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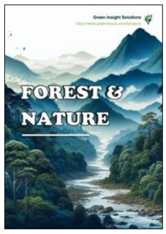

RESEARCH ARTICLE

Quantifying Marine Debris Pollution in Mangrove Ecosystems: A Study from Kalangan Hamlet, Lampung, Indonesia

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ABSTRACT

Mangrove ecosystems are currently facing severe threats due to the accumulation of marine debris, particularly plastic waste. This study aims to quantify the types and weights of marine debris in the mangrove ecosystem of Kalangan Hamlet, Lampung, Indonesia, and analyze their impact on various mangrove species. Data collection was conducted in three zones with different levels of human activity: low, medium, and high. Data on the types and weight of debris were collected using the transect plot method. Correspondence analysis was used to examine the relationship between debris types and the intensity of human activity. The results showed that plastic waste was the most dominant type in terms of both quantity and weight, particularly in areas with moderate to high levels of activity. Over 90% of the waste composition consisted of plastic, weighing over 9,000 g at Stations 2 and 3. Mangrove species of the genus *Rhizophora* were the most affected, likely due to their complex root structure, which effectively traps waste. Other types of waste, such as fabric, rubber, and glass, were also found in significant quantities and correlated with tourism and community activities. Waste accumulation, particularly plastic, not only alters habitat structure but also hinders mangrove regeneration, which could ultimately reduce ecosystem function and biodiversity. Waste management should align with the area's activity level, with high-activity zones requiring more intensive clean-ups, proper facilities, and regulation enforcement. Community engagement and awareness are crucial in reducing the impacts of marine debris on mangroves. Its temporal scope and sampling frequency limit this study; broader and longer-term research is recommended.

1. Introduction

Coastal areas are transitional zones between land and sea, influenced by both, resulting in high levels of dynamics in these locations. One of the transitional ecosystems found in coastal areas is the mangrove ecosystem. The mangrove ecosystem is one of the most important ecosystems in coastal areas. Mangrove ecosystems represent one of the most critical components of coastal environments due to their diverse ecological functions. They primarily serve as natural buffers against coastal abrasion and erosion (Kazemi et al., 2021; Rattanarama et al., 2024), while also providing essential habitat for a wide range of marine and estuarine biota (Akram et al., 2023). Moreover, these systems make significant contributions to the health of adjacent ecosystems, including seagrass beds and coral reefs. One of their key roles is functioning as sediment traps, which help maintain water clarity and, consequently, support the photosynthetic efficiency of seagrasses and corals (Hasim, 2021). Thus, mangroves play a crucial role in maintaining the stability and productivity of coastal and marine ecosystems, particularly by mitigating the impact of land-based influences.

Currently, coastal areas are under serious threat from various environmental pressures, primarily from anthropogenic activities. One of the most prominent issues today is marine debris. Marine debris refers to debris that enters marine areas, whether intentionally or unintentionally, originating from land-based and marine activities (Agamuthu et al., 2019). Indonesia is currently one of the countries contributing the most to marine debris (Jambeck et al., 2015). Marine debris has significant impacts on key ecosystems in coastal areas. In coral reef ecosystems, marine debris can cause structural damage to coral, lead to coral mortality, and reduce coral immunity (Lamb et al., 2018; Laura et al., 2018; Putra et al., 2021). In seagrass ecosystems, marine debris has an indirect impact by reducing the intensity of sunlight entering the water (Bamford et al., 2013; Rasyid et al., 2022).

Mangrove ecosystems are not immune to the impact of marine debris. Marine debris poses a significant threat to mangrove ecosystems, affecting their function as habitats for biota, reducing their aesthetic value, and potentially becoming a source of toxic substances (Li et al., 2021; Seeruttun et al., 2021). The presence of marine debris can be influenced by both natural and anthropogenic factors such as hydrodynamics, mangrove ecosystem conditions, tourism and coastal communities (Li et al., 2021; Lima et al., 2016; Rahim et al., 2020; Zhou et al., 2020). Furthermore, marine debris in mangrove ecosystems can cause death by covering the roots of the mangrove trees. The process of mangrove death caused by marine debris does not occur quickly but takes a considerable amount of time. Consequently, mangroves generally experience stress first, leading to a decline in health and ultimately to death (van Bijsterveldt et al., 2021).

One location with a large area of mangroves that is suspected of being polluted by marine debris is the Kalangan Hamlet area. The Kalangan Hamlet area is part of Pahawang Village, and its total area features a large mangrove forest with potential for environmentally friendly development (Reza et al., 2024). The potential of the Kalangan Hamlet is not immune to the threat of marine debris. Understanding the dynamics of the impact of marine debris on mangrove ecosystems is still limited, so this study aims to identify the types of debris commonly found in mangrove ecosystems, the mangrove species affected, the impacts caused, and the potential sources of marine debris. This research is expected to serve as a consideration for marine debris management, particularly in the waters surrounding the Kalangan Hamlet on Pahawang Island.

2. Materials and Methods

2.1. *Study Area*

The research was conducted in Kalangan Hamlet, Lampung. The mangrove community in Kalangan Hamlet is dominated by *Rhizophora mucronata*, *Rhizophora apiculata*, *Rhizophora stylosa*, and *Sonneratia alba*, alongside other species previously recorded, including *Bruguiera gymnorrhiza*, *Xylocarpus granatum*, *Xylocarpus moluccensis*, *Nypa fruticans*, *Heritiera littoralis*, and *Avicennia* spp. (Putriani et al., 2025). Quantitative assessments over the past two decades have indicated a fluctuating but generally positive trend in coverage, with a decrease from 109.75 ha in 2000 to 99.74 ha in 2010, followed by an increase to 120 ha in 2021 due to restoration and conservation initiatives (Irsyad et al., 2022). Data collection points were generally divided into three areas with different characteristics (**Fig. 1**). Point 1 is an area with low human activity. Point 1 is the farthest from settlements and tourist activities (less activity). Point 2 is an area close to tourist sites and a few settlements (moderate activity). Point 3 is an area surrounded by settlements (high activity). By distinguishing these three characteristics, it is possible to systematically determine whether there is a significant influence between human activity and the amount and type of waste found.

2.2. *Data Collection*

The method for collecting marine debris and mangrove data uses line transects and square plots, each measuring 10 m² (Bengen, 2004; Paulus et al., 2020). The data collected included mangrove vegetation data on exposed species to determine prevalence at the study site, as well as marine debris types, which were then identified based on Lippiatt et al. (2013) and categorized into several groups, such as plastic, fabric, glass, metal, rubber, and processed paper or wood.

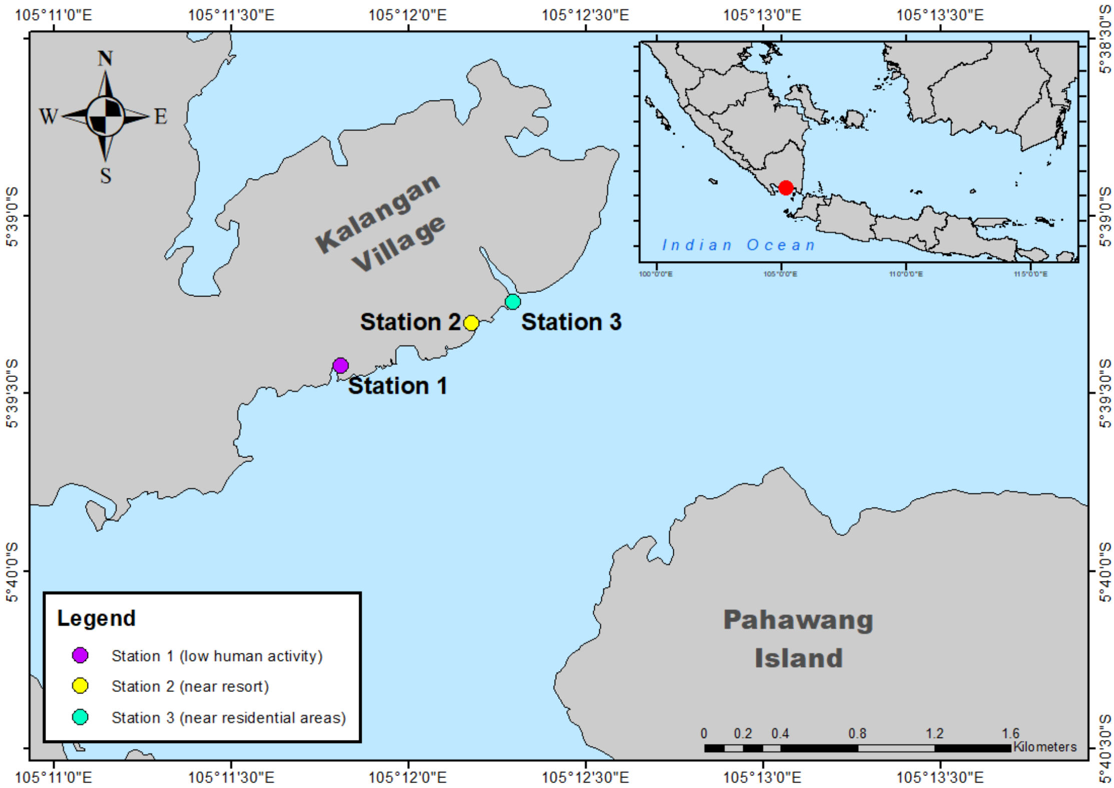

Fig. 1. Research map of marine debris in the mangrove ecosystem of Kalangan Hamlet.

2.3. Data Analysis

Data analysis in this study involves the identification and quantification of marine debris, including the number of types and the total weight of debris found at the study site. In addition, to understand the relationship between the types of coastal community activities and the types of debris produced, correspondence analysis (CA) was performed. The data analysis is explained as follows.

2.3.1. Number of Waste Types

The number of waste types is assessed by sorting the waste found according to predetermined categories. These categories include plastic, metal, glass, fabric, processed paper, and wood (Lippiatt et al., 2013). The number of waste types is expressed as a percentage, representing the number of types divided by the total amount of waste found. Equation 1 is used to calculate the percentage of waste types.

$$Ci, Type = \frac{Ni}{N} \times 100\% \quad (1)$$

where Ci is the percentage of the waste type, Ni is the quantity of the waste type, and N is the total quantity of all waste types. The percentage of each waste type is calculated to determine its relative contribution to the total waste.

2.3.2. Total Waste Weight

The total weight of waste is assessed by sorting the waste found according to predetermined categories. These categories include plastic, metal, glass, fabric, processed paper, and wood (Lippiatt et al., 2013). Equation 2 is used to calculate the total weight of waste.

$$W = \sum_{i=1}^{n} w_i \quad (2)$$

where W is the total weight of waste (g), w_i is the specific weight of waste type i, and n is the total number of waste types that have been counted.

2.3.3. Correspondence Analysis

Correspondence analysis (CA) was used to identify the relationship between types of marine debris and location types, based on the level of human activity, specifically low, moderate, and high activity. Through this approach, the multivariate relationships between variables can be visualized in the form of a two-dimensional diagram, making it easier to interpret the distribution patterns of debris. CA enables the grouping of debris types that are likely to be found in locations with specific activity characteristics.

3. Results and Discussion

3.1. Composition of Marine Debris

The composition of waste in the Kalangan mangrove ecosystem, as shown in **Fig. 2** and **Fig. 3**, indicates that plastic is the most dominant type of waste among the three observation stations. Stations 2 and 3 contributed significantly to the total plastic waste. Meanwhile, metal and rubber were only found at Station 1, which is strongly suspected to be related to local industrial or fishing activities that were then carried by currents, enabling the transport of waste debris to more distant locations (Nursyahnita et al., 2023). Textile and glass waste were more commonly found at Station 2, likely originating from domestic or tourist activities. Station 3 showed a relatively balanced distribution, particularly in terms of plastic, textile, and paper/wood waste debris. The variety of marine debris identified in the study area indicates the presence of multiple pollution sources. These sources include land-based inputs, particularly from residential settlements, as well as sea-based activities, such as maritime tourism. The multifaceted origin of these pollutants highlights the intricate and interconnected pathways through which human waste enters coastal ecosystems (Galgani et al., 2015).

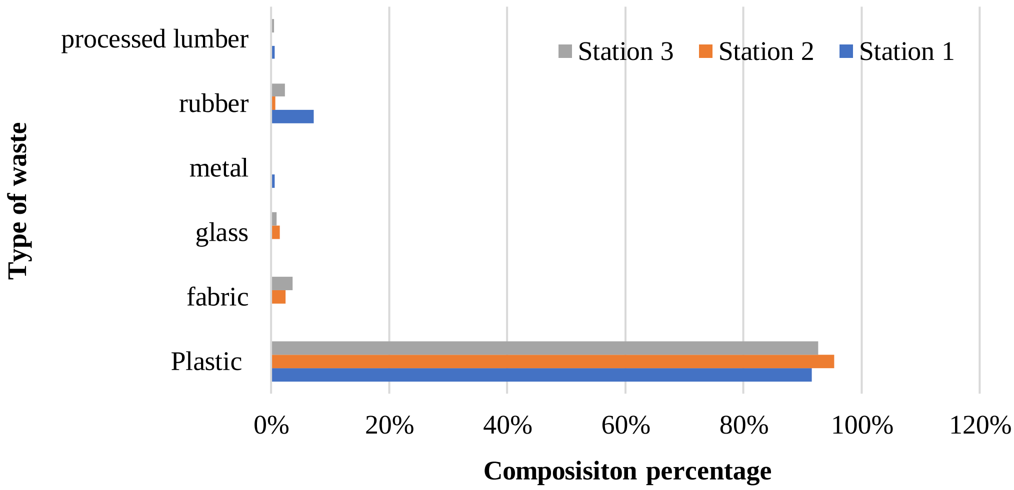

Fig. 2. Composition of marine debris found at the research site.

The presence of large amounts of plastic is particularly worrying because mangroves act as natural traps due to their complex root structure and location in tidal zones. These characteristics allow for the accumulation of plastic waste from various sources. Mangroves have a high potential for retaining plastic waste due to their unique breathing roots and their position as the boundary between land and sea, making them a prime location for plastic accumulation (Cappa et al., 2023).

3.1.1. Total Waste Weight

The results indicate that plastic waste dominates the total weight of marine debris at all stations, with the highest figures at Station 2 (9,855 g), followed by Station 3 (9,152 g) and Station 1 (1,280 g) (**Fig. 3** and **Fig. 4)**. This fact indicates that plastic is not only the most commonly found waste in terms of frequency, but also has a significant mass, reflecting the level of accumulation and resistance of plastic to degradation. Fabric was the next heaviest type of waste, weighing 3,845 g at Station 2 and 2,845 g at Station 3, while none was found at Station 1. This suggests that domestic or tourism activities around Station 2 and Station 3 are likely the primary sources of fabric waste, such as used clothing or household textiles. Other waste categories detected in significant quantities were rubber (480 g at Station 1 and 295 g at Station 3) and glass (470 g at Station 2 and 255 g at Station 3). These types of waste likely originate from fishing activities, small industries, or coastal communities. Meanwhile, metal and processed wood were only found in small quantities, particularly at Station 1.

(a) (b)

(c)

Fig. 3. Marine debris found in Station 1 (a), Station 2 (b), and Station 3 (c).

In terms of spatial distribution, Station 2 showed the highest total weight of waste compared to the other two locations, indicating higher anthropogenic pressure in this area, likely due to general human activities or its proximity to residential areas. In contrast, Station 1 tended to have lower pollution levels, although it still recorded significant amounts of plastic and rubber. Mangrove ecosystems have a high capacity to trap and accumulate plastic and other waste, due to their complex root structure and strategic position between the sea and land (Kataria et al., 2025). Additionally, the presence of large amounts of plastic reflects the lack of an effective waste management system in coastal areas, which can exacerbate the condition of mangrove habitats and the organisms that depend on them (Alli et al., 2024).

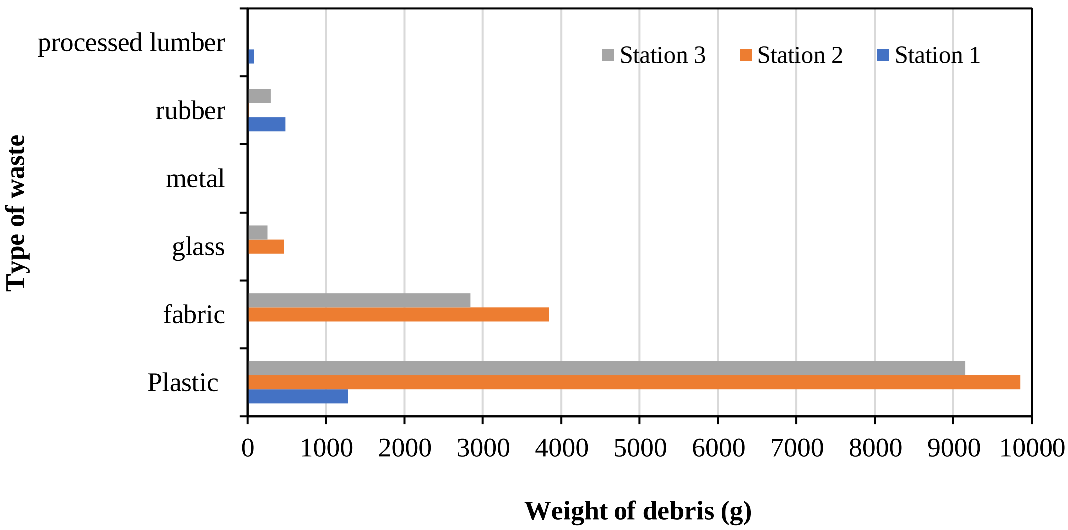

Fig. 4. Weight of debris found for each type.

3.2. Prevalence and Impact of Marine Debris on Mangrove Ecosystems

Mangrove ecosystems are one of the most important coastal habitats for coastal protection, carbon sequestration, and supporting biodiversity. Research findings indicate that marine debris can entangle, cover roots and substrates, and disrupt the functions of mangrove ecosystems due to non-organic pollution (**Fig. 5**). When compared to similar studies, the findings of this research are not significantly different. Based on research by Jayapala et al. (2024) in Negombo Lagoon, Sri Lanka, it was found that approximately 9.83% of mangrove substrates were covered by marine debris, with single-use plastics being the largest contributor. This debris causes physical damage to the roots, seedlings, and understory vegetation of mangroves through friction and abrasion, thereby disrupting their growth and regeneration. A similar study in Hong Kong by Vorsatz et al. (2025) revealed significant waste accumulation, approximately 0.071 items per square meter per day, with plastic accounting for 80% of the total marine debris. This marine debris accumulates more in the terrestrial zone, affecting mangrove seedling density and reducing habitat quality.

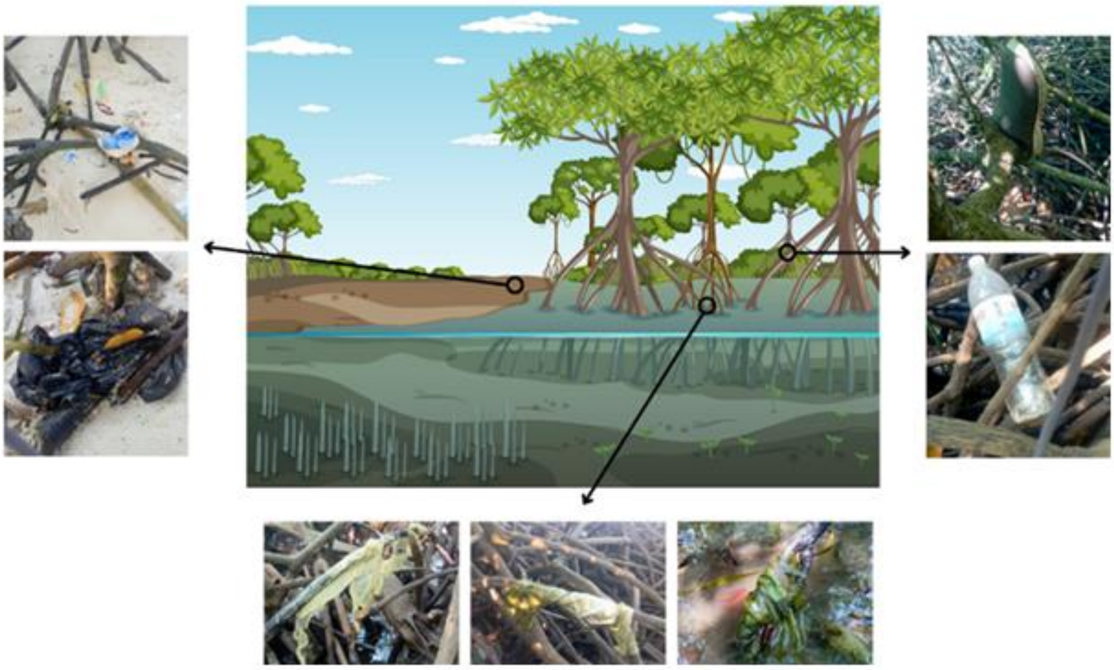

Fig. 5. The impact of marine debris on mangrove ecosystems found in the study.

According to Fajrin et al. (2024), the higher the density of marine debris, the lower the density of benthic biota, which means that the function of mangrove ecosystems as important habitats for various species is disrupted. The accumulation of marine debris, including microplastics, limits the formation and growth of mangrove seedlings and alters the physical structure of the habitat, ultimately reducing the stability of the mangrove ecosystem (P and Jayadev, 2023). Mangroves can act as “marine debris traps”, but this function ultimately leads to significant negative impacts, including declines in habitat quality, disruptions in mangrove plant growth and seedling development (Fatmalah et al., 2022), and reductions in benthic fauna and waterbird diversity (Amanu et al., 2024). Thus, the prevalence of affected mangrove types will vary depending on the ability of mangroves to trap debris.

Table 1 indicates a higher level of exposure to marine debris or the presence of species with root systems that are structurally effective in trapping debris. Mangroves from the genus *Rhizophora* have complex root systems, including prop roots and pneumatophores, which can function as physical traps for debris, particularly plastic. These roots can slow water flow and increase sedimentation of solid particles, including plastic debris, making mangroves natural traps for marine debris (Martin et al., 2019). The mangrove species *Excoecaria agallocha*, which lacks prop roots or pneumatophores, is still affected, indicating that debris accumulation is also influenced by physical site conditions such as geomorphology, tidal current intensity, and distance from debris sources (Vélez-Mendoza, 2022).

Table 1. Prevalence of mangroves affected by marine debris

No	Species	Station 1	Station 2	Station 3
1	*Rhizopora mucronata*	+		+
2	*Rhizopora apiculata*	+	+	+
3	*Rhizophora stylosa*		+	
4	*Bruguiera cylindrica*	+	+	
5	*Sonneratia alba*	+		
6	*Excoecaria agallocha*		+	

3.3. Analysis of the Relationship between Waste Types and Human Activities

Waste sources originate from various human activities in coastal areas, as well as from inland areas via rivers (Ahmad et al., 2025; Zhang et al., 2025; Lebreton et al., 2017). Similar to the findings of this study, based on the results of analysis using correspondence analysis (CA), **Fig. 6**, which displays waste type data and station activity categories, reveals several trends in waste types and activity intensity at each research site. There is a strong correlation between waste types and the intensity of human activity at the research locations. In general, plastic waste is found at all research sites, indicating a strong correlation with all types of activities.

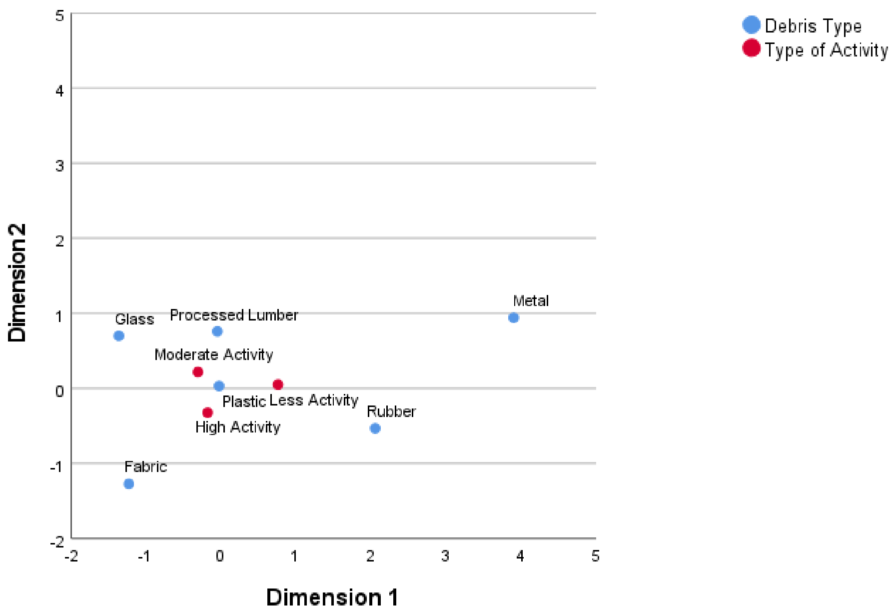

Fig. 6. The relationship between waste types based on location type using correspondence analysis.

Locations with high activity appear to be strongly associated with the accumulation of plastic and fabric waste, indicating that areas with intense human activity, such as densely populated settlements, generate more lightweight waste used daily, including food packaging and clothing, which are closely tied to human activities. Meanwhile, moderate activity is correlated with a more diverse range of waste types, including processed wood and glass, which typically originate from activities such as small-scale fishing and tourism. Low activity tends to be associated with rubber waste, indicating that in areas with low human activity, the accumulated waste originates more from passive transport (ocean currents) than from local activities. There is a category of waste types with a weak correlation, namely metal waste, which is far from the type of activity at the study site, indicating that metal generally arises from specific activities (e.g., ports or industries) rather than from routine community activities that are then carried by currents and become entangled at the site (Nursyahnita et al., 2023).

Although it tends to sink, there is a possibility that this type of waste could become entangled with other lighter waste. Human activity will determine the composition of waste types entangled in the mangrove ecosystem (Jayapala et al., 2024). Thus, the research results indicate that the intensity of human activity at the research station significantly influences the dominant types of waste, consistent with the distribution and physical characteristics of the waste (Gaibor et al., 2020; Li et al., 2016; NOAA Marine Debris Program, 2025; Unger and Harrison, 2016).

4. Conclusion

The marine debris, particularly plastic waste, is the most prevalent type of waste in terms of quantity and weight in Kalangan Hamlet, Pahawang Village. Fabric, glass, and rubber waste were also found in significant amounts, especially in locations with high human activity. The most affected mangrove species is the *Rhizophora* genus, which has a complex root structure and tends to trap debris. Accumulated marine debris can cause physical damage, including root and substrate coverage, entanglement of mangrove seedlings, and disruption of the growth and regeneration of mangrove vegetation. Additionally, the analysis revealed a correlation between the intensity of human activity around coastal areas and the composition of the debris found, indicating that domestic activities, tourism, and coastal settlements are potential sources of marine debris at the study site. Waste management should be adapted to the activity level of each area. More intensive efforts are needed in high-activity zones through regular clean-ups, proper waste disposal facilities, and strict enforcement of regulations. Community involvement is crucial, with awareness programs that educate residents and visitors about the impacts of marine debris on ecosystems such as mangroves. However, this research has limitations, including a limited temporal scope and sampling frequency, which may not fully capture seasonal variations or long-term trends in waste accumulation and mangrove response. Further studies with broader spatial and temporal coverage are recommended.

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Data Availability Statement: The datasets generated and analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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