DOI: 10.2478/cjf-2026-0008
CODEN RIBAEG ISSN 1330-061X (print)
1848-0586 (online)

THE ROLE OF MANGROVE DENSITY IN MARINE DEBRIS TRAPPING: A CASE STUDY OF BAROS COAST, YOGYAKARTA, INDONESIA

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ARTICLE INFO

Received: 4 November 2025
Accepted: 6 March 2026

Keywords:
Avicennia sp.,
Plastic pollution
Coastal ecosystems
PCA
Respiratory root

ABSTRACT

The increase in plastic production has led to a significant accumulation of plastic debris in the environment, particularly in coastal and marine ecosystems. This study aims to characterize the composition and quantify the abundance of marine debris, identify specific plastic polymers, and assess the statistical relationship between mangrove density and marine debris accumulation. Marine debris samples were collected at six sites, divided between the west and east sides of the mangrove ecosystem. The results showed that on the west side, Site 1 had the highest abundance of marine debris (1.2 items/m²), whereas on the east side, Site 3 recorded the highest abundance (0.88 items/m²). The most dominant types of marine debris were thin plastic, packaging, and glass, with a total weight of approximately 434 g at Site 3 on the west side. Analysis of plastic debris showed that polypropylene (PP) dominated on the west side at about 44.44%, while polyethylene (PE) dominated on the east side at about 55.56%. The density of mangroves, especially *Avicennia* sp., plays a vital role in trapping marine debris through their respiratory roots. A higher amount of marine debris was identified on the west side, which corresponds with higher mangrove density. PCA analysis showed a strong positive correlation between mangrove density, specifically the respiratory roots of *Avicennia* sp., and marine debris accumulation, identifying these roots as the primary factor influencing debris trapping.

How to Cite

Sulistiowati, S., Adharini, R.I., Prihatiningtyastuti, E., Manan, H. (2026): The role of mangrove density in marine debris trapping: a case study of Baros Coast, Yogyakarta, Indonesia. Croatian Journal of Fisheries, 84, 83-90. DOI: 10.2478/cjf-2026-0008.

INTRODUCTION

The increase in plastic production has led to an increase in the accumulation of plastic waste in the environment. The primary sources of plastic pollution include household products, industrial leaks, transportation, construction, daily activities, maritime activities, and waste management and recycling (Dalu et al., 2021; Scopetani et al., 2021; Mengatto and Nagai, 2022). Plastic has advantages such as durability, strength, and low cost; however, the lack of sustainable use and efficient waste management has led to a significant accumulation of plastic waste (Firdousie et al., 2021). Over the past few decades, marine ecosystems in Indonesia have been under significant anthropogenic pressure due to rapid human population growth, leading to increased water pollution (Adyasari et al., 2021). According to Hodson et al. (2017), around 54% of anthropogenic waste has entered the environment, with plastic being one of the most significant pollutants in coastal areas. The spread of plastic in the environment results from single-use plastics, poor plastic waste management, and low biodegradability (Pehlivan and Gedik, 2021). This urgent issue of plastic waste is now a major environmental concern (Kurtela and Antolović, 2019).

Mangrove ecosystems, among the most vulnerable to continuous plastic exposure from human activities (Bayen, 2012), have become sites of plastic waste accumulation from both marine and terrestrial sources (Deng et al., 2021). While the general presence of plastic in mangroves is well-documented, there is still a lack of specific quantitative evidence on how the structural complexity and density of mangrove vegetation, specifically in the unique hydrological context of the Southern Coast of Java, influence the efficiency of debris trapping mechanisms. Most existing studies focus on broad debris distribution or chemical impacts, but few provide high-resolution analysis of the correlation between specific vegetation metrics (such as density and root morphology) and the accumulation of plastic polymers like polypropylene and polyethylene in micro-locations such as the Baros Coast.

This study is crucial because Baros Beach serves as a vital ecological buffer for the Yogyakarta coastal area, being the only extensive mangrove ecosystem. Understanding the waste-capturing capacity of mangrove forests is crucial to prevent plastic waste from reaching more sensitive downstream ecosystems, such as coral reefs, where it can cause fatal bleaching and necrosis (Mueller et al., 2022). Furthermore, providing site-specific data on waste characteristics will assist local government in developing targeted waste mitigation strategies and increasing the effectiveness of mangrove conservation as a natural biofilter. Therefore, the objectives of this research include identifying the types of marine debris, quantifying the abundance of marine debris, analyzing the characteristics of plastic polymers, and examining the quantitative relationship between mangrove density and marine debris accumulation on the Baros Coast, Yogyakarta, Indonesia.

MATERIALS AND METHODS

The study was conducted in the mangrove ecosystem of Baros Beach, Yogyakarta, Indonesia (Fig. 1). The research location is known for tourism and is situated in the mangrove and beach ecosystems. Baros Beach separates the mangrove ecosystem, dividing it into the west and east sides. The sampling sites were divided into 3 locations on the west side and 3 locations on the east side. This tourism site was managed by a group that cleaned up garbage in the coastal area. However, no cleaning was carried out in the mangrove ecosystem, resulting in a large amount of garbage piling up in the mangrove area. Unlike typical mangrove ecosystems, the mangrove ecosystem at this location has sandy sediment mixed with dry, fine particles. No muddy, waterlogged areas were observed.

The quadrat transect was laid perpendicular to the coast, as shown in Fig. 2, with a size of 10 m x 10 m to observe trees (θ tree > 10 cm). The data recorded were the tree species, number of trees, tree height, and tree diameter. If a tree had more than one branch with a height of 1.2 m, the branches were counted as individual trees. The quadrat transect size used was 5 m × 5 m. For the type of sapling (4 cm < θ sapling < 10 cm), the transect used was 10 m × 10 m. The data recorded were the number of trees, tree diameter, and tree species. A quadrat transect of 1 m × 1 m was applied within a 5 m × 5 m transect for seedlings (θ seedling < 4 cm), and the number of seedlings and species were counted. Density was calculated using the following formula:

$$\text{Density} = \sum \text{Individu} / \text{plot area}$$

Marine debris collection was carried out at the front and back areas of the beach, as well as in mangroves with different composition types. Observation of marine debris followed the method of Cozzolino et al. (2020), using quadrat transects measuring 5 m × 5 m (25 m^2). Sampling was carried out under specific tidal conditions (this mangrove area is rarely submerged and barren). All samples were collected from the transects, washed, dried, and weighed. Marine debris types were categorized into eight categories: polymer artificial (plastic), rubber, cloth, paper, wood, iron, ceramic or glass, and unidentified goods. The polymer type of plastic was analysed using Fourier Transform Infrared Spectroscopy, Attenuated Total Reflectance (FTIR ATR). The collected marine debris was categorized into two sources: household sources and fishing activities. Household sources include diapers, food wrappers, plastic wrappers, plastic bags, thin plastic, toys, cosmetics, and bottles. The fishery source plastics include ropes, fishing lines, fishing rods, and styrofoam.

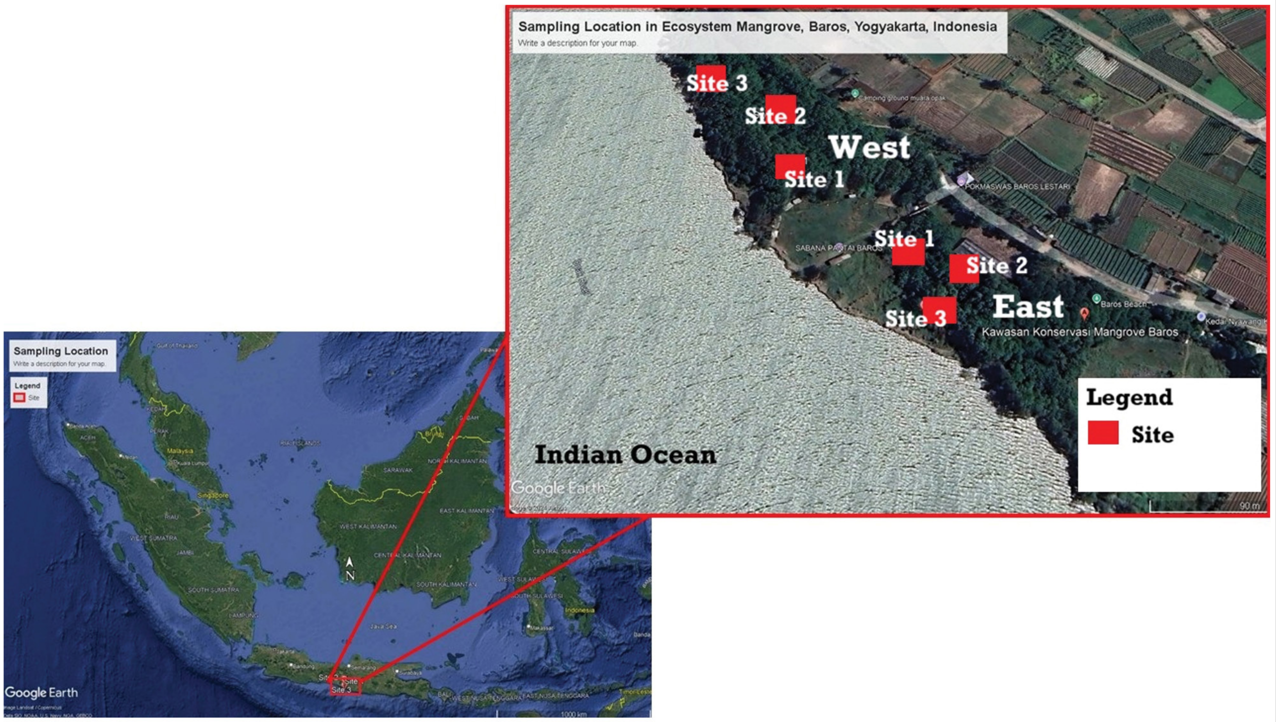

Fig 1. Sampling location in the Baros Coast mangrove ecosystem

Data interpretation was conducted using Microsoft Excel. Calculations for the analysis of mangrove vegetation were also carried out using Microsoft Excel. The relationship between mangrove density and the abundance of marine debris was analyzed using Origin software with Principal Component Analysis (PCA).

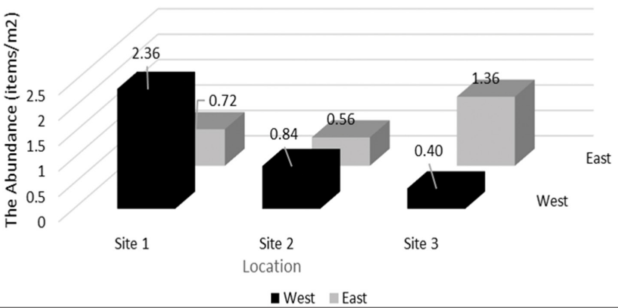

Fig 2. The abundance of marine debris in the mangrove ecosystem, Baros, Yogyakarta, Indonesia

RESULTS AND DISCUSSION

Based on the results from Site 1 on the west side, several types of marine debris were identified, showing variations in both quantity and weight. Packaging waste was the most common type, with 23 items weighing 151 g. The second most frequent type was thin plastic, with 16 items weighing 214 g. Notably, glass waste contributed significantly to the total weight; although only two items were identified, they weighed approximately 296 g, making glass the heaviest category of debris. Other identified marine debris included straws (3 items, 3 g), bags (1 item, 14 g), plastic bags (2 items, 22 g), styrofoam (2 items, 29 g), syringe components (1 item, 14 g), thick plastic (2 items, 19 g), and sandals (1 item, 18 g) (Table 1).

Table 1. Number of marine debris items found in the mangrove ecosystem in Baros on the west side of Site 1

Types of marine debris	Quantity (items)	Weight (g)
Packaging	23	151
Thin plastic	16	214
Straw	3	3
Bag	1	14
Plastic bag	2	22
Styrofoam	2	29
Glass	6	220
Syringe	1	14
Thick plastic	2	19
Sandal	1	18
Glass	2	296

At Site 2 on the west side, diverse types of marine debris were identified with varying quantities and weights (Table 2).

Table 2. The number of marine debris items identified in the mangrove ecosystem in Baros on the west side of Site 2

Types of marine debris	Quantity (items)	Weight (g)
Packaging	5	54
Plastic bag	1	28
Styrofoam	2	25
Thin plastic	6	16
Shoe	6	271
Face mask	1	12

Shoes were the heaviest category of debris, contributing significantly to the total weight (271 g) despite having a relatively low frequency (6 items). The most frequently identified debris was thin plastic (6 items), weighing approximately 16 g. In addition, packaging waste was also prevalent, with 5 items weighing 54 g. Although plastic bags and styrofoam were identified in small quantities (1 or 2 items, respectively), they contributed notable weights of 28 g and 25 g. Furthermore, one medical mask was identified, weighing approximately 12 g, indicating the presence of medical waste at this location. These data show that while some types of debris are more common, items with higher individual weights, such as shoes, contribute more substantially to the total biomass of marine debris at this site.

At Site 3 on the west side, the most dominant marine debris identified was thin plastic, with 3 items of a total weight of 434 g, making it the heaviest type of marine debris at this location (Table 3). In addition, three plastic bags were identified with a total weight of 287 g, indicating a significant volume and weight. One bottle weighing 209 g also contributed significantly to the total weight of marine debris at this site. Other types of marine debris identified were one item of packaging weighing 43 g, one item of thick plastic weighing 32 g, and one item of lightweight styrofoam weighing only 3 g.

Table 3. The number of marine debris items identified in the mangrove ecosystem in Baros on the west side of Site 3

Types of marine debris	Quantity (items)	Weight (g)
Crackle	3	287
Packaging	1	43
Thin plastic	3	434
Bottle	1	209
Styrofoam	1	3
Thick plastic	1	32

In the study conducted on the west side at three sites, lot of variations were identified in the types and numbers of marine debris. At Site 1, packaging waste dominated in terms of quantity, while glass had the highest weight. Thin plastic was also a significant type of marine debris in both quantity and weight. At Site 2, shoe waste had the highest weight, although found in small numbers, while thin plastic and packaging were also found in large numbers. At Site 3, thin plastic waste dominated in weight, followed by plastic bags and bottles, which also contributed significantly to the total weight of the waste. Overall, thin plastics and plastic bags dominated in both quantity and weight. However, larger and heavier types of marine debris, such as glass and shoes, contributed significantly to the total weight, although identified in smaller quantities.

All marine debris identified on the west side originated from land-based anthropogenic activities; no evidence of debris from marine-based activities was observed. The discovery of a syringe at Site 1 suggests potential inadequacies in hospital waste management. However, this does not exclude the possibility that these items were discarded by individuals rather than a healthcare facility. These findings align with Kesavan et al. (2021), who state that the primary source of marine debris in mangrove ecosystems is land-based.

Based on the data collected on the types of marine debris on the east side, plastic packaging was identified as the most dominant type of marine debris, with a total of 143 g (Table 4). Packaging materials were the most prominent marine debris type by weight, which accounted for 143 g across 5 items, indicating a significant contribution to the overall mass of marine debris. Styrofoam, also represented by 5 items, contributed only 13 g, reflecting its much lighter composition. Glass waste was represented by a single item with a weight of 16 g, while other smaller marine debris items included straws, spoons, and matches, contributing 6 g, 5 g, and 9 g, respectively.

Table 4. The number of marine debris items identified in the mangrove ecosystem in Baros on the east side of Site 1

Types of marine debris	Quantity (items)	Weight (g)
Packaging	5	143
Glass	1	16
Straw	2	6
Spoon	2	5
Match	1	9
Thick plastic	1	10
Rope	1	3
Styrofoam	5	13

Notably, thick plastic and rope contributed 10 g and 3 g, respectively.

The types of marine debris on the east side of the site indicate a diverse composition of waste collected at the study site, varying in both quantity and weight. The heaviest contributor was a single bag weighing 315 g, followed by glass (2 items totaling 210 g) and rubber (1 item at 151 g) (Table 5). Straws, although represented by only 1 item, contributed 98 g, highlighting that even small quantities can significantly add to the overall weight. Packaging materials (10 items) weighed 53 g, while styrofoam (12 items) weighed 50 g, showing that even with a larger quantity, lighter materials had a smaller weight impact. Other types of marine debris included sandals (24 g), thin plastic (2 items at 12 g), pampers (12 g), thick plastic (20 g), and bottle caps (2 items at 18 g). This variation in marine debris types and their contributions underscores the need for tailored waste management strategies that address both the heaviest and most prevalent materials.

Table 5. The number of marine debris items identified in the mangrove ecosystem in Baros on the east side of Site 2

Types of marine debris	Quantity (items)	Weight (g)
Straw	1	98
Packaging	10	53
Sandal	1	24
Thin plastic	2	12
Pampers	1	12
Styrofoam	12	50
Rubber	1	151
Bottle cap	2	18
Thick plastic	1	20
Glass	2	210
Bag	1	315

The type of marine debris identified on the east side at Site 3 is shown in Table 6. The results of this study indicated a range of waste types collected at the study site, differing in quantity and weight. Glass waste, consisting of 2 items, was the heaviest category, contributing 30 g. Packaging materials accounted for 6 items, with a total weight of 27 g. Thick plastic followed, with a single item weighing 12 g. In contrast, thin plastic (2 items) and straws (2 items) contributed 9 g and 3 g, respectively, while styrofoam, despite its lightweight nature, contributed only 2 g with a single item. The variation in marine debris types and their differing weights suggests a mix of materials, emphasizing the importance of targeted strategies for handling both heavier items, such as glass, and more common but lighter materials, such as packaging and styrofoam.

Table 6. The number of marine debris items in the mangrove ecosystem in Baros on the west side of Site 3

Types of marine debris	Quantity (items)	Weight (g)
Packaging	6	27
Thin plastic	2	9
Straw	2	3
Glass	2	30
Thick plastic	1	12
Styrofoam	1	2

The comparison of the three datasets on the east side reveals differences in marine debris composition. Table 5 records the heaviest items, including bags (315 g) and glass (210 g), making it the most weight-dominated set. In Table 4, packaging waste was identified as a significant contributor with 143 g across 5 items, while in Table 6, the weights were generally lighter, with glass (30 g) being the heaviest. Common items like styrofoam and packaging also varied, with styrofoam varying greatly in its weight impact (from 2 g in Table 6 to 50 g in Table 5). Straws and thin plastic also vary in their weight contributions, showing how different types of marine debris contribute to the overall marine debris profile. This variability highlights the importance of targeted waste management strategies that address both heavier and lighter materials. Marine debris identified on the east side originated predominantly from land-based anthropogenic activities. However, in contrast to the west side, ropes were also discovered, indicating the presence of debris derived from marine-based activities. The frequent occurrence of ropes is common in mangrove ecosystems near maritime operations, where such materials are extensively used. These findings are consistent with previous studies, which also documented the presence of marine-derived debris in similar environments (Kesavan et al., 2021).

The abundance of marine debris trapped in the mangrove ecosystem is shown in Fig. 2. On the west side, the highest abundance was identified at Site 1, while on the east side, the highest abundance was identified at Site 3. The average abundance of marine debris on the west side was 1.2 items/m^2, while the east side had a lower abundance of 0.88 items/m^2. A previous study by Fong et al. (2023) found that marine debris in the mangrove ecosystem in Singapore ranged from 0.37 to 2.57 items/m^2. The abundance of marine debris in the mangrove ecosystem in Grande de Santa Marta, Colombia reached about 0.05 items/m^2 (Garcés-Ordóñez et al., 2019), while in the Pujada Bay mangrove ecosystem, Philippines, the marine debris was about 0.04 items/m^2 (Abreo et al., 2021). In this study, the abundance of mangroves on the west side was high, resulting in more marine debris being trapped in the pneumatophores of *Avicennia* sp. Research by Martin et al. (2019) also identified significant amounts of waste trapped in the roots of *Avicennia* sp. The numerous upward-extending roots of *Avicennia* sp. were found to trap large amounts of marine debris. The respiratory roots of *Avicennia* sp. are finger-shaped, erect vertically, and measure 30-40 cm (Martin et al., 2019; Hao et al., 2021).

Based on the percentage data of marine debris polymers on the west and east sides, significant differences existed in the distribution of polymer types identified at both locations. On the west side, polypropylene (PP) dominated at 44.44%, followed by polyethylene (PE) at 33.33% and polystyrene (PS) at 22.22%. Meanwhile, on the east side, the dominant plastic polymer changed, with PE becoming the most dominant at 55.56% (Fig. 3). In comparison, PP dropped sharply to 22.22%, equal to the percentage of PS, which also reached 22.22%.

This comparison shows that the west side was more dominated by PP polymer, while the east side had a higher dominance of PE. PS polymer showed the same consistency at both sites, each with a percentage of 22.22%. This reflects variation in the distribution of plastic polymers at both locations, which may be caused by differences in sources or local environmental factors that affect the distribution of plastics.

The presence of these three plastic polymers within the mangrove ecosystem has also been documented by Li et al. (2019). However, in contrast to our findings, Li et al. (2019) reported these polymers as microplastics. The macro-debris identified in this study also has the potential to fragment into microplastics through environmental degradation processes.

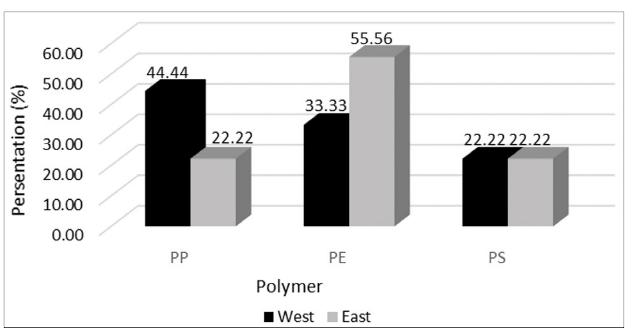

Fig 3. Marine debris polymer in the mangrove ecosystem, Baros, Yogyakarta, Indonesia

The multivariate relationship between mangrove structural parameters and marine debris accumulation was further elucidated using Principal Component Analysis (PCA). The analysis identified two primary components that explain a cumulative variance of 100%, PC1 explaining 90.80% (eigenvalue = 1.81) and PC2 explaining 9.20% (eigenvalue = 0.18). These results indicate a robust correlation between mangrove density and marine debris.

The PCA biplot categorized the study areas into two distinct groups, labeled as P1 and P2 (Fig. 4). Group P1 represents the east side, where A3 showed the most distinct grouping. In contrast, Group P2 represents the west side of Baros Beach, specifically A1 and A2. This group is closely associated with variables A1–A2 (marine debris abundance) and D1–D3 (mangrove density). The spatial distribution of the PCA scores suggests that the west side is significantly more efficient in trapping marine debris due to its higher mangrove density compared to the east side.

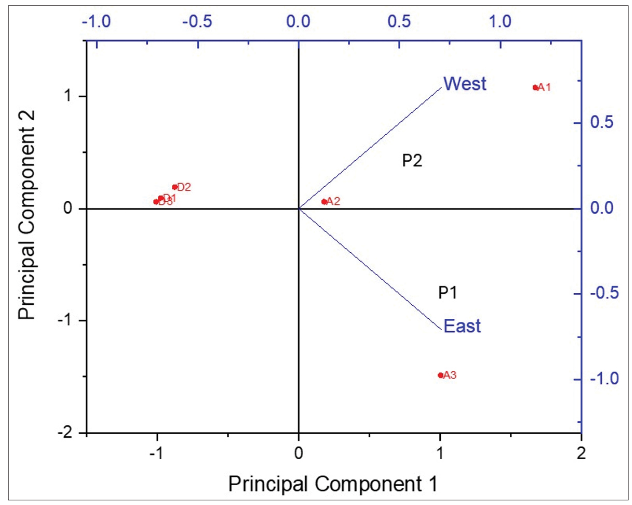

Fig 4. PCA analysis between mangrove density and the abundance of marine debris (A1: abundance of marine debris at Site 1; A2: abundance of marine debris at Site 2; A3: abundance of marine debris at Site 3; D1: mangrove density at Site 1; D2: mangrove density at Site 2; D3: mangrove density at Site 3)

The high abundance of debris on the west side is ecologically linked to the dominance of *Avicennia* sp., which is characterized by its complex pneumatophores (respiratory roots). These numerous roots extend vertically from the substrate and function as a mechanical sieve or physical barrier, impeding the movement of debris carried by tidal currents. This finding is consistent with studies by Lonard et al. (2017) and Ray et al. (2021), which found that the structural complexity of *Avicennia* sp. allowed it to accumulate significantly more material, including anthropogenic waste, compared to other mangrove species with less complex root architectures.

CONCLUSION

The composition of marine debris varied significantly between the west and east sides. Marine debris on the west side originated exclusively from land-based anthropogenic activities, whereas the east side received input from both land-based and marine-based activities. The highest debris abundance was recorded at Site 1 on the west side and Site 3 on the east side. Three types of polymers were identified throughout the study area: polypropylene (PP), polyethylene (PE), and polystyrene (PS). Plastic composition analysis revealed that polypropylene (PP) was the dominant polymer on the west side, while polyethylene (PE) predominated on the east side. The mangrove ecosystem at Baros Beach, Yogyakarta plays a vital role in trapping marine debris, mainly plastic. An abundance of debris was identified in areas with greater mangrove density, such as the west side dominated by *Avicennia* sp. The most common types of debris identified were thin plastic, plastic packaging, and glass with polypropylene (PP) and polyethylene (PE) as the most dominant plastic polymers on the west and east sides, respectively. PCA analysis showed a positive correlation between mangrove density and marine debris accumulation. This highlights the importance of mangrove conservation and management in reducing the impact of plastic pollution in coastal areas in the years to come.

ACKNOWLEDGEMENT

The author would like to express special gratitude to Universitas Gadjah Mada for funding this research project. The main author, Sulistiowati, received an excellent C academic research grant titled **Abundance and characteristics of marine debris in the coastal mangrove ecosystem of the southern coast**, with contract number 4481 / UN1 / DITLIT / PT.01.03 / 2024.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analysed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

ULOGA GUSTOĆE MANGROVA U ZADRŽAVANJU MORSKOG OTPADA NA OBALI BAROS, YOGYAKARTA, INDONEZIJA

SAŽETAK

Povećanje proizvodnje plastike dovelo je do značajnog nakupljanja plastičnog otpada u okolišu, posebno u obalnim i morskim ekosustavima. Cilj ovog istraživanja je utvrditi količinu morskog otpada u ekosustavu mangrova na plaži Baros, Yogyakarta, Indonezija, te analizirati karakteristike akumuliranog morskog otpada i njegov odnos s vegetacijom mangrova. Prikupljanje morskog otpada provedeno je na šest lokacija podijeljenih na zapadnu i istočnu stranu ekosustava mangrova. Rezultati su pokazali da je na zapadnoj strani lokacija 1 imala najveću količinu morskog otpada s prosjekom od 1,2 komada/m², dok je na istočnoj strani lokacija 3 imala najveću količinu s 0,88 komada/m². Najdominantnije vrste morskog otpada bile su tanka plastika, ambalaža i staklo, s ukupnom težinom od 434 grama na lokaciji 3 na zapadnoj strani. Analiza plastičnog otpada pokazala je da polipropilen (PP) dominira na zapadnoj strani (44,44%), dok polietilen (PE) dominira na istočnoj strani (55,56%). Gustoća mangrova, posebno vrste *Avicennia* sp., igra vitalnu ulogu u hvatanju morskog otpada putem respiratornog korijenja, koje je učinkovitije na zapadnoj strani s većom gustoćom. PCA analiza pokazala je snažnu pozitivnu korelaciju između gustoće mangrova, posebno respiratornog korijenja *Avicennia* sp., i nakupljanja morskog otpada.

Ključne riječi: *Avicennia* sp., onečišćenje plastikom, obalni ekosustavi, PCA, respiratorni korijen

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