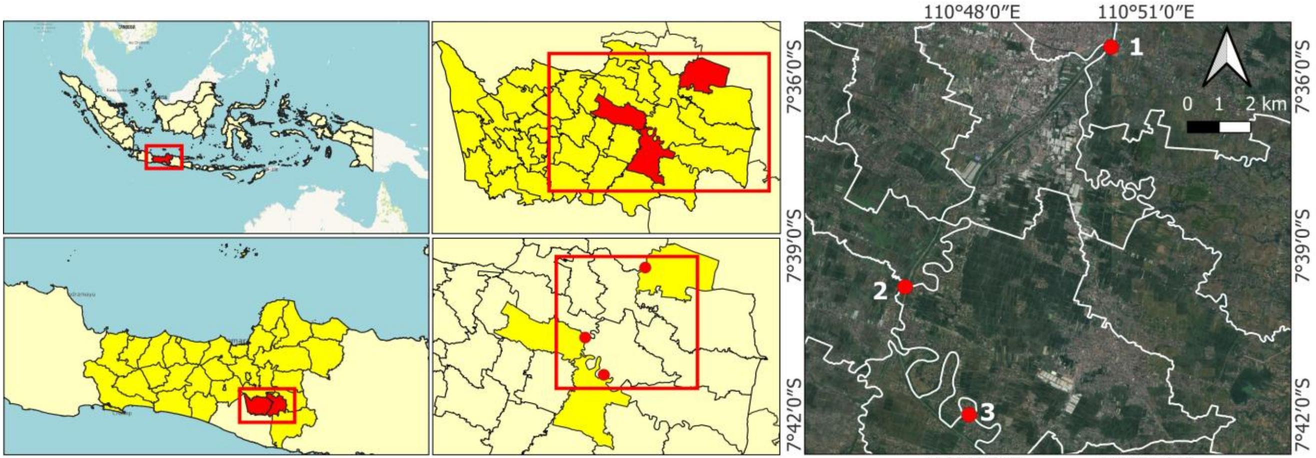

**Figure 1.** Map showing the location of the three oxbow stream sampling sites along the upper Bengawan Solo River, Central Java, Indonesia: Site I (Kadokan), Site II (Tangkisan), and Site III (Sidowarno)

### 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 |

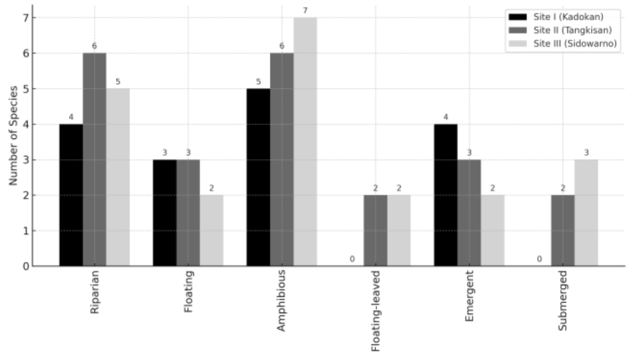

**Figure 2.** Life form composition across the three sites in the upper Bengawan Solo River oxbow streams, Central Java, Indonesia

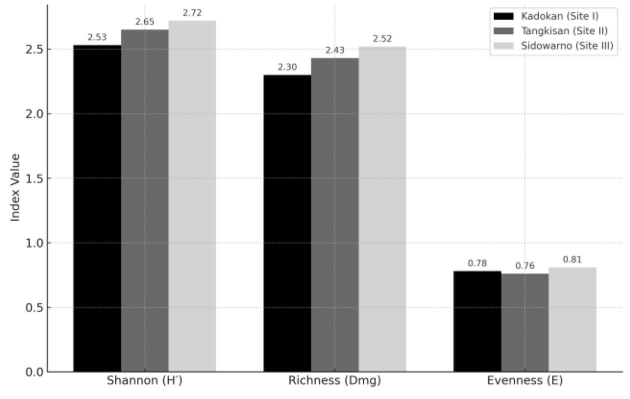

**Figure 3.** Comparison of diversity indices across oxbow stream sites. Bar chart comparing Shannon-Wiener Diversity Index (H′), Species Richness Index (Dmg), and Evenness Index (E) across the three oxbow stream sites in the upper Bengawan Solo River, Central Java, Indonesia

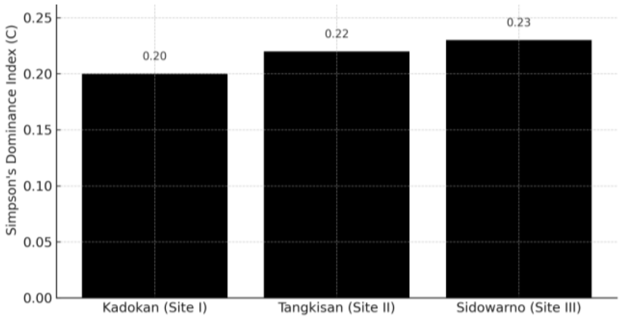

**Figure 4.** Simpson’s Dominance Index (C) across the three oxbow stream sites in the upper Bengawan Solo River, Central Java, Indonesia

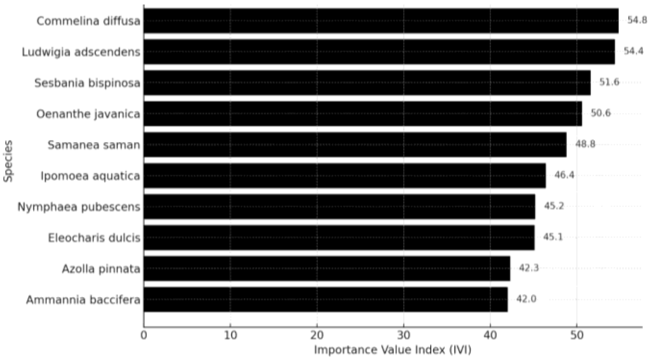

**Figure 5.** Bar chart of the top 10 dominant macrophyte species based on Importance Value Index (IVI) in the upper Bengawan Solo River oxbow streams, Central Java, Indonesia

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.

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# Aquatic insect diversity and spatial distribution in a tropical reservoir ecosystem of Kedungombo, Central Java, Indonesia

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[2]Department of Forest Management, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia
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**Abstract.** *Taqwim MHA, Mardiyanto MB, Wijayanti M, Wardha'adhlina WA, Putra YM, Mahajoeno E, Indrawan M, Yap CK, Setyawan AD. 2025. Aquatic insect diversity and spatial distribution in a tropical reservoir ecosystem of Kedungombo, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 40-48.* Aquatic insects are essential components of freshwater ecosystems, functioning as bioindicators and key players in trophic interactions. This study evaluated the species richness, spatial distribution, and ecological roles of aquatic and semi-aquatic insects across three distinct habitat types—forested margins, rice field edges, and open unvegetated shores—within the Kedungombo Reservoir, Central Java, Indonesia. Sampling was carried out during the dry season (September–October 2024) using purposive random sampling and hand net techniques. A total of 16 species representing 4 insect orders and 13 families were identified, with dominant taxa including *Culex tritaeniorhynchus*, *Diplonychus rusticus*, *Paederus fuscipes*, and *Chironomus striatipennis*. Species richness and diversity indices (Shannon–Wiener, Pielou's evenness, and Margalef's richness) varied significantly across habitats, with the rice field edge (Station 2) exhibiting the highest diversity. Predatory insects were the most prevalent functional group, followed by detritivores and generalist omnivores. Several species showed station-specific occurrence, suggesting narrow habitat preferences and potential as ecological indicators. The open shoreline habitat had the lowest richness and was dominated by disturbance-tolerant taxa, while shaded and vegetated zones supported more diverse and specialized assemblages. These findings underscore the ecological significance of microhabitat heterogeneity in maintaining aquatic insect communities within artificial lentic systems. Conservation and management strategies for tropical reservoirs should prioritize habitat complexity and buffer zones to sustain insect-mediated ecosystem functions under increasing anthropogenic pressures.

**Keywords:** Aquatic insects, biodiversity, functional groups, habitat heterogeneity, Kedungombo, tropical reservoir

## INTRODUCTION

Aquatic insects represent a significant component of freshwater biodiversity and are widely recognized for their ecological roles in trophic dynamics, organic matter decomposition, and water quality monitoring (Williams and Williams 2017; Parr et al. 2019). They occupy diverse niches across aquatic habitats, from temporary puddles to large reservoirs, and display varying degrees of tolerance to environmental changes (Choudhury and Gupta 2017; Zhao et al. 2021). Because of their sensitivity to habitat alteration, aquatic insects are often used as bioindicators to assess ecological integrity in both lotic and lentic systems (Mahmoud et al. 2022). Understanding the structure and distribution of aquatic insect communities is crucial for tracking ecosystem health and detecting anthropogenic pressures in tropical freshwater environments.

Reservoirs in Southeast Asia, particularly those embedded in rural or semi-urban landscapes, serve as multifunctional ecosystems that support fisheries, agriculture, tourism, and water supply. In Indonesia, large man-made reservoirs such as Kedungombo represent vital resources for regional development, yet are often subjected to multiple stressors including land-use changes, eutrophication, and pollutant inputs (Makmur et al. 2017). While reservoir-based aquatic ecology has gained increasing attention, the insect communities in such systems remain underrepresented in ecological assessments. Aquatic insects in reservoirs may differ markedly in diversity and distribution compared to rivers or ponds due to spatial heterogeneity in hydrology, vegetation, and human activity (Zheng et al. 2021).

Located in Central Java, Indonesia, Kedungombo Reservoir spans approximately 6,576 hectares and intersects three administrative regions—Boyolali, Sragen, and Grobogan (Ariyani et al. 2020). It comprises varied microhabitats including forested edges, agricultural runoff zones, and unvegetated margins that influence aquatic insect assemblages through nutrient input, substrate complexity, and vegetation cover (Popoola and Otalekor 2011). Such environmental variability presents an opportunity to examine how aquatic insect diversity responds to contrasting habitat conditions within a single lentic system. Yet, baseline data on the entomofauna of Kedungombo is scarce, limiting its use for long-term ecological monitoring or reservoir management planning.

Recent studies from tropical Asia have shown that orders such as Odonata, Hemiptera, and Coleoptera are dominant in freshwater ecosystems and display habitat-specific patterns (Letsch et al. 2016). Odonates, in particular, are known for their dual life cycle and sensitivity to water quality and vegetation structure, making them effective indicators of semi-natural aquatic habitats (Ihamdi et al. 2021). Hemipterans such as *Limnogonus fossarum* and coreids are common in slow-moving or still waters, while coleopterans like *Paederus* spp. are adapted to humid microhabitats and often function as predators (Li et al. 2017). Incorporating multiple insect orders enhances the representativeness of aquatic surveys and allows for more nuanced ecological interpretation.

Despite the ecological and bioindicator value of aquatic insects, their assemblages in Indonesian reservoirs remain poorly documented. Most entomological studies have concentrated on rivers (Atmowidi et al. 2022) or rice field agroecosystems (Wakhid et al. 2020), leaving large impoundments relatively unexplored. This gap hampers the development of regionally tailored biodiversity indices and undermines the integration of insect-based monitoring into freshwater management. Assessing aquatic insect diversity in reservoirs is particularly relevant under the current pressures of climate change, hydrological alteration, and agricultural intensification in Java.

This study aims to assess the species richness, taxonomic composition, and spatial distribution of aquatic insects in Kedungombo Reservoir by comparing three contrasting habitat types: forested margins, rice-field interfaces, and unvegetated open water zones. Using standard sampling techniques and diversity indices, this study provides a foundational dataset on aquatic entomofauna in one of Central Java's largest reservoirs. The findings are expected to inform conservation planning, ecological monitoring, and future studies on freshwater biodiversity in tropical lentic environments. Additionally, the study contributes to the broader goal of enhancing insect-based indicators for water quality assessment in Indonesia's rapidly changing inland aquatic ecosystems.

## MATERIALS AND METHODS

### Study area

The study was conducted at Kedungombo Reservoir, a large artificial reservoir located in Central Java, Indonesia (Figure 1). It spans the administrative regions of Boyolali, Sragen, and Grobogan Districts. The reservoir covers a total area of approximately 6,576 hectares, consisting of 2,830 hectares of open water and the remainder being terrestrial zones. Kedungombo plays a multifunctional role, including water storage for irrigation, flood control, aquaculture, and domestic use. It also serves as an important artificial freshwater ecosystem supporting a wide range of aquatic biodiversity.

Three distinct habitat types were selected for this study to represent different environmental conditions and land-use interfaces (Table 1). Station 1 was located along a forested margin with dense riparian vegetation and partial canopy cover, providing a shaded and relatively stable microhabitat. Station 2 bordered active rice fields and was characterized by semi-aquatic vegetation and seasonal agricultural runoff. Station 3 was an open, unvegetated shoreline exposed to direct sunlight and fluctuating water levels, typical of disturbed littoral zones.

The ecological differences among these stations allowed the researchers to evaluate the influence of habitat heterogeneity on the composition and distribution of aquatic and semi-aquatic insect communities. Site selection was also influenced by accessibility and safety during the sampling period.

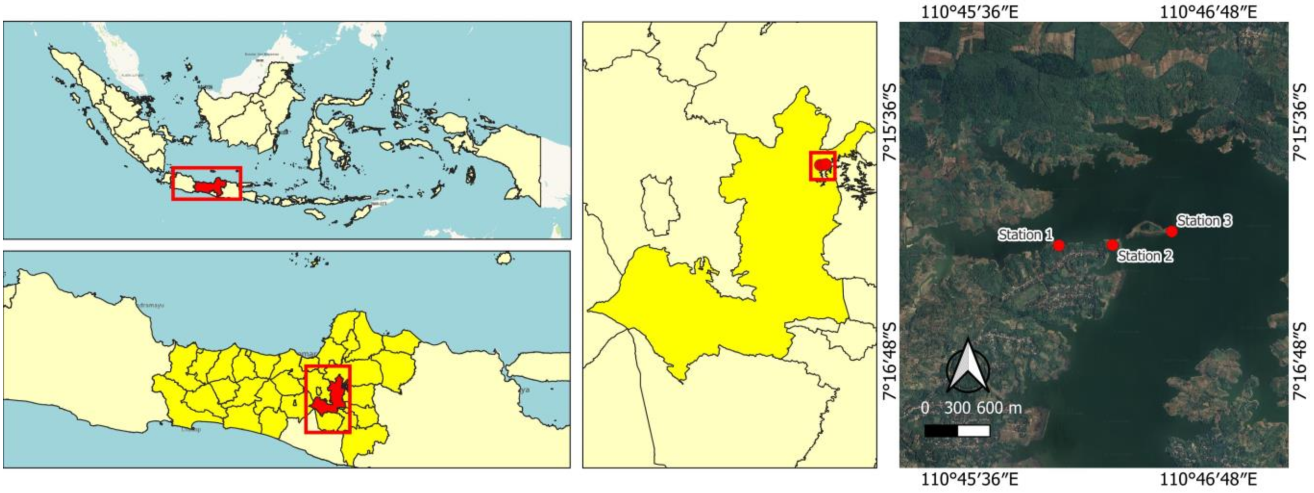

**Figure 1.** Map of the study area at Kedungombo Reservoir, Boyolali District, Central Java, Indonesia

## Sampling design

A purposive random sampling approach was employed to capture aquatic insect diversity across distinct habitat types within the reservoir. The method allowed for targeted site selection based on ecological characteristics while maintaining unbiased insect collection within each station. Sampling was conducted three times during the dry season (September to October 2024), with an interval of approximately 10-15 days between each sampling event, to account for short-term variability and improve the representativeness of insect community data across habitat types.

At each station, three plots of approximately 50 m² were established as active observation areas, each spaced 50-100 meters apart to capture spatial heterogeneity within the habitat. Insects were collected using hand nets (sweep nets) and, where appropriate, with the aid of small aspirator bottles for smaller or surface-dwelling individuals. Each plot was observed for approximately 30 minutes during two time windows—morning (07:00-10:00) and late afternoon (15:30-17:30)—to account for diel variation in insect presence and behavior (Table 2).

All collected specimens were handled carefully to preserve morphological features crucial for taxonomic identification. Each insect was placed in a labeled plastic vial and photographed on-site using a high-resolution digital camera. Specimens were temporarily preserved in 70% ethanol for subsequent laboratory identification and documentation.

## Specimen collection and identification

All insect specimens observed or captured during field sampling were documented systematically for taxonomic identification. Collection included both aquatic and semi-aquatic forms that interacted directly with the reservoir environment, such as those found on the water surface, among vegetation, or along the margins. Photographic documentation was performed in situ using a digital camera equipped with macro settings to capture detailed images of critical morphological traits such as antennae, wings, and body segmentation.

Specimens that could not be identified in the field were preserved in labeled vials containing 70% ethanol and brought to the laboratory for further examination. Taxonomic identification was conducted using standard morphological keys and field guides, including Merritt et al. (1996), Borror et al. (2005), and Abowei and Ukoroije (2012). For species-level identification, only individuals with complete and intact diagnostic features were considered. Some taxa were identified only to the genus level due to incomplete morphological characteristics or the lack of comprehensive regional keys, particularly for small or cryptic taxa.

Scientific names were cross-checked for validity and accuracy using international taxonomic databases, namely the Global Biodiversity Information Facility (GBIF, https://www.gbif.org), Catalogue of Life (https://www.catalogueoflife.org), and Integrated Taxonomic Information System (ITIS, https://www.itis.gov). These databases ensured consistency in nomenclature and distributional data.

## Data analysis

Data collected from each station were analyzed to assess aquatic insect community structure based on species richness, diversity, and evenness (Table 3). Three ecological indices were employed: the Shannon–Wiener diversity index (H′), Pielou's evenness index (J′), and Margalef's species richness index (Dmg). These indices were selected for their relevance in measuring species composition and ecological balance in freshwater systems.

**Table 1.** Geographic coordinates and habitat descriptions of each sampling station

| Station | Coordinates | Habitat type | Habitat description |
|---|---|---|---|
| Station 1 | 7°16'13.10" S, 110°46'2.95" E | Forested margin | Vegetated shoreline with dense riparian vegetation and partial canopy cover, providing shade and stable microclimate. |
| Station 2 | 7°16'12.93" S, 110°46'19.09" E | Rice field edge | Interface between reservoir and rice paddies, characterized by semi-aquatic vegetation and influenced by agricultural runoff. |
| Station 3 | 7°16'8.89" S, 110°46'36.98" E | Open unvegetated zone | Bare shoreline with minimal vegetation, exposed to direct sunlight and fluctuating water levels. |

**Table 2.** Sampling time and collection methods at each observation station

| Station | Observation time (hr) | Methods used | Notes |
|---|---|---|---|
| 1 | 3 (morning and afternoon) | Hand net sweep, direct pick | Shaded, rich vegetation cover |
| 2 | 3 (morning and afternoon) | Sweep net, aspirator | Edge of rice fields, dense herbaceous cover |
| 3 | 3 (morning and afternoon) | Hand net, surface collection | Open, unshaded, minimal vegetation |

**Table 3.** Formulas and ecological interpretation of biodiversity indices used

| Index | Formula | Ecological meaning |
|---|---|---|
| Shannon–Wiener (H′) | $H' = -\sum(pi \times \ln pi)$ | Species diversity considering abundance and dominance |
| Pielou's Evenness (J′) | $J' = H' / \ln S$ | Uniformity of individual distribution across species |
| Margalef Richness (Dmg) | $Dmg = (S - 1)/\ln N$ | Species richness relative to sample size |

The Shannon–Wiener index (H′) was calculated using the formula $H' = -\sum(p_i \times \ln p_i)$, where pi represents the proportion of individuals belonging to the i-th species. Higher H′ values indicate greater diversity and lower dominance by a single species. Pielou's evenness index (J′) was computed as $J' = H' / \ln S$, where S is the total number of species, reflecting how evenly individuals are distributed across taxa. Margalef's richness index (Dmg) was calculated using $Dmg = (S - 1)/\ln N$, where S is the number of species and N is the total number of individuals observed.

Values from the three indices were compared across stations to evaluate the ecological variability of each habitat. Graphical visualizations and summary tables were generated to highlight trends in diversity and to support the interpretation of spatial patterns.

## RESULTS AND DISCUSSION

### Species richness and composition

A total of 16 species of aquatic and semi-aquatic insects were recorded from three stations within the Kedungombo Reservoir ecosystem (Table 4). These species belong to four insect orders and 13 families, reflecting a moderate level of taxonomic diversity (Figure 2). The highest species richness was observed at Station 2 (rice field edge), followed by Station 1 (forested margin), while Station 3 (open zone) had the lowest richness (Figure 3). This pattern suggests that habitat complexity and vegetation cover may influence the availability of microhabitats for different taxa (Figure 4).

The species overlap among the three stations is illustrated in the Venn diagram (Figure 4). Five species were shared among at least two stations, while only two species—*Culex tritaeniorhynchus* and *Paederus fuscipes*—occurred in all three stations, indicating their broad ecological tolerance. Station 2 shared more species with Station 1 (four species) than with Station 3 (three species), suggesting greater ecological similarity between the forested margin and rice field edge compared to the open zone. Several taxa, such as *Diplonychus rusticus*, *Hydrophilus* sp., and *Notonecta glauca*, were exclusive to Station 2, reinforcing the distinctiveness of this habitat. These patterns of overlap highlight the role of habitat complexity and vegetative cover in structuring aquatic insect communities.

Across all stations, the most frequently encountered species included *C. tritaeniorhynchus*, *D. rusticus*, *P. fuscipes*, and *Chironomus striatipennis*. These taxa were widely distributed and tolerant of a variety of environmental conditions. Conversely, certain species such as *Hydrophilus* sp., *Laccotrephes robustus*, *N. glauca*, *Coccinella transversalis*, and *Ranatra linearis* were found exclusively in a single station, indicating habitat specificity or restricted range.

In terms of functional roles, the recorded insects included predators (e.g., *D. rusticus*, *L. robustus*), detritivores (e.g., *C. striatipennis*), herbivores, and generalist scavengers. This functional diversity suggests the presence of multiple trophic interactions within the reservoir ecosystem. Additionally, several taxa, such as *P. fuscipes* and *Gerris* sp., are known bioindicators of environmental change and may serve as sentinel species for monitoring reservoir health.

### Distribution patterns across habitats

The distribution of aquatic and semi-aquatic insect species varied markedly among the three habitat types studied. Station 1, situated in a forested margin, supported 10 species and showed moderate levels of diversity. The presence of shade-tolerant taxa such as *Sceliphron caementarium* and *Rhynocoris* sp. suggests that certain species are adapted to microclimatic stability and protected edge zones. The combination of riparian vegetation and canopy cover likely buffers environmental fluctuations, supporting insects that rely on cooler, more humid conditions and detrital inputs.

Station 2, located at the interface of the reservoir and adjacent rice fields, exhibited the highest species richness and abundance, with 12 of the 16 recorded species found in this habitat. The structurally complex environment—comprising dense semi-aquatic vegetation, shallow stagnant waters, and nutrient input from agricultural runoff—provides a mosaic of microhabitats that support a wide range of aquatic and semi-aquatic insect taxa. Several species showed strong habitat specificity in this site, including *D. rusticus*, *Hydrophilus* sp., *N. glauca*, *C. transversalis*, and *R. linearis*, which were not detected elsewhere. These taxa likely depend on vegetated, low-flow conditions and organic enrichment typical of agro-reservoir margins. In contrast, widely distributed generalist species such as *C. tritaeniorhynchus* and *P. fuscipes* were present across all three stations, reflecting their ecological plasticity and tolerance to a range of environmental conditions.

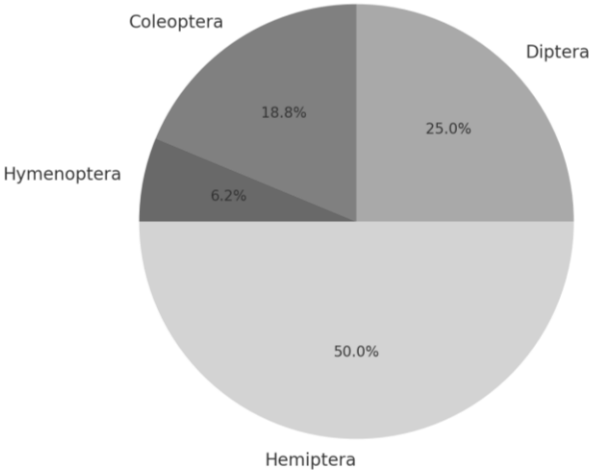

**Figure 2.** Proportional representation of insect orders across all stations (n = 16 species)

**Table 4.** Summary of aquatic and semi-aquatic insect specimens collected from each station

| Order | Family | Species name | Station 1 | Station 2 | Station 3 | Total |
|---|---|---|---|---|---|---|
| Diptera | Culicidae | *Culex tritaeniorhynchus* (Giles, 1901) | 4 | 8 | 5 | 17 |
| Hemiptera | Belostomatidae | *Diplonychus rusticus* (Fabricius, 1871) | 0 | 6 | 0 | 6 |
| Coleoptera | Staphylinidae | *Paederus fuscipes* (Curtis, 1826) | 2 | 4 | 2 | 8 |
| Diptera | Chironomidae | *Chironomus striatipennis* (Kieffer, 1910) | 3 | 5 | 1 | 9 |
| Hemiptera | Gerridae | *Gerris* sp. | 2 | 2 | 0 | 4 |
| Hemiptera | Notonectidae | *Notonecta glauca* (Linnaeus, 1758) | 0 | 3 | 0 | 3 |
| Coleoptera | Hydrophilidae | *Hydrophilus* sp. | 0 | 2 | 0 | 2 |
| Hemiptera | Nepidae | *Laccotrephes robustus* (Stål, 1871) | 1 | 0 | 0 | 1 |
| Diptera | Chironomidae | *Polypedilum* sp. | 0 | 1 | 1 | 2 |
| Diptera | Culicidae | *Anopheles vagus* (Dönitz, 1902) | 1 | 0 | 2 | 3 |
| Hymenoptera | Sphecidae | *Sceliphron caementarium* (Drury, 1773) | 1 | 1 | 1 | 3 |
| Coleoptera | Coccinellidae | *Coccinella transversalis* (Fabricius, 1781) | 0 | 1 | 0 | 1 |
| Hemiptera | Pyrrhocoridae | *Dysdercus cingulatus* (Fabricius, 1775) | 1 | 0 | 0 | 1 |
| Hemiptera | Corixidae | *Micronecta* sp. | 1 | 0 | 1 | 2 |
| Hemiptera | Nepidae | *Ranatra linearis* (Linnaeus, 1758) | 0 | 1 | 0 | 1 |
| Hemiptera | Reduviidae | *Rhynocoris* sp. | 1 | 1 | 0 | 2 |
| | | Total | 17 | 45 | 13 | 75 |

Note: Station 1: Forested margin, Station 2: Rice field edge, Station 3: Open unvegetated zone

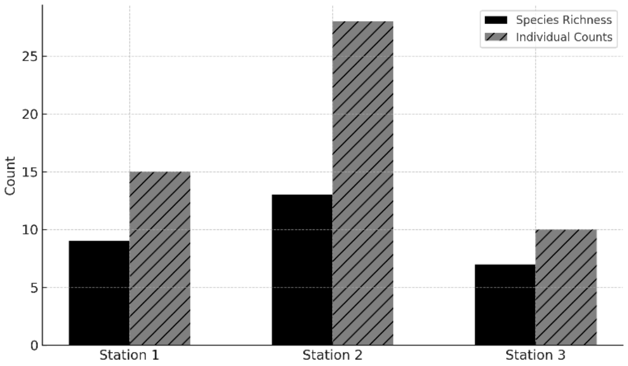

**Figure 3.** Bar chart showing species richness and individual counts per station

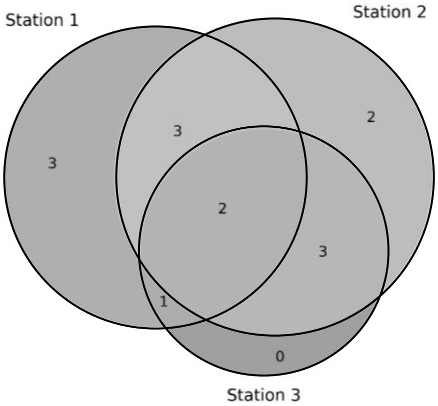

**Figure 4.** Venn diagram illustrating species overlap among the three sampling stations

Station 3, located along the open, unvegetated shoreline, exhibited the lowest species richness, with only 7 of the 16 recorded species present. The exposed nature of this habitat—characterized by direct sunlight, minimal vegetation, and fluctuating water levels—creates harsh abiotic conditions that limit aquatic insect diversity. Species encountered at this site, such as *Anopheles vagus*, *Polypedilum* sp., and *Micronecta* sp., are generally recognized for their tolerance to disturbed, low-cover environments. The absence of shade and submerged structures reduces available refugia and breeding substrates, favoring generalist or stress-tolerant taxa over habitat specialists. These findings suggest that shoreline simplification may reduce ecological complexity and affect trophic dynamics at the reservoir margin.

## Diversity indices

Diversity analysis using three ecological indices—Shannon–Wiener (H′), Pielou's Evenness (J′), and Margalef's Richness (Dmg)—revealed distinct patterns among the three habitat types in Kedungombo Reservoir (Table 5, Figure 5). Station 2 consistently showed the highest values across all indices, reflecting its complex habitat structure and diverse microenvironments.

The Shannon–Wiener index (H′) was highest at Station 2 (2.42), followed by Station 1 (2.13), and lowest at Station 3 (1.78). This indicates that species diversity was greatest where environmental conditions were moderate and heterogeneous. Pielou's evenness (J′) showed similar trends, with Station 2 reaching 0.91, suggesting a relatively balanced distribution of individuals across species. The lowest evenness value (0.75) was recorded at Station 3, where a few species dominated the community.

Margalef's richness index (Dmg) followed the same order, with Station 2 (3.14) outperforming Station 1 (2.47) and Station 3 (1.86). These results further emphasize the ecological advantage provided by semi-natural agricultural interfaces, which appear to support higher insect richness compared to both forested and barren littoral zones.

### Dominant and indicator species

Analysis of species abundance revealed a small subset of taxa that were dominant across multiple habitats. The most abundant species overall was *C. tritaeniorhynchus*, contributing 17 individuals and appearing in all three stations, confirming its status as a generalist mosquito with high ecological tolerance. Other widespread and relatively abundant species included *C. striatipennis* (9 individuals) and *P. fuscipes* (8 individuals), both of which are known to thrive in nutrient-rich and disturbed aquatic environments (Figure 6).

Station-specific dominance was also evident. At Station 2, *D. rusticus* showed a notably high abundance (6 individuals), reflecting its affinity for shallow, vegetated waters adjacent to agricultural fields. Several other species, such as *Hydrophilus* sp., *N. glauca*, *C. transversalis*, and *R. linearis*, were also restricted to Station 2, albeit in low numbers, indicating narrower ecological niches. Meanwhile, *L. robustus* was found only in Station 1, suggesting a preference for shaded, forested margins. This pattern of occurrence underscores the role of habitat heterogeneity in shaping insect distribution within the reservoir.

Several taxa showed potential as indicator species for specific habitat conditions. For example, *N. glauca*, a backswimmer typically associated with calm and vegetated waters, was found only in Station 2, aligning with its known habitat preferences. Similarly, *S. caementarium*, a mud-dauber wasp, occurred in all stations but only in low numbers, suggesting a broader but low-density distribution potentially linked to nesting substrate availability rather than water quality.

The presence of *Rhynocoris* sp. and *D. cingulatus* in shaded, less disturbed zones further support their value as indicators of low-disturbance or edge habitats. These patterns of dominance and specificity enhance the understanding of how insect assemblages respond to microhabitat features within reservoir ecosystems.

### Ecological roles and functional group composition

The aquatic and semi-aquatic insect community recorded from the Kedungombo Reservoir consisted of taxa occupying diverse ecological roles, including predators, detritivores, herbivores, and omnivores (Figure 7). Predators were the most dominant functional group, accounting for approximately 50% of the total species recorded. Representative taxa include *D. rusticus*, *N. glauca*, *L. robustus*, and *Rhynocoris* sp., all of which are active hunters of aquatic larvae, small insects, or zooplankton.

Detritivorous species such as *C. striatipennis* and *Polypedilum* sp. were also frequently encountered, particularly in Stations 2 and 3, where organic matter tends to accumulate. Their presence reflects the productivity of these habitats and the availability of sediment-based resources. Herbivores and generalist feeders were less common but included taxa such as *Gerris* sp. and *D. cingulatus*, which may exploit periphyton or decaying plant material along the water margin.

Omnivorous or facultatively scavenging species—such as *P. fuscipes* and *C. tritaeniorhynchus*—were widespread across habitats, demonstrating their adaptability and tolerance to environmental fluctuations. The presence of these functionally diverse groups suggests that the reservoir supports a relatively complex trophic structure, even in its simplified artificial state.

**Table 5.** Diversity indices (Shannon–Wiener, Pielou's Evenness, and Margalef's Richness) for each sampling station

| Station | Shannon–Wiener (H′) | Pielou's Evenness (J′) | Margalef's Richness (Dmg) |
|---|---|---|---|
| Station 1 | 2.13 | 0.84 | 2.47 |
| Station 2 | 2.42 | 0.91 | 3.14 |
| Station 3 | 1.78 | 0.75 | 1.86 |

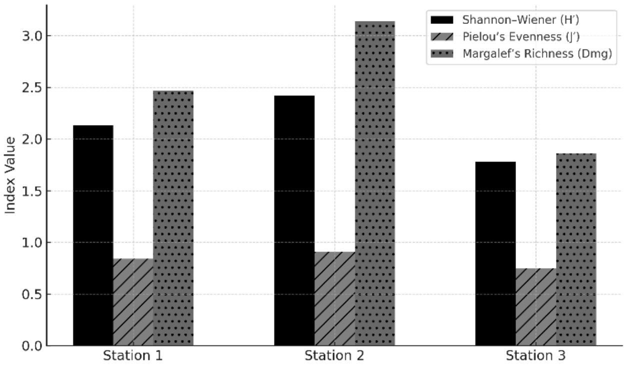

**Figure 5.** Bar chart comparing H′, J′, and Dmg values across the three sampling stations

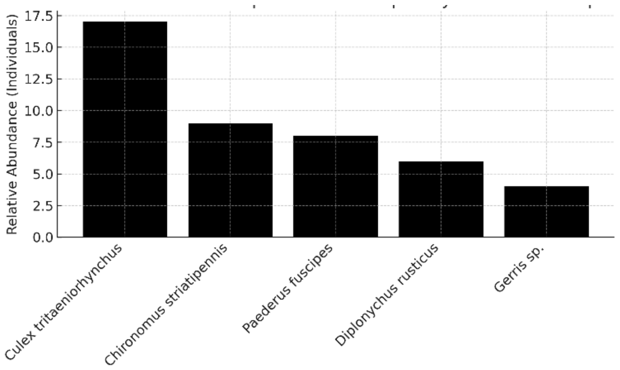

**Figure 6.** Relative abundance of the top five most frequently encountered species across all stations

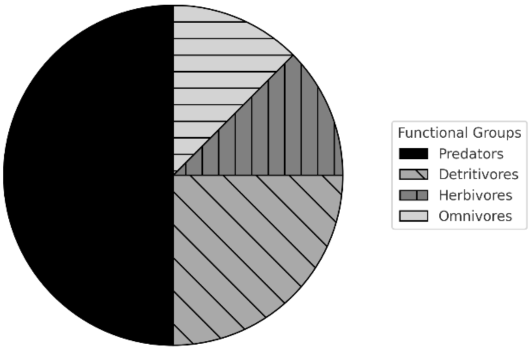

**Figure 7.** Functional group composition of aquatic and semi-aquatic insect species recorded from all sampling stations

## Discussion

### *Aquatic insect diversity in a tropical reservoir context*

The recorded diversity of 16 aquatic and semi-aquatic insect species across three habitat types in Kedungombo Reservoir provides a valuable insight into the ecological dynamics of tropical man-made freshwater ecosystems. Although this number may seem modest compared to natural riverine systems or wetlands, it aligns with diversity levels reported in other tropical reservoir studies, where environmental stability, water chemistry, and habitat complexity often constrain community richness (Nguyen et al. 2021).

The dominance of Diptera and Hemiptera, particularly members of Culicidae, Chironomidae, and Nepidae, is consistent with patterns observed in tropical standing waters. Such taxa are typically adapted to lentic conditions, high organic content, and shallow, sunlit environments that are common in reservoir littoral zones (Yule and Yong 2004). Moreover, the co-occurrence of both predators (e.g., *D. rusticus*) and detritivores (e.g., *C. striatipennis*) indicates a structured trophic web supported by diverse resource inputs, particularly from shoreline vegetation and agricultural runoff.

While some species like *C. tritaeniorhynchus* and *P. fuscipes* showed wide distribution and numerical dominance, the detection of rare or habitat-restricted taxa such as *L. robustus* and *D. cingulatus* highlights the importance of microhabitat variability within the reservoir system. The presence of such taxa may be underreported in large-scale surveys and points to the value of site-specific sampling approaches for biodiversity assessment (Harvey and Altermatt 2019).

In a broader ecological context, the species richness observed here underscores the role of artificial reservoirs as secondary refuges for insect biodiversity in increasingly modified tropical landscapes. Although they cannot replace the ecological functions of natural freshwater systems, reservoirs like Kedungombo may provide essential habitats—especially when managed with attention to edge vegetation and pollutant control (Dias-Silva et al. 2021). Thus, even low richness may still signify stable trophic interactions under constrained conditions.

### *Habitat-specific patterns and environmental drivers*

The contrasting species compositions observed among the three stations reflect how microhabitat features influence aquatic insect distribution within a reservoir system. Station 2, which bordered rice fields, had the highest species richness and diversity, likely due to a combination of shallow water, abundant macrophytes, and nutrient influx from agricultural runoff. These conditions are known to support higher insect productivity by increasing food availability and structural habitat complexity (Merritt et al. 1996; Hoang et al. 2022).

In comparison, Station 1—situated along a forested margin—supported moderately high diversity, dominated by taxa that favor shaded and stable shoreline conditions, such as *S. caementarium* and *Rhynocoris* sp. The presence of canopy cover likely contributes to more stable thermal and humidity conditions, while detritus input from forest litter may enrich benthic substrates for detritivores. Such interfaces between terrestrial vegetation and reservoir water bodies act as critical transition zones that buffer environmental extremes (Callisto et al. 2014).

Station 3, the open and unvegetated shoreline, showed the lowest richness and functional diversity. Harsh abiotic factors such as direct sunlight, fluctuating water levels, and a lack of refugia likely limit insect colonization. This habitat type appears to favor a few tolerant taxa such as *A. vagus* and *Polypedilum* sp., both known to thrive in disturbed, low-cover environments with minimal competition or predation pressure (Benetti and Hamada 2003).

The spatial segregation of taxa also suggests varying sensitivity to habitat degradation. Species restricted to vegetated or shaded zones may serve as early indicators of habitat disturbance or shoreline alteration. In contrast, widespread generalists may persist under a range of environmental pressures but are less informative for ecosystem health assessments.

### *Functional roles and trophic implications*

The functional diversity observed among the aquatic insect assemblages in Kedungombo Reservoir highlights the complexity of trophic interactions even within an artificial lentic system. Predatory taxa, including species such as *D. rusticus, N. glauca*, and *Rhynocoris* sp., comprised approximately half of the total species recorded, underscoring their role in regulating prey populations and maintaining ecological balance (Dudgeon et al. 2006). These predators exert top-down control, potentially influencing the abundance of mosquito larvae and other invertebrates, which is significant for ecosystem health and vector management.

Detritivores, particularly dipterans like *C. striatipennis* and *Polypedilum* sp., play a crucial role in the decomposition of organic matter, facilitating nutrient cycling within the reservoir. Their presence correlates with organic-rich sediments and contributes to energy transfer from detritus to higher trophic levels, including fish and amphibians (Wallace and Webster 1996). Herbivorous and omnivorous species, though less abundant, contribute to the regulation of primary production and scavenging activities, supporting overall ecosystem resilience.

The coexistence of these functional groups reflects a relatively balanced food web structure in Kedungombo Reservoir despite anthropogenic pressures. However, fluctuations in habitat conditions—such as nutrient loading from agricultural runoff or physical disturbance of shoreline vegetation—may disrupt these trophic interactions, leading to shifts in community composition and potential declines in biodiversity (Allan et al. 1997).

Understanding the functional roles of aquatic insects in reservoirs provides insight into ecosystem processes that underpin water quality, nutrient dynamics, and biological control. Future management efforts should prioritize the maintenance of habitat heterogeneity to support diverse functional groups, thereby enhancing ecosystem services and resilience.

### *Comparison with other tropical freshwater systems*

The aquatic insect diversity and community patterns observed in Kedungombo Reservoir are comparable to those reported in other tropical freshwater ecosystems, including natural lakes, wetlands, and reservoirs across Southeast Asia. For instance, studies in reservoirs of Malaysia and Thailand have documented similar dominance of Diptera and Hemiptera, with species richness ranging between 15 to 25 taxa per site (Yule and Yong 2004; Prommi et al. 2024). However, the total of 16 species recorded in Kedungombo can be considered relatively modest. Several factors may explain this. First, Kedungombo is an artificial reservoir with dynamic water level fluctuations, sparse submerged vegetation, and significant human activity along its margins, all of which can reduce habitat stability and limit the presence of specialist taxa. Second, sedimentation and agricultural runoff may lead to eutrophication and habitat homogenization, favoring generalist and pollution-tolerant species but suppressing sensitive groups (Benetti and Hamada 2003; Dias-Silva et al. 2021).

In contrast, aquatic insect assemblages in Indonesian natural lakes such as Rawa Pening and Lake Toba tend to be richer, likely due to more stable hydrological regimes, greater macrophyte diversity, and reduced physical disturbance (Sinambela et al. 2023; Sutrisno and Handoko 2024). This aligns with broader ecological theory suggesting that man-made impoundments often reduce niche availability, trophic stratification, and spatial complexity (Faghihinia et al. 2021).

Nevertheless, the functional composition observed in Kedungombo—predator dominance alongside detritivore presence—is consistent with patterns seen in tropical lentic systems subject to moderate eutrophication and nutrient influx. These functional groups may sustain simplified but still ecologically meaningful food webs, even in disturbed conditions (Dias-Silva et al. 2021). Comparative analyses highlight the importance of habitat heterogeneity and water quality management to conserve aquatic insect biodiversity in tropical reservoirs. Conservation strategies implemented in other Southeast Asian reservoirs, such as riparian buffer restoration, macrophyte replanting, and agrochemical input reduction, are equally applicable to Kedungombo.

### *Limitations and recommendations for future research*

This study has several limitations that should be addressed in future research. Firstly, the data were collected during a single sampling event in the dry season, limiting the ability to assess seasonal dynamics and temporal variability of aquatic insect communities. Seasonal fluctuations can significantly influence species composition and abundance, especially in tropical ecosystems with distinct wet and dry periods (Ramírez et al. 2018). Secondly, the reliance on morphological identification without molecular confirmation could lead to taxonomic uncertainties, particularly for cryptic or closely related species. Incorporating DNA barcoding and molecular tools would enhance accuracy and allow for the detection of hidden diversity.

Furthermore, abiotic parameters such as water temperature, pH, dissolved oxygen, and nutrient concentrations were not systematically measured during sampling, restricting the ability to correlate environmental variables with insect community patterns. Future studies should integrate physicochemical assessments to better understand habitat drivers. Expanding sampling frequency to cover multiple seasons and including additional microhabitats would provide a more comprehensive picture of biodiversity and ecosystem health.

Lastly, despite the study's focus on biodiversity assessment, there is a need to link insect community data with ecosystem services such as water purification, pest regulation, and fisheries productivity. Such integrative approaches will support reservoir management policies that balance human use and conservation goals. The study highlights the need to integrate aquatic insect indicators into reservoir management plans, emphasizing the conservation of vegetated shorelines to sustain biodiversity and ecosystem function.

In conclusion, the present study provides a baseline assessment of aquatic and semi-aquatic insect diversity and distribution within the Kedungombo Reservoir, Central Java, Indonesia. Our findings reveal that habitat heterogeneity across forested margins, agricultural edges, and open littoral zones significantly influences species richness, community composition, and functional group dynamics. The reservoir supports a moderate but ecologically important assemblage dominated by Diptera, Hemiptera, and Coleoptera, with a balance of predators, detritivores, and generalists that contribute to ecosystem functioning. The rice field interface habitat exhibited the highest diversity and evenness, highlighting the role of agricultural landscapes as transitional zones that can sustain aquatic biodiversity when managed sustainably. Conversely, unvegetated open shores displayed lower diversity and were dominated by a few tolerant species, underscoring the importance of vegetation structure in maintaining healthy insect communities. This study underscores the value of tropical reservoirs as supplementary habitats for freshwater biodiversity in human-modified landscapes. Continued monitoring and integrated management practices that preserve habitat complexity and water quality are critical to sustaining these insect communities and their associated ecological services. These findings provide a basis for incorporating insect-based indicators in reservoir biodiversity monitoring and habitat management policies in tropical Southeast Asia.

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## REFERENCES

Abowei JFN, Ukoroije BR. 2012. The identification, types, taxonomic orders, biodiversity and importance of aquatic insects. Br J Pharmacol Toxicol 3 (5): 218-229.

Allan JD, Erickson DL, Fay J. 1997. The influence of catchment land use on stream integrity across multiple spatial scales. Freshw Biol 37 (1): 149-161. DOI: 10.1046/j.1365-2427.1997.00134.x.

Ariyani N, Fauzi A, Umar F. 2020. Faktor-faktor yang mempengaruhi partisipasi pemangku kepentingan pada pengembangan kawasan wisata Kedung Ombo. Jurnal Pariwisata Terapan 4 (2): 147-162. DOI: 10.22146/jpt.60678. [Indonesian]

Atmowidi T, Setiawan B, Sulistijorini S. 2022. Kemelimpahan anggang-anggang *Ptilomera dromas* Breddin (Hemiptera: Gerridae) di Sungai Ciliwung dalam kaitannya dengan kualitas air. Jurnal Entomologi Indonesia 19 (1): 1-8. DOI: 10.5994/jei.19.1.1. [Indonesian]

Benetti CJ, Hamada N. 2003. Fauna de coleópteros aquáticos (insect: coleoptera) na Amazônia central, Brasil. Acta Amaz 33: 701-710. DOI: 10.1590/S0044-59672003000400015.

Borror DJ, Triplehorn CA, Johnson NF. 2005. An Introduction to the Study of Insects. 7th ed. Brooks/Cole, Thomson Learning, Belmont, CA.

Callisto M, Molozzi J, Barbosa J. 2014. Eutrophication of lakes. In: Ansari A, Gill S (eds). Eutrophication: Causes, Consequences and Control. Springer, Dordrecht. DOI: 10.1007/978-94-007-7814-6_5.

Choudhury D, Gupta S. 2017. Impact of waste dump on surface water quality and aquatic insect diversity of Deepor Beel (Ramsar site), Assam, North-east India. Environ Monit Assess 189 (11): 540. DOI: 10.1007/s10661-017-6233-7.

Dias-Silva K, Vieira TB, de Matos TP, Juen L, Simião-Ferreira J, Hughes RM, Júnior PDM. 2021. Measuring stream habitat conditions: Can remote sensing substitute for field data? Sci Total Environ 788: 147617. DOI: 10.1016/j.scitotenv.2021.147617.

Dudgeon D, Arthington AH, Gessner MO, Kawabata ZI, Knowler DJ, Lévêque C, Naiman RJ, Prieur-Richard AH, Soto D, Stiassny MLJ, Sullivan CA. 2006. Freshwater biodiversity: Importance, threats, status and conservation challenges. Biol Rev 81: 163-182. DOI: 10.1017/S1464793105006950.

Faghihinia M, Xu Y, Liu D, Wu N. 2021. Freshwater biodiversity at different habitats: Research hotspots with persistent and emerging themes. Ecol Indic 129: 107926. DOI: 10.1016/j.ecolind.2021.107926.

Harvey E, Altermatt F. 2019. Regulation of the functional structure of aquatic communities across spatial scales in a major river network. Ecology 100 (4): e02633. DOI: 10.1002/ecy.2633.

Hoang T, Foquet B, Rana S, Little DW, Woller DA, Sword GA, Song H. 2022. Development of RNAi methods for the Mormon cricket, *Anabrus simplex* (Orthoptera: Tettigoniidae). Insects 13 (8): 739. DOI: 10.3390/insects13080739.

Ihamdi ML, Idrus AA, Santoso D, Hadiprayitno G, Syazali M. 2021. The species richness and conservation priority of dragonflies in the Suranadi Ecotourism Area, Lombok, Indonesia. Biodiversitas 22 (4): 1846-1852. DOI: 10.13057/biodiv/d220430.

Letsch H, Gottsberger B, Ware JL. 2016. Not going with the flow: A comprehensive time-calibrated phylogeny of dragonflies (Anisoptera: Odonata: Insecta) provides evidence for the role of lentic habitats on diversification. Mol Ecol 25 (6): 1340-1353. DOI: 10.1111/mec.13562.

Li H, Leavengood JM, Chapman EG, Burkhardt D, Song F, Jiang P, Liu J, Zhou X, Cai W. 2017. Mitochondrial phylogenomics of Hemiptera reveals adaptive innovations driving the diversification of true bugs. Proc R Soc B: Biol Sci 284 (1862): 20171223. DOI: 10.1098/rspb.2017.1223.

Mahmoud AM, El-Naggar HA, Hasaballah AI, Haggag AA, Selim TA. 2022. Aquatic insects as a biomonitoring and bioindicators for trace metals in the contaminated Al-Mahmoudia Canal, River Nile, Egypt. Egypt J Aquat Biol Fish 26: 365-386. DOI: 10.21608/ejabf.2022.217582.

Makmur S, Rahardjo M, Sukimin S. 2017. Biologi reproduksi ikan gabus (*Channel striata* Bloch) di daerah banjiran Sungai Musi Sumatera Selatan. Jurnal Iktiologi Indonesia 3 (2): 57-62. DOI: 10.32491/jii.v3i2.258. [Indonesian]

Merritt RW, Cummins KW, Berg MB. 1996. An Introduction to the Aquatic Insects of North America (4th ed.). Kendall/Hunt Publishing, Dubuque.

Nguyen TN, Nguyen TX, Pham TV, Nguyen DT. 2021. Applying the soil and water assessment tool model for integrated lake basin management in northern Vietnam: case study of the Thac Ba Reservoir Basin. Environ Eng Sci 38 (11): 1027-1035. DOI: 10.1089/ees.2020.0378.

Parr TB, Capps KA, Inamdar SP, Metcalf KA. 2019. Animal-mediated organic matter transformation: Aquatic insects as a source of microbially bioavailable organic nutrients and energy. Funct Ecol 33 (3): 524-535. DOI: 10.1111/1365-2435.13242.

Popoola KOK, Otalekor A. 2011. Analysis of aquatic insects' communities of Awba Reservoir and its physico-chemical properties. Res J Environ Earth Sci 3: 422-428.

Prommi TO, Khamboonruang P, Klorvuttimontara S. 2024. Diversity and structure of aquatic insect communities in relation to water quality parameters in The Kasetsart University Drainage Ditches, Central Thailand. J Food Health Bioenviron Sci 17 (1): 11-22.

Ramírez A, Gutiérrez-Fonseca PE, Kelly SP, Engman AC, Wagner K, Rosas KG, Rodríguez N. 2018. Drought facilitates species invasions in an urban stream: results from a long-term study of tropical island fish assemblage structure. Front Ecol Evol 6: 115. DOI: 10.3389/fevo.2018.00115.

Sinambela M, Simangunsong M, Simorangkir A, Harahap A. 2023. Correlation of macrozoobenthos diversity index with physico-chemical factors in Lake Toba, Toba Samosir Regency. Intl J Sci Technol Manag 4 (3): 575-581. DOI: 10.46729/ijstm.v4i3.829.

Sutrisno AJ, Handoko M. 2024. Spatial distribution of water quality classes of Rawa Pening Lake. IOP Conf Ser: Earth Environ Sci 1384 (1): 012013. DOI: 10.1088/1755-1315/1384/1/012013.

Wakhid, Rauf A, Krisanti M, Sumertajaya IM, Maryana N. 2020. Species richness and diversity of aquatic insects inhabiting rice fields in Bogor, West Java, Indonesia. Biodiversitas 21 (1): 34-42. DOI: 10.13057/biodiv/d210106.

Wallace JB, Webster JR. 1996. The role of macroinvertebrates in stream ecosystem function. Ann Rev Entomol 41 (1): 115-139. DOI: 10.1146/annurev.en.41.010196.000555.

Williams DD, Williams SS. 2017. Aquatic insects and their potential to contribute to the diet of the globally expanding human population. Insects 8 (3): 72. DOI: 10.3390/insects8030072.

Yule CM, Yong HS. 2004. Freshwater Invertebrates of the Malaysian Region. Academy of Sciences Malaysia, Kuala Lumpur.

Zhao CS, Pan X, Yang ST, Xiang H, Zhao J, Gan XJ, Ding SY, Yu Q. 2021. Effects and prediction of nonpoint source pollution on the structure of aquatic food webs. Ecohydrology 14 (1): e2257. DOI: 10.1002/eco.2257.

Zheng L, Wang X, Li D, Xu G, Guo Y. 2021. Spatial heterogeneity of vegetation extent and the response to water level fluctuations and micro-topography in Poyang Lake, China. Ecol Indic 124: 107420. DOI: 10.1016/j.ecolind.2021.107420.

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# Spatial and temporal dynamics of mangrove cover change in five estuaries along the North Coast of Central Java, Indonesia (2014-2024)

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[2]Disaster Research Center, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia
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**Abstract.** *Candraningtyas CF, Hafiffah AS, Widowati D, Mardiyanto MB, Saputri AB, Setyawan AD. 2024. Spatial and temporal dynamics of mangrove cover change in five estuaries along the North Coast of Central Java, Indonesia (2014-2024). Intl J Bonorowo Wetlands 15: 40-48.* Mangrove ecosystems are critical coastal habitats that provide essential ecological services, including shoreline protection, carbon sequestration, and biodiversity support, yet they are increasingly threatened by anthropogenic pressures. This study investigates spatial and temporal changes in mangrove cover from 2014 to 2024 across five estuaries along the north coast of Central Java, Indonesia—Sriwulan, Pemali, Comal, Bodri, and Cisanggarung—using Landsat 8 satellite imagery processed via Google Earth Engine and ArcGIS. Mangrove extents were manually digitized and classified into zones of loss, gain, and stability, with field surveys and photographic documentation employed for validation. Results revealed significant mangrove loss in Sriwulan (-47.03%), Cisanggarung (-50.00%), Comal (-11.31%), and Bodri (-1.59%), driven by land conversion for aquaculture and settlements, destructive fishing practices, and hydrological disruptions. In contrast, the Pemali Estuary exhibited a notable 79.83% increase in mangrove cover, primarily due to sediment accretion and community-led restoration efforts, especially silvofishery-based rehabilitation. The study demonstrates that integrating remote sensing with ground truthing is a robust approach for monitoring mangrove dynamics and identifying localized drivers of change. The contrasting trends across estuaries highlight the heterogeneity of coastal ecosystem responses and underscore the importance of site-specific management strategies. While some estuaries face continued degradation, others show promising signs of recovery, illustrating both the challenges and potential in mangrove conservation. These findings emphasize the urgent need for adaptive coastal management that incorporates ecological monitoring, sustainable land-use planning, and active community participation. As mangrove loss continues globally, this research provides important insights into effective restoration and protection strategies for tropical estuarine environments, offering a model for balancing development and conservation in similar socio-ecological settings across Southeast Asia.

**Keywords:** Central Java, coastal conservation, land use change, mangrove cover change, rehabilitation, remote sensing

## INTRODUCTION

Mangrove ecosystems are among the most productive and ecologically significant coastal habitats worldwide. They serve as critical buffers between terrestrial and marine environments, providing a wide array of ecosystem services including shoreline stabilization, carbon sequestration, nursery grounds for fisheries, and habitat for diverse flora and fauna (Nagelkerken et al. 2008; Anu et al. 2024). These intertidal forests occur predominantly in tropical and subtropical regions, thriving in the brackish waters of estuaries, bays, and river mouths where saline and freshwater mix (Godoy and Lacerda 2015). Indonesia holds the largest expanse of mangrove forests globally, estimated at approximately 2.7 million hectares in 2020, accounting for roughly 23% of the world's total mangrove area (Basyuni et al. 2022). This makes the country a critical global hotspot for mangrove conservation and management.

Despite their ecological importance, mangrove ecosystems face increasing threats from anthropogenic pressures. Land-use change driven by urbanization, aquaculture development, agricultural expansion, and infrastructure growth has led to significant mangrove degradation and loss in recent decades (Kusmana 2015; Friess et al. 2019). The conversion of mangrove areas into shrimp ponds and coastal settlements is particularly prevalent in densely populated coastal regions such as Java, Indonesia's most populous island. These activities not only diminish mangrove cover but also disrupt ecosystem functioning and reduce the services these forests provide to coastal communities. However, with these collective efforts, we can mitigate these threats and protect these vital ecosystems. Moreover, environmental stressors such as coastal erosion, sedimentation changes, and pollution further exacerbate mangrove vulnerability (Sanderman et al. 2018).

Monitoring mangrove cover changes is therefore essential to inform effective conservation strategies and policy interventions. Remote sensing technology, especially the use of multispectral satellite imagery, has emerged as a powerful tool for mapping and monitoring mangrove dynamics over time and space (Kuenzer et al. 2011; Pham and Yoshino 2015). Landsat satellites, with their long-term data archives and moderate spatial resolution, have been widely applied in mangrove studies, enabling assessments of deforestation, degradation, and rehabilitation across large geographic extents (Chen et al. 2018; As-Syakur et al. 2023). The integration of cloud computing platforms like Google Earth Engine has further facilitated the efficient processing of large satellite datasets, improving temporal resolution and analytical capability.

The northern coast of Central Java, Indonesia, presents a compelling case for such analyses due to its ecological complexity and intense anthropogenic activity. The region encompasses multiple estuarine systems where mangroves interact with diverse land uses, including fisheries, agriculture, urban development, and industrial zones. This spatial heterogeneity poses challenges for conservation but also opportunities for adaptive management based on detailed spatial data. Past studies in the region have highlighted both losses and gains in mangrove cover, with some estuaries experiencing severe degradation while others show signs of recovery through rehabilitation initiatives (Damastuti and de Groot 2017; Fikriyya et al. 2023).

However, comprehensive assessments spanning multiple estuaries over a decadal period remain limited, particularly for integrating remote sensing data with ground-based observations and socio-environmental context. Understanding the spatial and temporal patterns of mangrove change across several key estuaries along Central Java's northern coast is critical for identifying drivers of change and tailoring management responses. Moreover, evaluating the success of rehabilitation efforts and conservation programs requires consistent and accurate monitoring frameworks.

This study aims to fill these gaps by assessing mangrove cover changes between 2014 and 2024 in five major estuaries along the North Coast of Central Java: Sriwulan, Pemali, Comal, Bodri, and Cisanggarung. Using Landsat 8 imagery processed through Google Earth Engine and ArcGIS, we quantify spatial extents and trends of mangrove cover in each estuary. We further analyze the potential drivers of these changes, including anthropogenic land conversion, natural sedimentation dynamics, and community-based restoration efforts. Complementary field surveys and photographic documentation are integrated to validate remote sensing classifications and provide ground truth.

By examining both losses and gains within this regional context, the study provides insights into the complex dynamics shaping mangrove ecosystems on Java's north coast. The findings are expected to inform targeted conservation strategies, enhance monitoring protocols, and support sustainable coastal management in Indonesia and comparable tropical regions worldwide.

## MATERIALS AND METHODS

### Study area

*Geographic location and climate*

The study area covers five major estuaries located along the northern coast of Central Java, Indonesia (Figure 1): Sriwulan, Pemali, Comal, Bodri, and Cisanggarung. These estuaries are situated between approximately 6°50' to 7°20' S and 109° to 110° E, extending from Demak District in the east to Cirebon District in the west. This coastal region forms part of the Java Sea coastline and is characterized by a tropical monsoon climate with distinct wet and dry seasons.

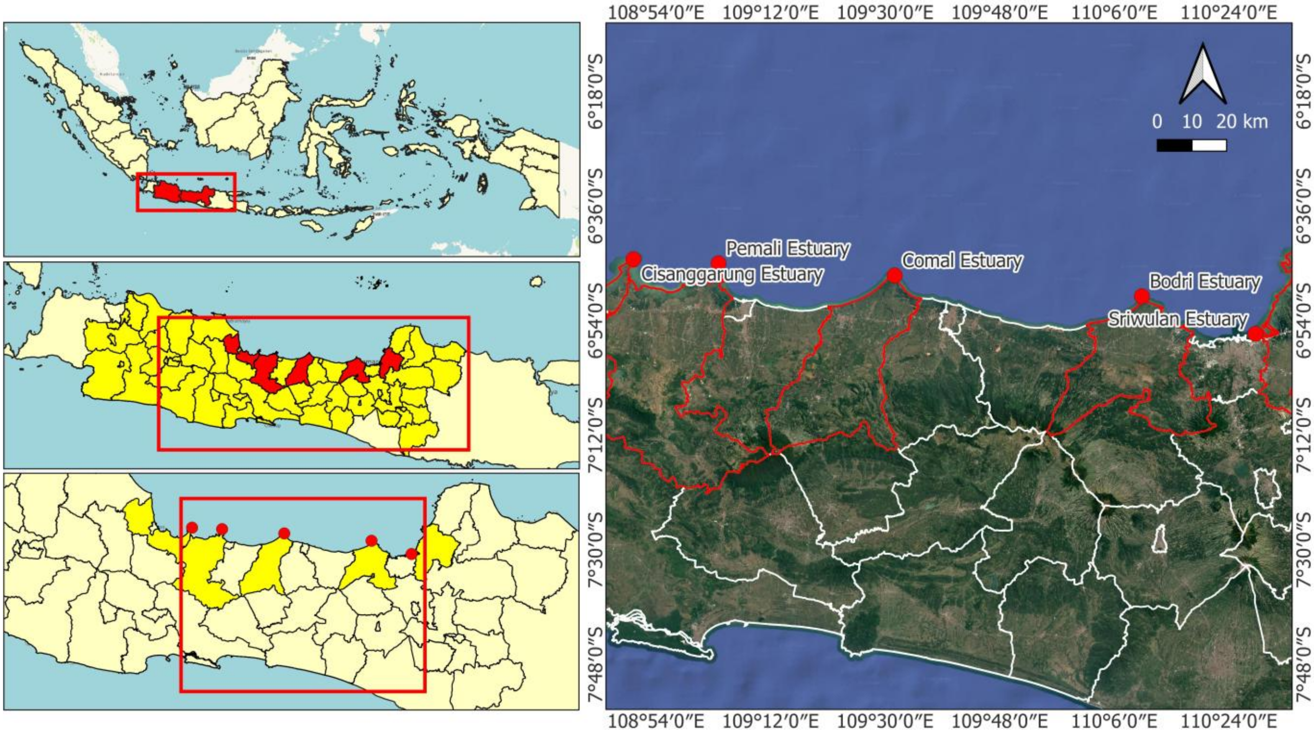


**Figure 1.** Spatial distribution maps of mangrove cover across the five studied estuaries on the north coast of Central Java, Indonesia

The average annual rainfall ranges from 1,800 to 2,500 mm, predominantly occurring between November and March, while the dry season extends from June to September. Temperatures fluctuate between 24°C and 33°C throughout the year. The tidal regime is semidiurnal with moderate amplitude, influencing the hydrological dynamics and sediment transport in the estuaries. These physical and climatic conditions provide suitable habitats for mangrove forests, which thrive in the intertidal zones of these estuarine systems.

*Characteristics of the five estuaries (Sriwulan, Pemali, Comal, Bodri, Cisanggarung)*

Each of the five estuaries presents unique geomorphological, ecological, and anthropogenic features:

**Sriwulan Estuary** is located in Demak District and is characterized by relatively fertile waters with substantial nutrient input, supporting dense mangrove vegetation. The estuary supports local fisheries, settlements, and aquaculture activities. However, increasing urbanization and industrial development have exerted pressure on the mangrove ecosystem, causing fragmentation and degradation.

**Pemali Estuary** lies in Brebes District and features a delta formed by fluvial and marine sedimentation processes. The region has experienced notable mangrove expansion, attributed largely to successful rehabilitation and silvofishery practices that combine aquaculture and mangrove preservation. The gentle seabed topography facilitates sediment deposition, fostering mangrove growth.

**Comal Estuary** in Pemalang District serves as an important waterway for fishing and transportation. Recent river diversion efforts to improve navigation have altered hydrodynamics, resulting in localized mangrove loss due to sediment changes and abrasion. Conservation groups have initiated mangrove planting programs, but challenges such as extreme weather reduce seedling survival.

**Bodri Estuary** is situated in Kendal District and features a dynamic sediment environment with active accretion processes. Despite some industrial and residential development, the mangrove cover has remained relatively stable with minor reductions, mainly due to conversion into salt ponds. The estuary's geomorphology includes sandbars and a sloped riverbed, influencing sediment distribution.

**Cisanggarung Estuary** is located in Cirebon District, is part of an actively expanding delta with high sedimentation rates forming a bird's foot pattern. While sedimentation facilitates new mangrove habitat formation, the rapid expansion of aquaculture ponds on newly formed land has resulted in significant mangrove loss. Mangroves are also maintained along pond embankments, reflecting complex land use patterns.

*Socio-economic and land use context*

The northern coast of Central Java is densely populated, with communities heavily reliant on coastal resources for livelihoods, including fishing, aquaculture, agriculture, and small-scale industry. Population growth and economic development have accelerated land conversion, particularly the expansion of shrimp and fish ponds, residential settlements, and industrial zones. These activities frequently encroach upon mangrove areas, leading to habitat loss and fragmentation.

Local knowledge and community participation vary among the estuaries, influencing the success of mangrove conservation and rehabilitation initiatives. For example, in the Pemali Estuary, community-driven silvofishery practices have enhanced mangrove restoration. At the same time, in the Sriwulan and Cisanggarung estuaries, conflicting land uses and regulatory enforcement gaps pose significant challenges.

Land use in the study areas typically includes a mosaic of mangrove forests, aquaculture ponds, agricultural fields, urban settlements, and industrial infrastructure. The balance between these land uses is dynamic and directly affects the spatial distribution and health of mangrove ecosystems. Effective management requires integrating socio-economic considerations with ecological monitoring to ensure sustainable coastal development and conservation outcomes.

## Data acquisition

*Satellite imagery sources and specifications (Landsat 8)*

For this study, multispectral satellite imagery from the Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) was acquired to analyze mangrove cover changes between 2014 and 2024. Landsat 8 imagery is publicly accessible and provides data at a spatial resolution of 30 meters, suitable for regional-scale ecosystem monitoring. The selected bands for this analysis included Band 4 (Red), Band 5 (Near-Infrared), and Band 6 (Shortwave Infrared 1), which are effective in differentiating vegetation types and detecting mangrove vegetation based on their spectral reflectance properties. These spectral bands were processed to generate false-color composites, enhancing the contrast between mangroves, water bodies, and other land covers.

The satellite images were sourced through the Google Earth Engine (GEE) platform, which allows for efficient cloud filtering, atmospheric correction, and batch processing of large datasets. Images with less than 10% cloud cover over the study area were selected for each target year to minimize atmospheric distortion. The temporal window focused on the dry season months (June-September) to reduce phenological variability and water turbidity effects.

*Ancillary data (administrative boundaries, hydrology maps)*

Aancillary geospatial data were incorporated to delineate study areas precisely and assist spatial analysis. Administrative boundaries for the Central Java districts encompassing the five estuaries were obtained from official government geodata repositories. These boundaries facilitated the accurate extraction and masking of satellite imagery to the study extents.

Hydrological maps and river network data were used to define estuarine zones, tidal influence areas, and river mouths critical for understanding mangrove spatial distribution. Topographic maps and Land Use Land Cover (LULC) data from previous studies and regional planning agencies supplemented satellite imagery for contextual interpretation of land-use dynamics and anthropogenic pressures. The integration of these datasets ensured that mangrove mapping and change detection were spatially accurate and reflected on-the-ground conditions within the administrative and ecological boundaries relevant to management and policy.

## Image preprocessing and classification

### Selection of spectral bands and false-color composite

To enhance the differentiation of mangrove vegetation from other land covers, the Landsat 8 bands 4 (Red), 5 (Near-Infrared, NIR), and 6 (Shortwave Infrared 1, SWIR1) were selected for analysis. These bands were combined into false-color composite images with Band 5 assigned to red, Band 6 to green, and Band 4 to blue, a configuration that highlights healthy vegetation in bright red tones, facilitating visual identification of mangrove areas. This spectral combination exploits the strong reflectance of vegetation in the NIR band and absorption characteristics in the red and SWIR bands.

### Image filtering and cloud masking

Prior to classification, the raw satellite images underwent preprocessing steps to ensure quality and reliability. Images were filtered to exclude scenes with cloud cover exceeding 10% over the study area. Clouds and their shadows were masked using the pixel quality assessment bands available in the Landsat 8 Surface Reflectance dataset, removing artifacts that could confound classification results. Atmospheric corrections embedded in the dataset further refined reflectance values to standardize conditions across different acquisition dates.

### Mangrove area delineation and digitization in ArcGIS

Mangrove extents were manually digitized in ArcGIS 10.8 by interpreting the false-color composites alongside ancillary data such as hydrological boundaries and previous land use maps. This manual digitization approach enabled careful delineation of mangrove polygons, especially in areas where spectral confusion with other vegetation or land covers could occur. Polygons were traced along visible mangrove boundaries, considering tidal influence zones and estuarine topography.

Each polygon was attributed with relevant metadata, including estimated area in hectares. The accuracy of the digitized mangrove map was cross-verified through field observations at selected sample points and supplemented by photographic documentation where available. This approach ensured that mangrove boundaries reflected realistic spatial patterns consistent with both satellite imagery and ground truth data.

## Change detection analysis

### Methodology for comparing 2014 and 2024 mangrove extents

The digitized mangrove polygons from 2014 and 2024 were compared spatially using GIS overlay techniques to quantify changes in mangrove cover over the ten years. The 2014 mangrove layer was subtracted from the 2024 layer to identify areas of loss, gain, and persistence. This spatial comparison allowed for the classification of mangrove change into three categories: deforestation (loss), afforestation or natural regeneration (gain), and stable mangrove cover.

Geoprocessing tools such as 'Erase' and 'Intersect' in ArcGIS were employed to compute the spatial extent and location of these changes at each estuary. The analysis was conducted separately for each of the five estuaries to discern local variation in mangrove dynamics.

### Calculation of area changes and percentage differences

The areas of mangrove cover for 2014 and 2024 were calculated in hectares based on the digitized polygons. The absolute change in area (ha) was determined by subtracting the 2014 mangrove extent from the 2024 extent. The percentage change was calculated using the formula:

$$\text{Percentage Change} = \frac{\text{Area}_{2024} - \text{Area}_{2014}}{\text{Area}_{2014}} \times 100\%$$

This metric provided a normalized measure of change, facilitating comparison across estuaries with different initial mangrove extents. The results were tabulated and visualized to illustrate the magnitude and direction of mangrove cover changes spatially and temporally.

## Validation and accuracy assessment

### Field survey design and data collection

Field validation was conducted at selected sites within the five estuaries to verify the accuracy of mangrove classification derived from satellite imagery. Sampling points were chosen to represent diverse mangrove conditions, including dense, sparse, degraded, and rehabilitated areas. At each point, GPS coordinates were recorded, and detailed observations on vegetation type, canopy cover, and health status were documented. Photographs were taken to provide visual evidence supporting classification accuracy.

### Use of photographic documentation and publicly available images

In addition to field surveys, photographic documentation obtained during fieldwork supplemented validation efforts. Where direct field access was limited, publicly available images from platforms such as Google Maps Photos and iNaturalist were used cautiously as supplementary references. These external images helped confirm mangrove presence and conditions in areas not covered during field visits, but were not relied upon as primary validation data due to potential discrepancies in location accuracy and timing.

### Limitations of validation data

While efforts were made to ensure robust validation, certain limitations are acknowledged. Field surveys were constrained by accessibility issues, especially in remote or privately owned areas, limiting the spatial coverage of ground truth points. Furthermore, the use of publicly sourced images introduced uncertainties related to metadata accuracy. Despite these challenges, the combination of satellite interpretation, targeted field verification, and supplemental imagery provided a reasonable level of confidence in the mangrove classification and change detection results. Although only 35 validation points were collected, sampling was stratified to capture different vegetation densities and estuarine conditions. Nonetheless, the limited number of ground points may affect the representation of highly fragmented or transitional zones

### Data analysis and interpretation

*Spatial analysis of mangrove loss and gain*

The spatial distribution of mangrove loss, gain, and stable areas was analyzed using GIS tools to identify patterns and hotspots across the five estuaries. Next, overlay maps highlighting areas of significant deforestation and afforestation were generated to visualize spatial trends. These maps facilitated understanding of the geographic context of mangrove dynamics, indicating zones heavily impacted by anthropogenic activities or benefiting from natural regeneration and rehabilitation efforts.

*Identification of drivers of change*

Integrating spatial analysis results with ancillary land use data, field observations, and a literature review identified key drivers influencing mangrove cover change**.** These included land conversion for aquaculture and settlements, coastal erosion, sediment deposition, and community-led rehabilitation programs. The relative impact of each driver was assessed qualitatively, providing insight into the complex socio-environmental interactions shaping mangrove ecosystems in Central Java.

*Integration of remote sensing and field data*

The integration of remote sensing data with field validation and socio-environmental context enabled a comprehensive interpretation of mangrove dynamics. This holistic approach enhanced the reliability of change detection and supported the formulation of management recommendations tailored to local conditions. The combined dataset provided a strong evidentiary basis for understanding mangrove ecosystem status and guiding future conservation strategies.

## RESULTS AND DISCUSSION

### Overview of mangrove cover in 2014 and 2024

*Total mangrove area per estuary*

The total mangrove area in the five estuaries along the north coast of Central Java showed significant spatial variation in 2014 and 2024. Table 1 presents the total mangrove areas for each estuary at both time points. Overall, the cumulative mangrove area increased from 706.25 ha in 2014 to 838.29 ha in 2024, primarily due to the substantial expansion observed in the Pemali Estuary. Meanwhile, the other estuaries experienced varying degrees of mangrove loss, with the greatest declines noted in the Cisanggarung and Sriwulan estuaries. These contrasting trends highlight the heterogeneous nature of mangrove dynamics along this coastal stretch. Figure 2 illustrates the spatial distribution of mangrove cover in 2014 and 2024, providing a visual comparison of mangrove extent changes across the five estuaries.

*Spatial distribution patterns*

The spatial distribution of mangrove cover across the five estuaries varied notably between 2014 and 2024. Mangrove patches in the Sriwulan and Cisanggarung estuaries were highly fragmented by 2024, with significant areas converted to aquaculture ponds, built-up land, and bare substrates. However, the Pemali Estuary presented a beacon of hope, exhibiting an expansion of mangrove areas, particularly along deltaic fronts and newly accreted lands, indicating successful sedimentation and restoration efforts.

Figure 2 presents detailed maps showing mangrove spatial patterns for each estuary at both time points, highlighting zones of loss, gain, and stable coverage. The fragmentation observed in the declining estuaries reflects increasing anthropogenic pressures and environmental degradation, underscoring the urgent need for targeted conservation programs. More continuous mangrove coverage in Pemali further emphasizes the importance of such efforts. These spatial trends emphasize the heterogeneity of mangrove ecosystem responses within a relatively small geographic area and underscore the importance of site-specific management and restoration strategies.

### Mangrove cover change analysis

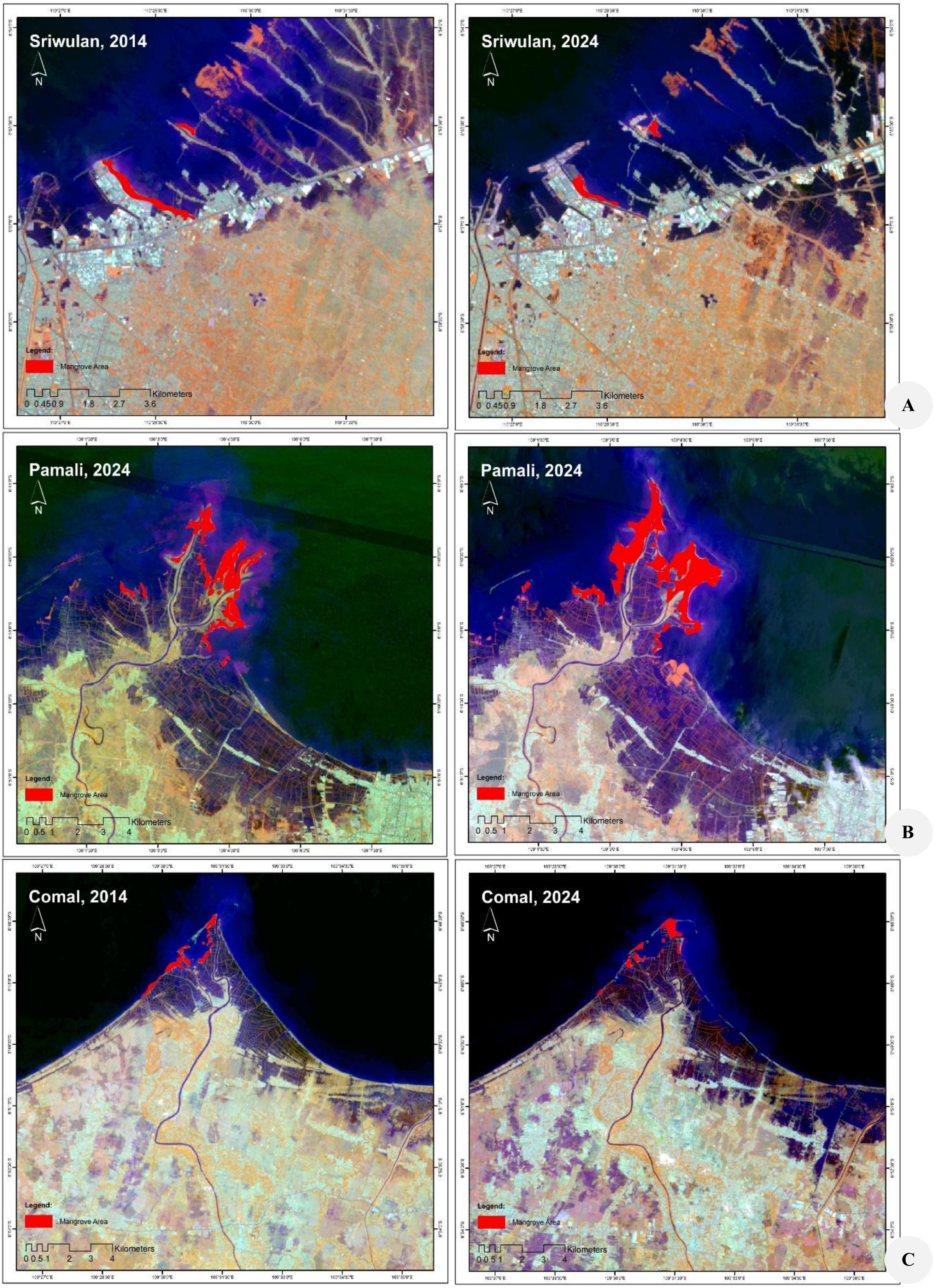
*Areas of mangrove loss*

Significant mangrove loss was observed in four of the five estuaries between 2014 and 2024. The most extensive losses occurred in the Cisanggarung Estuary, where approximately 99.01 hectares (50%) of mangrove cover were lost, primarily due to conversion to aquaculture ponds and urban development. The Sriwulan Estuary experienced a loss of 26.39 hectares (47.03%), with similar causes including industrial expansion and settlement growth.

Comal and Bodri estuaries also exhibited declines, albeit smaller in scale, with losses of 8.61 hectares (11.31%) and 0.66 hectares (1.59%), respectively. These reductions were largely attributed to abrasion, sediment changes, and localized land conversion.

**Table 1.** Summarizes the mangrove extent in hectares for each estuary in 2014 and 2024, along with absolute and percentage changes

| Estuary | Mangrove area 2014 (ha) | Mangrove area 2024 (ha) | Change (ha) | % change |
|---|---|---|---|---|
| Sriwulan | 56.11 | 29.72 | -26.39 | -47.03% |
| Pemali | 334.13 | 600.85 | 266.72 | 79.83% |
| Comal | 76.15 | 67.54 | -8.61 | -11.31% |
| Bodri | 41.87 | 41.20 | -0.66 | -1.59% |
| Cisanggarung | 197.99 | 98.98 | -99.01 | -50.00% |


Sriwulan, 2014
N
Legend:
🟥 : Mangrove Area
0 0.45 0.9 1.8 2.7 3.6 Kilometers
Sriwulan, 2024
N
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0 0.45 0.9 1.8 2.7 3.6 Kilometers
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Pamali, 2024
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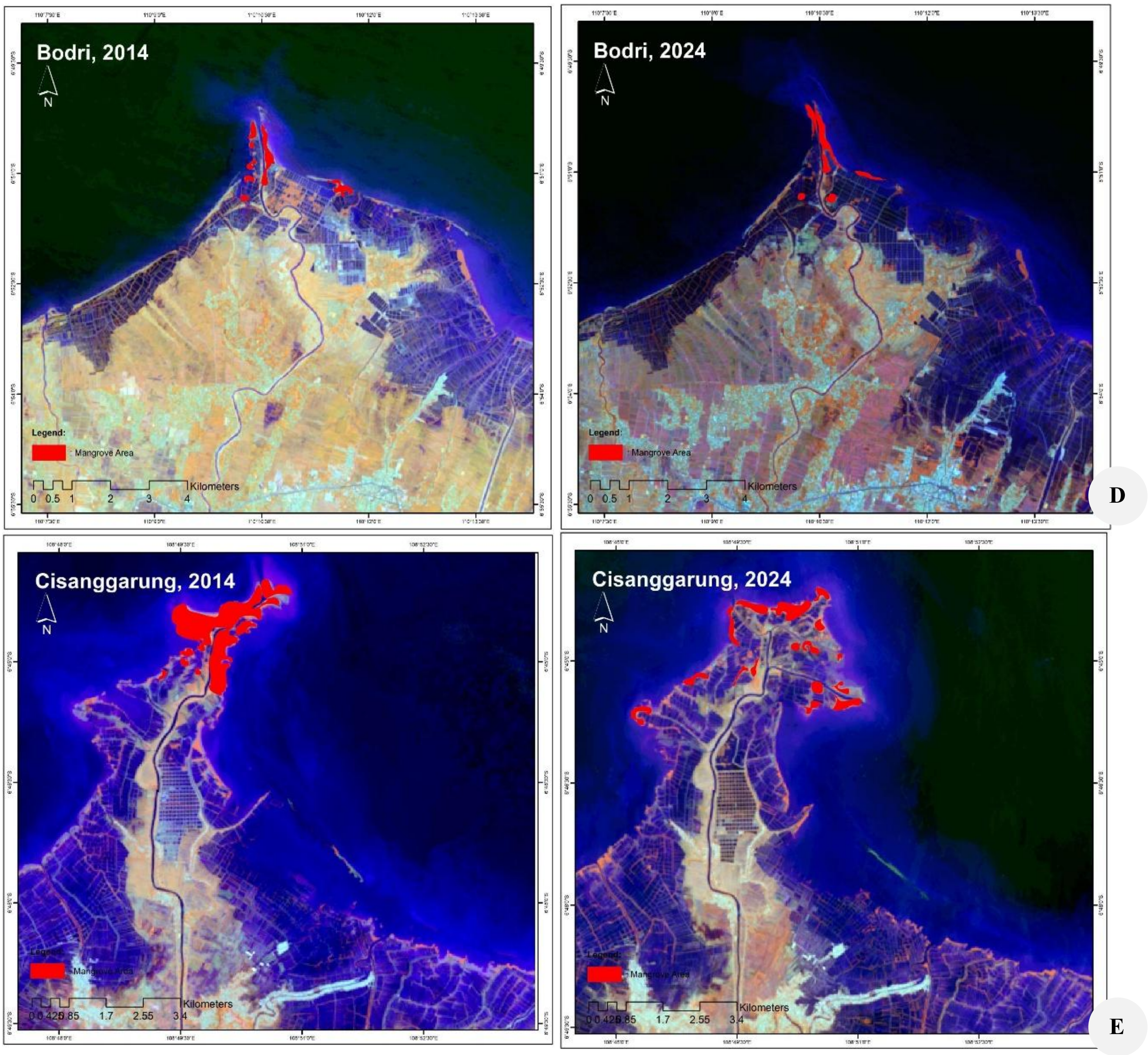

**Figure 2.** Detailed maps depicting spatial patterns of mangrove loss, gain, and stable areas between 2014 and 2024 for each estuary in the North Coast of Central Java, Indonesia: A. Sriwulan, B. Pemali, C. Comal, D. Bodri, and E. Cisanggarung

*Areas of mangrove gain*

In contrast, the Pemali Estuary demonstrated a substantial increase in mangrove cover, expanding by 266.72 hectares (79.83%). This gain is attributed to successful mangrove rehabilitation programs and natural sediment accretion, which facilitate mangrove establishment in newly formed land areas. This rapid increase may be attributed to accretion of new land along the delta front, as well as reoccupation of previously abandoned aquaculture zones, which were subsequently revegetated through assisted or natural regeneration.

*Stable mangrove zones*

Areas where mangrove cover remained relatively stable were identified primarily in the Bodri Estuary, with minimal losses, and in portions of the Comal Estuary where reforestation efforts have helped maintain existing mangrove stands. Table 2 summarizes the magnitude of mangrove loss, gain, and stable areas across the five estuaries, while Figure 3 visually represents these changes spatially.

## Estuary-specific mangrove dynamics

*Sriwulan Estuary*

The Sriwulan Estuary exhibited a significant reduction in mangrove cover, declining by 47.03% from 56.11 hectares in 2014 to 29.72 hectares in 2024. This loss was primarily associated with the expansion of residential and industrial areas and destructive crab fishing practices that damaged mangrove root structures. Field observations indicated poor survival rates of replanted mangrove seedlings, likely due to suboptimal planting periods and environmental stressors. The fragmented mangrove patches are increasingly vulnerable to erosion and habitat degradation (Figure 4.A).

*Pemali Estuary*

In contrast, the Pemali Estuary experienced a substantial increase in mangrove cover of 79.83%, expanding from 334.13 hectares to 600.85 hectares. This gain is largely attributed to effective community-led rehabilitation programs incorporating silvofishery techniques, which integrate sustainable aquaculture with mangrove conservation. Sediment deposition processes also contributed to the formation of new land suitable for mangrove colonization. The resultant mangrove expansion supports enhanced coastal protection and biodiversity values (Figure 4.B).

*Comal Estuary*

The Comal Estuary showed a moderate decline of 11.31%, with mangrove area decreasing from 76.15 hectares to 67.54 hectares. Key factors included river diversion works altering hydrodynamics, leading to sediment transport changes and localized erosion. Mangrove restoration efforts have been initiated, but survival rates remain low due to episodic flooding and salinity fluctuations. Patches of stable mangrove are mainly found in less disturbed zones near river mouths (Figure 4.C).

*Bodri Estuary*

Mangrove cover in the Bodri Estuary remained relatively stable, with a slight decrease of 1.59% (from 41.87 to 41.20 hectares). The estuary features active sediment accretion that supports mangrove persistence despite some conversion of marginal mangrove areas to salt ponds. The relatively continuous mangrove stands contribute to maintaining ecosystem services such as fish nursery habitats and shoreline stabilization (Figure 4.D). The minimal change detected in Bodri may also reflect the spatial scale and detection limits of the 30-meter Landsat resolution, which may underrepresent subtle changes or narrow regeneration zones along accreting riverbanks

*Cisanggarung Estuary*

The Cisanggarung Estuary suffered the most severe mangrove loss among the studied estuaries, with a 50% decline from 197.99 hectares to 98.98 hectares. The rapid conversion of newly formed deltaic land to aquaculture ponds and urban development drove this loss. Mangrove stands remaining along pond embankments are fragmented and susceptible to further degradation. The estuary represents a critical site for targeted conservation and sustainable land use planning (Figure 4.E).

**Validation and accuracy assessment results**

Validation of mangrove classification was performed by comparing satellite-based mapping results with ground truth data collected during field surveys and supplemented by photographic documentation. A total of 35 ground truth points were used across the five estuaries, representing a range of mangrove conditions, including dense, sparse, degraded, and rehabilitated areas.

The overall classification accuracy was estimated at 89%, with a Kappa coefficient of 0.86, indicating strong agreement between satellite classification and field observations. The user's accuracy for the mangrove class was 91%, while the producer's accuracy was 88%, demonstrating reliable detection of mangrove areas (Table 3).

Limitations in field data coverage, particularly in inaccessible or privately owned locations, introduced some uncertainty in accuracy estimates. Supplementary validation using publicly available images helped reduce this uncertainty, but could not entirely substitute for comprehensive ground truthing. These results support the robustness of the remote sensing approach used in this study for monitoring mangrove dynamics in the study area.

**Table 2.** Summary of mangrove loss, gain, and stable areas (hectares) in five estuaries between 2014 and 2024

| Estuary | Loss (ha) | Gain (ha) | Stable (ha) |
|---|---|---|---|
| Sriwulan | 26.39 | 0.00 | 29.72 |
| Pemali | 0.00 | 266.72 | 334.13 |
| Comal | 8.61 | 0.00 | 67.54 |
| Bodri | 0.66 | 0.00 | 41.20 |
| Cisanggarung | 99.01 | 0.00 | 98.98 |

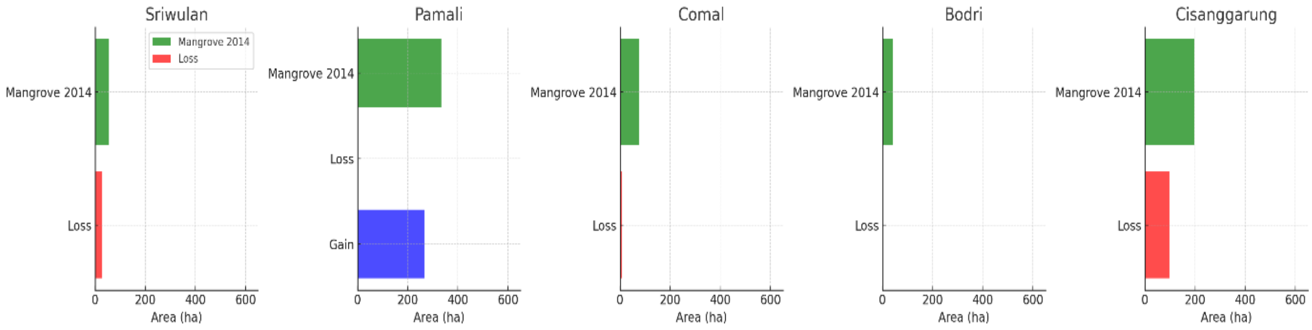

**Figure 3.** Visualization of mangrove cover change categories (loss, gain, and stable zones) across the five estuaries in the North Coast of Central Java, Indonesia, from 2014 to 2024

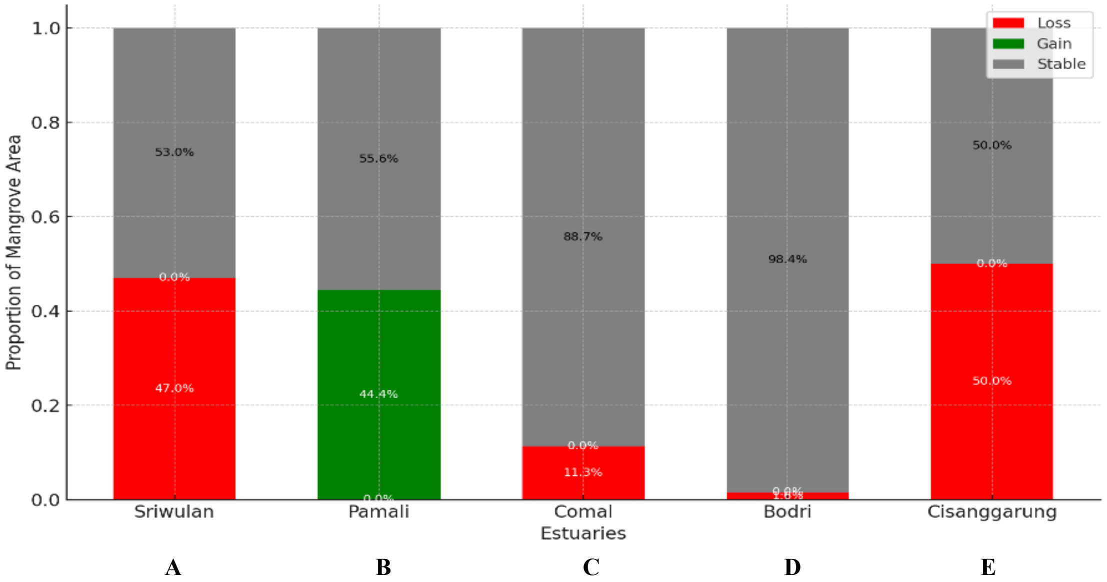

**Figure 4.** Estuary-specific mangrove cover change between 2014 and 2024 in the North Coast of Central Java, Indonesia: A. Sriwulan, B. Pemali, C. Comal, D. Bodri, and E. Cisanggarung estuaries

**Table 3.** Accuracy assessment metrics for mangrove classification in the five estuaries in the North Coast of Central Java, Indonesia

| Accuracy metric | Value (%) |
|---|---|
| Overall accuracy | 89 |
| Kappa coefficient | 0.86 |
| User's accuracy | 91 |
| Producer's accuracy | 88 |

### Summary of drivers behind mangrove changes

The analysis identified several key drivers influencing mangrove cover changes across the five estuaries. Anthropogenic factors such as land conversion for aquaculture ponds, urban expansion, and infrastructure development emerged as primary causes of mangrove loss in Sriwulan, Cisanggarung, Comal, and Bodri estuaries. These activities have led to habitat fragmentation and degradation, reducing mangrove extent and ecosystem function. In contrast, natural processes like sediment deposition and accretion played a positive role in mangrove expansion, particularly evident in the Pemali Estuary. Community-led rehabilitation initiatives, incorporating sustainable silvofishery techniques, have also contributed significantly to mangrove recovery in these estuaries.

Environmental stressors such as coastal erosion, changes in hydrology due to river diversion, and destructive fishing practices further impacted mangrove health and regeneration capacity in several estuaries. The interplay between socio-economic pressures and environmental dynamics underscores the complexity of mangrove ecosystem changes in Central Java. Effective conservation and management require integrating these drivers into adaptive strategies tailored to local conditions.

## Discussion

### *Interpretation of mangrove cover changes*

**Patterns of mangrove loss and gain.** The spatial and temporal analysis of mangrove cover from 2014 to 2024 reveals distinct patterns of loss and gain across the five estuaries studied. Overall, four estuaries—Sriwulan, Cisanggarung, Comal, and Bodri—experienced varying degrees of mangrove loss, whereas Pemali Estuary displayed a substantial gain. The losses ranged from minimal (1.59% in Bodri) to severe (50% in Cisanggarung), indicating differential vulnerability influenced by local environmental and anthropogenic factors (Figure 5).

Mangrove loss commonly manifests as fragmentation and ongoing reduction in forest area, often associated with land conversion for aquaculture ponds, urban development, and infrastructure expansion. Such fragmentation not only reduces habitat area but also impairs ecosystem connectivity and resilience, making mangrove forests more susceptible to environmental stressors.

Conversely, the substantial mangrove increases in Pemali Estuary, at nearly 80%, highlights the effectiveness of sediment deposition and successful rehabilitation initiatives. This increase contributed to increased mangrove continuity and expanded coastal protection functions. The presence of new mangrove stands on accreted deltaic land suggests favorable natural conditions synergized with human intervention.

**Estuary-specific drivers of change.** Each estuary exhibited unique drivers shaping mangrove dynamics over the study period:

Sriwulan Estuary: Rapid urbanization, industrial expansion, and destructive fishing methods, particularly crab harvesting, which damaged root systems, were the primary drivers of mangrove loss. Poorly timed and managed reforestation efforts further hampered natural regeneration.

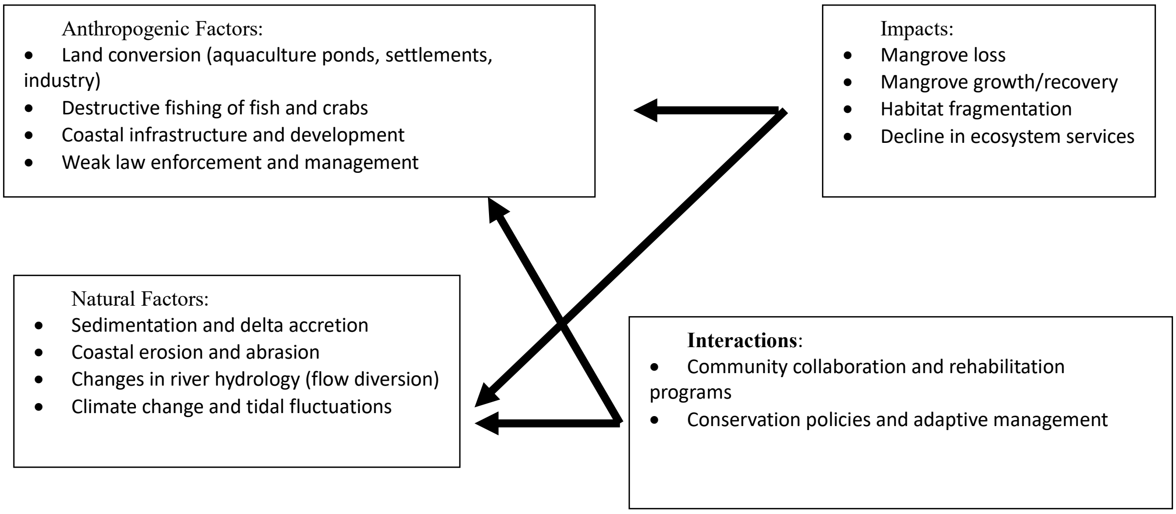

**Figure 5.** Conceptual diagram summarizing the main anthropogenic and natural drivers influencing mangrove cover changes in the five studied estuaries on the north coast of Central Java, Indonesia

Cisanggarung Estuary: Extensive conversion of deltaic land to aquaculture ponds and settlement development drove the most severe mangrove loss. Rapid land-use change on newly formed sediment posed challenges to sustainable mangrove conservation.

Comal Estuary: Alterations in river flow from diversion projects affected sediment distribution, leading to erosion and localized mangrove degradation. Flooding and salinity fluctuations limited seedling survival despite planting efforts.

Bodri Estuary: Despite active sediment accretion supporting mangrove persistence, marginal conversion to salt ponds caused minor declines. Stable mangrove areas benefit from geomorphological conditions but face encroachment pressures.

Pemali Estuary: Natural sedimentation processes combined with community-driven silvofishery rehabilitation programs facilitated substantial mangrove recovery. Sustainable integration of aquaculture and mangrove conservation has created a positive feedback loop promoting ecosystem resilience.

Understanding these estuary-specific drivers is essential for tailoring conservation and restoration strategies that effectively address local socio-environmental contexts. The interplay of natural and human-induced factors demands integrated management approaches to balance development and ecosystem sustainability.

### *Comparison with previous studies*

**Regional and national trends.** The mangrove cover changes observed in this study align with broader patterns documented throughout Central Java and Indonesia as a whole. Indonesia has been reported to experience significant mangrove loss, with annual deforestation rates estimated between 1% and 3% over recent decades, largely driven by coastal development, aquaculture expansion, and infrastructure projects (Kusmana 2015; Richards and Friess 2016). The severe losses identified in Sriwulan and Cisanggarung estuaries exceed these national averages, underscoring localized hotspots of intense anthropogenic pressure.

At the regional scale, studies in Java and neighboring islands have similarly reported high rates of mangrove degradation linked to population growth and economic activities (Damastuti and de Groot 2017; Fikriyya et al. 2023). However, pockets of mangrove recovery, as seen in the Pemali Estuary, reflect the growing effectiveness of community-based rehabilitation and sustainable aquaculture practices. These findings corroborate regional efforts to restore mangrove ecosystems while supporting livelihoods.

**Global mangrove dynamics.** Globally, mangrove ecosystems have undergone dramatic declines in the past century, with approximately one-third of the world's mangroves lost due to deforestation and land conversion (Hamilton and Casey 2016; Friess et al. 2020). Southeast Asia remains a critical hotspot, accounting for a substantial share of this loss. However, recent studies indicate a slow reversal trend in some areas due to improved conservation policies and restoration initiatives.

The contrasting trajectories within this study's five estuaries mirror global patterns of simultaneous loss and gain, driven by a complex mix of natural processes and human interventions (Kuenzer et al. 2011; Alongi 2015). The significant gains in the Pemali Estuary exemplify successful rehabilitation models that have been replicated in other tropical regions, highlighting the potential for recovery under appropriate management. These comparisons emphasize the importance of spatially explicit, long-term monitoring to capture dynamic mangrove changes and inform adaptive management strategies worldwide.

### *Implications for conservation and management*

**Effectiveness of rehabilitation programs.** The marked increase in mangrove cover observed in the Pemali Estuary highlights the potential success of well-implemented rehabilitation programs. Community-led silvofishery practices, which integrate sustainable aquaculture with mangrove restoration, have proven effective in promoting natural regeneration and increasing forest resilience. These initiatives illustrate how combining ecological restoration with livelihood enhancement can achieve conservation goals while supporting local economies. However, the limited success in other estuaries, such as Sriwulan and Comal, suggests that rehabilitation efforts require careful timing, species selection, and ongoing maintenance to overcome environmental challenges.

**Role of community participation.** Community involvement emerged as a critical factor influencing mangrove conservation outcomes. In Pemali, the active participation of local stakeholders in planning and managing rehabilitation efforts contributed to improved survival rates and sustainable resource use. Conversely, a lack of community engagement in areas with mangrove decline often correlates with continued degradation and ineffective enforcement of protection measures. Empowering local communities through education, capacity building, and incentives is essential to foster stewardship and long-term conservation success.

**Policy and regulatory considerations.** Effective mangrove management also depends on robust policy frameworks and regulatory enforcement. The varying degrees of mangrove loss and gain observed among estuaries underscore the importance of coherent land use planning and strict adherence to conservation regulations. Policies facilitating integrated coastal zone management, including habitat protection, sustainable aquaculture zoning, and environmental impact assessments, can mitigate pressures on mangrove ecosystems. Strengthening institutional coordination and monitoring mechanisms is necessary to address illegal encroachment and ensure compliance.

### *Methodological considerations*

**Strengths and limitations of remote sensing approach.** The use of Landsat 8 satellite imagery and Google Earth Engine provided an efficient and cost-effective means of assessing mangrove dynamics across multiple estuaries over a decade. The multispectral bands selected allowed for reliable discrimination of mangrove vegetation from other land covers, and the temporal availability of data supported consistent change detection. However, the moderate spatial resolution (30 m) of Landsat imagery may limit detection of small-scale changes, edge effects, or sparse mangrove stands. Manual digitization helped address some classification ambiguities but introduced potential subjectivity.

**Validation and accuracy challenges.** Field validation strengthened confidence in the classification results, yet was constrained by limited accessibility to some sites and the relatively small number of ground truth points. Supplementary use of publicly available imagery helped mitigate these limitations, but cannot fully replace comprehensive field surveys. Temporal mismatches between satellite acquisition and field visits may also affect validation accuracy. Future studies could incorporate higher-resolution imagery (e.g., Sentinel-2, UAV data) and expand field sampling to enhance precision and robustness. Additionally, small-scale mangrove regrowth—particularly scattered seedlings or narrow fringe restoration areas—may not have been captured as 'gain' due to the spatial resolution limits of Landsat imagery or conservative classification criteria

**Recommendations for future research and practice.** Based on the findings and methodological insights of this study, several recommendations are proposed to strengthen mangrove conservation and research in Central Java and similar tropical coastal areas. Future studies should utilize higher-resolution remote sensing data (e.g., Sentinel-2 or UAVs) to capture fine-scale changes, and expand field validation efforts through systematic ground-truth sampling to enhance classification accuracy. Integrating socio-economic data and local stakeholder perspectives is essential to understand the drivers of change and support more holistic management. Conservation efforts should prioritize community engagement, capacity building, and sustainable livelihoods to ensure long-term success. Additionally, adaptive management strategies informed by ongoing monitoring are needed to respond to emerging challenges. Policymakers must reinforce coastal management policies, enforce environmental regulations, and promote multi-stakeholder collaboration to balance development with ecological preservation.

In conclusion, this study provides a comprehensive assessment of mangrove cover changes between 2014 and 2024 across five estuaries on the north coast of Central Java, Indonesia. This study reveals contrasting dynamics, with significant mangrove losses in Sriwulan, Cisanggarung, Comal, and Bodri estuaries, and a substantial gain in the Pemali Estuary driven by effective rehabilitation and natural sedimentation. These patterns reflect the complex interactions between anthropogenic pressures, environmental processes, and community engagement shaping mangrove ecosystems. The high rates of mangrove loss in some estuaries highlight urgent needs for strengthened conservation efforts, improved land use planning, and enforcement of protective regulations. Conversely, the success in Pemali underscores the value of integrated restoration approaches that combine ecological and socio-economic dimensions. Remote sensing proved a valuable tool for monitoring spatial and temporal mangrove changes, although it requires complementary ground validation to enhance accuracy. Future efforts should prioritize multi-scale monitoring, stakeholder involvement, and adaptive management to ensure the sustainability of these vital coastal ecosystems. This study contributes important insights for policymakers, conservation practitioners, and researchers working towards balancing coastal development and mangrove preservation in Indonesia and similar tropical regions worldwide.

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## REFERENCES

Alongi DM. 2015. The impact of climate change on mangrove forests. Curr Clim Change Rep 1: 30-39. DOI: 10.1007/s40641-015-0002-x.

Anu K, Henna Parveen K, Sneha VK, Busheera P, Muhammed J, Augustine A. 2024. Mangroves in environmental engineering: Harnessing the multifunctional potential of nature's coastal architects for sustainable ecosystem management. Results Eng 21: 101765. DOI: 10.1016/j.rineng.2024.101765.

As-Syakur AR, Aryunisha PEP, Wijana IMS, Novanda IGA, Dewi IGAIP, Andiani AAE, Premananda MG, Sugiana IP. 2023. Comparison of mangrove canopy covering accuracy using landsat 8 and landsat 9 imagery based on several vegetation indices in West Bali National Park. E3S Web Conf 442: 03001. DOI: 10.1051/e3sconf/202344203001.

Basyuni M, Sasmito SD, Analuddin K, Ulqodry TZ, Saragi-Sasmito MF, Eddy S, Milantara N. 2022. Mangrove biodiversity, conservation and roles for livelihoods in Indonesia. In: Das SC, Pullaiah, Ashton EC (eds). Mangroves: Biodiversity, Livelihoods and Conservation. Springer, Singapore. DOI: 10.1007/978-981-19-0519-3_16.

Chen Q, Li J, Zhao Q, Jian S, Ren H. 2018. Changes in the benthic protozoan community during succession of a mangrove ecosystem in Zhanjiang, China. Ecosphere 9 (4): e02190. DOI: 10.1002/ecs2.2190.

Damastuti E, de Groot R. 2017. Effectiveness of community-based mangrove management for sustainable resource use and livelihood support: A case study of four villages in Central Java, Indonesia. J Environ Manag 203 (Part 1): 510-521. DOI: 10.1016/j.jenvman.2017.07.025.

Fikriyya N, Putri AK, Silalahi M. 2023. Riparian vegetation diversity of the Banjaran River, Banyumas Regency, Central Java. Buletin Kebun Raya 26 (3): 126-139. DOI: 10.55981/bkr.2023.2443. [Indonesian]

Friess DA, Rogers K, Lovelock CE, Krauss KW, Hamilton SE, Lee SY, Lucas R, Primavera J, Rajkaran A, Shi S. 2019. The state of the world's mangrove forests: Past, present, and future. Ann Rev Environ Resour 44: 89-115. DOI: 10.1146/annurev-environ-101718-033302.

Friess DA, Yando ES, Abuchahla GMO et al. 2020. Mangroves give cause for conservation optimism, for now. Curr Biol 30 (4): R153-R154. DOI: 10.1016/j.cub.2019.12.054.

Godoy MD, de Lacerda LD. 2015. Mangroves response to climate change: A review of recent findings on mangrove extension and distribution. An Acad Bras Cienc 87: 651-667. DOI: 10.1590/0001-3765201520150055.

Hamilton SE, Casey D. 2016. Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). Glob Ecol Biogeogr 25 (6): 729-738. DOI: 10.1111/geb.12449.

Kuenzer C, Bluemel A, Gebhardt S, Quoc TV, Dech S. 2011. Remote sensing of mangrove ecosystems: A review. Remote Sens 3 (5): 878-928. DOI: 10.3390/rs3050878.

Kusmana C. 2015. Pengelolaan hutan mangrove yang berkelanjutan dan terintegrasi. J Pengelolaan Sumberdaya Alam dan Lingkungan 5 (1): 1-6. DOI: 10.29244/jpsl.5.1.1. [Indonesian]

Nagelkerken I, Blaber SJM, Bouillon S, Green P, Haywood M, Kirton LG, Meynecke J-O, Pawlik J, Penrose HM, Sasekumar A, Somerfield PJ. 2008. The habitat function of mangroves for terrestrial and marine fauna: A review. Aquat Bot 89 (2): 155-185. DOI: 10.1016/j.aquabot.2007.12.007.

Pham T-D, Yoshino K. 2015. Mangrove mapping and change detection using multi-temporal Landsat imagery in Hai Phong City, Vietnam. In: The International Symposium on Cartography in Internet and Ubiquitous Environments 2015. Tokyo, Japan.

Richards DR, Friess DA. 2016. Rates and drivers of mangrove deforestation in Southeast Asia, 2000-2012. Proc Natl Acad Sci 113 (2): 344-349. DOI: 10.1073/pnas.1510272113.

Sanderman J, Hengl T, Fiske G et al. 2018. A global map of mangrove forest soil carbon at 30 m spatial resolution. Environ Res Lett 13 (5): 055002. DOI: 10.1088/1748-9326/aabe1c.