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RESEARCH ARTICLE

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Marine Debris Pollution and Its Impact on the Mangrove Ecosystem (Case Study: Karimunjawa Island and Kemujan Island, Indonesia)

Erba Rafsanjani Fajrin[a], Ario Damar[b,c] and Taryono[b]

[a] Study Program of Coastal and Marine Resource Management, Graduate School of IPB University, IPB Darmaga Campus, Bogor, 16680, Indonesia

[b] Department of Aquatic Resource Management, Faculty of Fisheries and Marine Science, IPB University, IPB Darmaga Campus, Bogor, 16680 Indonesia

[c] Center for Coastal and Marine Resources Studies (PKSPL), IPB University, IPB Baranangsiang Campus, Bogor, 16127, Indonesia

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ABSTRACT

Coastal areas possess a diverse potential wealth of natural resources that can be developed and utilized by humans, such as fisheries, marine tourism, and transportation. One form of disruption to the balance of coastal and marine ecosystems is the pollution caused by waste. The Karimunjawa Islands face serious challenges related to waste pollution. Therefore, an identification of carried out regarding the composition of polluting waste as well as impacts or disruptions caused by marine waste pollution on the mangrove ecosystem in the coastal areas of Karimunjawa Island and Kemujan Island. Various types of waste were found at the research site, including plastic, metal, glass, rubber, organic, and others. Based on the enteri locations of Karimunjawa Island and Kemujan Island, 370 items of plastic waste and macro-debris amounted to 442, predominantly on Lumbung Beach. The dominant mangrove is *Rhizophora* sp., which has muddy sandy substrate. From the results of this study, it can be concluded that this waste situation makes the coastal areas of Karimunjawa Island and Kemujan Island vulnerable to environmental pollution problems. The impact on the environment is a decrease in benthic biota density owing to the abundance of waste. The higher the density of waste, the lower the density of benthic species found in the mangrove ecosystem environment.

Introduction

This coastal area possesses a diverse wealth of natural resources and the potential for human development and utilization, such as in the fields of fisheries, marine tourism, and transportation. One form of disruption to the balance of coastal and marine ecosystems is pollution caused by waste known as marine debris [1]. Karimunjawa Island faces serious challenges related to waste issues and there is limited quantitative information on marine waste pollution. Therefore, waste pollution composition and the impact or disturbance caused by marine pollution on mangrove ecosystems in the coastal areas of Karimunjawa Island and Kemujan Island should be identified. The types of waste found at this location are plastic waste and macro-debris. The dominant mangrove species was *Rhizopora* sp., which has muddy sandy substrates. The disturbance was a decrease in benthic biota density at the research site, which was affected by the abundance of waste. The higher the density of waste, the lower the density of benthos in the mangrove ecosystem.

Oceans and coastal regions play crucial roles in biological productivity, geochemistry, and human activities. Coastal areas essentially serve as the interface between the sea and land and are mutually influenced by each other in terms of bio-geophysical and socioeconomic aspects. In the planning context, coastal refers to a region that has become the focus of resource management in order to address its responsibilities. Coastal

Corresponding Author: Erba Rafsanjani Fajrin Erbarafsanjani@apps.ipb.ac.id Study Program of Coastal and Marine Resource Management, Graduate School of IPB University, Bogor, Indonesia.

areas possess a diverse wealth of natural resources and have the potential to be developed and utilized by humans through fisheries, marine tourism, and transportation [2]. One form of disturbance in the balance between coastal and marine ecosystems is waste pollution, which has become increasingly prominent in recent years. Marine waste pollution negatively impacts ecosystem health, including that of aquatic organisms. The primary sources of marine waste pollution originate from human activities on both land and sea. The impacts of activities in this coastal area can also be negative, such as an increase in waste volume in coastal regions exacerbated by waste carried by seawater from activities in the sea. This waste is known as marine debris [3].

The Karimunjawa Islands constitute a national marine park located in the northern part of Jepara Regency, Central Java Province. This area consists of several small islands, with the Karimunjawa and Kemujan Islands being the primary islands [4]. The Karimunjawa Islands have been designated as marine tourism destinations in Indonesia, covering a land area of 7,033 ha and a marine area of 104,592 ha, with a total area of 111,625 ha [5]. Despite its strong tourist appeal, the Karimunjawa Islands face serious challenges related to waste issues, and quantitative information regarding marine waste pollution in this area is still limited.

The increase in population, tourism activities, and development projects in the Karimunjawa Islands poses a risk to the quality of coastal and marine environments. This is due to the high vulnerability of coastal and marine areas to environmental change [6]. The consequences of this situation can be negative if left unchecked, including aesthetic disturbances in coastal areas, impacts on marine biota, and hindrances to coastal ecosystem productivity, particularly in mangroves. Given these issues, research needs to be conducted to identify the composition of waste pollution and assess the impacts or disturbances caused by marine waste pollution in mangrove ecosystems along the coasts of the Karimunjawa and Kemujan Islands. This research is expected to contribute to an integrated, preventive, and pragmatic approach to waste pollution management issues as well as to achieving sustainable waste management. Therefore, the aim of this study was to identify the composition of marine waste pollution in the mangrove ecosystem and the disturbances caused by marine waste pollution on the mangrove ecosystem in the coastal areas of Karimunjawa and Kemujan Islands.

Methods

Study Area

This research was conducted on Karimunjawa and Kemujan Islands. This study was conducted between April and May 2022. In this study, marine waste samples were collected from six different locations, with three points situated to the west, namely at Ujung Gelam and Lumbung Beach on Karimunjawa Island, and at Mrican Beach and Ujung Jelamun Beach on Kemujan Island (Figure 1). The other three points were in the eastern part, specifically at Legon Lele Beach on Karimunjawa Island and Legon Nipah Beach on Kemujan Island. All the sampling points were located within the mangrove ecosystem.

Karimunjawa Island and Kemujan Island are two of the 27 islands in the Karimunjawa Archipelago. There is a connected coastline between these two islands because of the mangrove forest growing between them [7]. Referring to Law No. 27 of 2007 concerning Coastal Zone Management, these two islands were classified as small islands because their areas were less than 2,000 km^2. Laksono and Mussadun [8] explained several potential features present in the Karimunjawa Archipelago, such as high biodiversity, natural beauty with pristine forests, and abundant resources for both marine tourism and the environment at national and international scales.

Looking at oceanographic parameter data, the current patterns during transition season 1 [9] around Karimunjawa indicate different directions on various sides. On the western, eastern, and southern sides of Karimunjawa, the current tends to flow southeastward before turning southward. On the northern side of Karimunjawa, the predominant current direction is eastward before turning northward. Generally, the current velocities are stronger during the western monsoon than during the eastern monsoon. During the western monsoon (December – February) in the waters of Karimunjawa, currents typically move from west or northwest to east or southeast. During the transition from the western monsoon to the eastern monsoon (March – May), currents in the waters of Karimunjawa commonly move from northwest to southeast. When the eastern monsoon arrives (June – August), currents in the waters of Karimunjawa flow from the east to the west or northwest. During the transition from the eastern monsoon back to the western monsoon (September – November), the currents reverted from the west or northwest to the east or southeast.

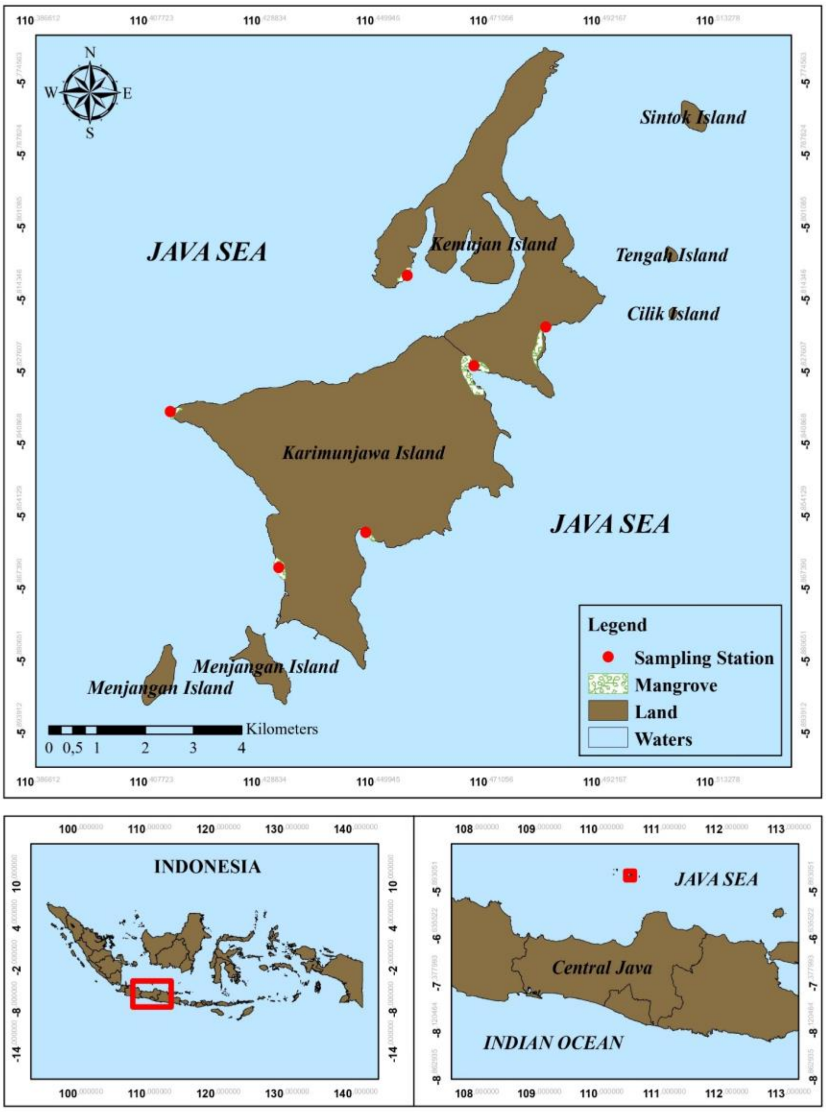

Figure 1. Study area.

Data Collection

Marine waste data were collected directly along the coastline using a line transect method. In the line transect approach, marine waste was collected at intervals along the transect line at each observation station, where each station had one transect line running straight parallel to the coastline and measuring 50 m in length. Along each transect line, it was divided into five 10 × 10 m plots (Figure 2) [10]. The collected samples were identified based on the grouping of marine waste sizes and were categorized into several classes. The next step involved drying the items in each category followed by counting and weighing them. The measured parameters included the number of items (pieces m^{-2}) and their weights (g m^{-2}) [11].

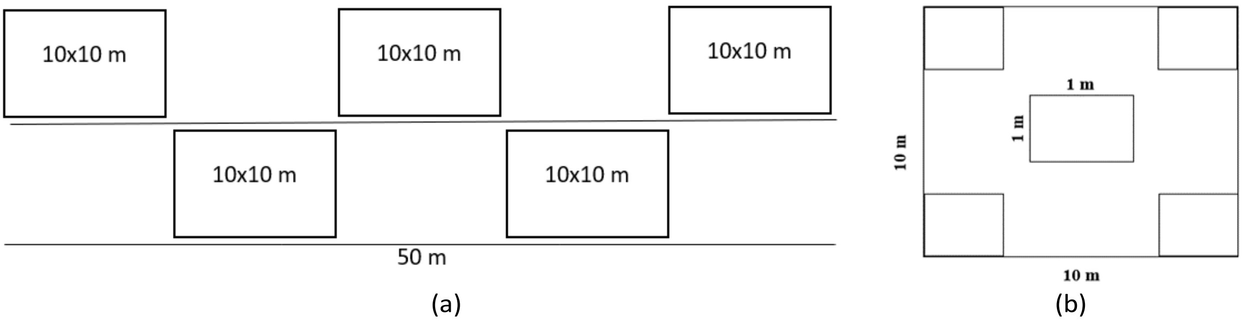

Figure 2. (a) Transect setup for marine litter data collection and (b) transect setup for associative biota data collection.

Data Analysis

Debris Data Analysis

The data collected from each variable were processed according to the objectives using quantitative and qualitative data analysis approaches. Information regarding the observed waste composition, including the quantity and weight of each categorized waste type, was then processed using a formula modified from Coe and Rogers [12] in Hermawan [13]. The results were subjected to statistical analysis using one-way analysis of variance (ANOVA) with SPSS 20.00 application. If significant differences were found, a follow-up test (Post Hoc) was conducted using Tukey's test.

$$\text{Density (quantity of waste)} = \frac{\text{Quantity of waste in each category (pieces)}}{\text{Area size (m}^2\text{)}} \quad (1)$$

$$\text{Density (weight of waste)} = \frac{\text{Weight of waste in each category (gram)}}{\text{Area size (m}^2\text{)}} \quad (2)$$

Associated Biota Analysis

Information about associated biota collected through the line transect method was subsequently analyzed using density index formulas to estimate the number of individuals of each benthic organism type. Benthic densities at various locations were compared, particularly between impacted and unaffected sites. Benthos densities among the stations were compared using ANOVA. The hypothesis posited is that stations exposed to waste will exhibit lower benthos densities than those not affected by waste. The formula used to calculate the density of associated biota is as follows [14]:

$$\text{Quantity density} = \frac{\text{Number of individual of a species (Ind)}}{\text{Area size (m}^2\text{)}} \quad (3)$$

Additionally, regression and correlation tests were conducted on waste density (Variable X) in relation to benthic biota (Variable Y). Regression analysis was applied to understand the relationship between the independent variable (waste density) and dependent variable (benthic biota). This analytical approach aims to measure the degree of influence of waste density (X) on benthic biota (Y). In accordance with Steel and Torrie [15], the formulae used for the regression calculation are as follows:

$$\mathrm{Y} = \mathrm{a} + \mathrm{bX} \quad (4)$$

where Y is the density of the benthic biota, X is the marine waste density, a is a constant, and b is the slope.

Regression and Correlation Statistical Unit

Furthermore, a correlation test was conducted to determine whether a relationship existed between the variables. The results of the analysis were evaluated based on the significance and strength of the relationship, which is reflected in the correlation coefficient (r) value. According to, the formula used in the correlation calculation is based on that of Steel and Torrie [15]. The correlation categories in the relationship between the two variables, as described by Steel and Torrie [15], can be divided into five criteria with specific values. A value of 0.00 indicates no correlation, while value between 0.00 to <0.25 reflect a very weak correlation, between 0.25 to <0.50 reflect a moderate correlation, between 0.50 to <0.75 reflect a deemed strong correlation, and between 0.75 to <1.00 reflect a very strong correlation.

$$r = \frac{Sxy}{\sqrt{(Sxy)^2 (Sy)^2}} \quad (5)$$

where r is correlation coefficient, Sxy is distribution of value of variable x and y, Sx^2 is variability of values variable x, and Sy^2 is variability of values variable y.

Results and Discussion

Marine Debris Pollution Condition

The classification of waste types follows the guidelines by National Oceanic and Atmospheric Administration (NOAA) [16], in which marine debris is grouped into several categories: plastic, metal, glass, rubber, organic, and others. Other categories encompass items such as clothing, styrofoam, bags, and similar items. During observations at six stations on Karimunjawa Island and Kemujan Island, various types and categories of waste were identified, with plastic waste emerging as the dominant waste type (Table 1). Based on surveys and interviews, the dominant plastic waste originates from both marine activities and waste disposal from land-based communities that enter the sea owing to tides and ocean currents. Yuliadi [17] reported that coastal plastic waste typically originates from household waste and tourist activities and enters waters carried by currents and tidal waves.

The highest amount of plastic waste was observed at Lumbung Beach, reaching 370 items m^{-2}, with a total weight of 6.3 kg, and an overall waste weight of 15.3 kg. Mrican Beach came in second with 327 pieces m^{-2} of plastic waste, weighing approximately 5.5 kg and a total waste weight of 13.1 kg. Lego Nipah Beach showed a lower count of plastic waste compared to other locations, with only 121 plastic m^{-2} waste items weighing 1.6 kg and a total waste weight of 6.1 kg. The types and weights of the waste found at each station are listed in Table 1. The density of plastic waste at Lumbung Beach increased because of the presence of a small dock used for crossings. Their proximity to residential areas results in a volume of marine debris from household activities being directly dumped into the sea and carried by currents, leading to waste accumulation in the area. Vermeiren et al. [18] said the presence of accumulated waste in a region, particularly in water bodies, is influenced by factors, such as wind patterns that form currents, waves, and tides.

Table 3. Type and weight of litter at each station.

Category	Mrican		Lumbung		Ujung gelam		Ujung jelamun		Legon nipah		Legon lele	
	J	B	J	B	J	B	J	B	J	B	J	B
Plastic	327	5.5	370	6.3	169	2	273	5	121	1.6	242	3.7
Metal	0	0	4	0.5	0	0	0	0	2	0.2	1	0.2
Glass	1	0.1	1	0.5	4	0.5	3	0.2	1	0.1	2	0.2
Rubber	3	0.5	12	1.8	13	1.6	15	1.5	8	1	15	2
Organic	36	3	32	1.5	43	2	37	1.3	40	2	29	1
Other	18	4	35	4.7	21	1.6	20	2	30	1.2	19	1
Total	385	13.1	454	15.3	250	7.7	348	10	202	6.1	308	8.1

J = Quantity of waste (pieces $500m^{-2}$), B = Weight of waste (Kg).

The primary reason for the high presence of plastic waste on each beach is the influx of waste from the community, which then enters the water through currents and tides. This is evident from the land area of Karimunjawa Island, which is 7,033 ha and has a population of approximately 500,000 people [7]. This is because plastic waste is buoyant and can be carried by water currents that are influenced by waves. Consequently, plastics tend to be the most accumulated type of waste in coastal waters. In general, plastic waste typically takes between 50 and 200 years to degrade [19].

Categories such as metal, glass, rubber, organic, and others showed similar results. Among all the research locations, the least frequently encountered category was metal waste, with a count below 10 items. According to Lippiat et al. [20], marine debris has been classified into five categories: mega-debris (>1 m), macro-debris (2.5–100 cm), meso-debris (0.5–2.5 cm), micro-debris (0.33–5 mm), and nano-debris (<1 µm). Based on the data presented in this study, the analyzed waste sizes are limited to the meso size (Table 2), from which it is evident that macro-sized debris dominates at all research locations, followed by meso-sized debris, and mega-sized debris is the least common.

Table 2. Found size of litter.

Location	Amount of waste		
	Mega	Macro	Meso
Mrican	4	368	13
Lumbung	2	442	10
Ujung gelam	10	238	2
Ujung jelamun	7	328	13
Legon nipah	16	183	3
Legon lele	1	297	10
Total	40	1,856	51

Waste with larger dimensions (macro), which is dominant at research locations, is believed to be related to the fact that such waste types are often used in daily activities. Djaguna et al. [21] detailed various types of macro-debris and meso-debris are commonly used by the community in daily routines, such as plastic bags, bottles, food wrappers, soap wrappers, straws, and other solid plastic items. Plastic is a synthetic organic polymer that possesses properties suitable for everyday use, showing that the most abundant waste in the Karimunjawa Islands has dimensions 2.5–100 cm, which falls into the macro-debris category.

Macro-sized waste at the research site dominated significantly compared to other waste sizes, with a total of 1,856 macro-sized wastes found in the Karimunawa location. This aligns with the research conducted by the Indonesian Ministry of Environment and Forestry in 2017, where 72% of the dominant waste in the Karimunjawa Islands falls into the category of macro-debris, measuring 2.5–100 cm. This is suspected to be due to the fact that this size of waste is most commonly used in daily life. Djaguna et al. [21] Mention various types of macro-debris and meso-debris are common plastic wastes used in everyday life by the community, such as plastic bags, water bottles, food wrappers, soap wrappers, straws, and other solid plastics. Plastics are synthetic organic polymers suitable for everyday use [22].

The condition of marine litter contamination in the Karimunjawa Islands, when assessed from the research results, tended to be relatively low compared to other islands. A possible reason for the low waste composition in the Karimunjawa Islands compared to other island regions is suspected to be related to the sampling period that took place during the transitional period from the west monsoon to the east monsoon. During this season, the wind speed and currents experienced a significant decrease to reach their lowest points. This statement is consistent with the observation of Hermawan [13], which states that a gradual decrease in waste accumulation occurs every day due to reduced currents and wind speeds, especially towards the end of April. During this current decline, the quantity of marine litter carried by the currents decreased, resulting in additional waste reduction. Another factor influencing marine litter composition is the sampling performed after beach cleaning initiatives by the local community and government have taken place. The presence of these activities indicates that the waste collected during sampling consists of leftovers that were not gathered during beach cleaning activities and additional waste carried by currents and other activities occurring after beach cleaning.

Based on the research results, it can be concluded that this waste situation makes the areas in Karimunjawa and the Kemujan Islands vulnerable to environmental pollution issues, with one of the causes being high tourism activity. Therefore, an ideal waste management strategy needs to be implemented, including enhancing waste management facilities and infrastructure as well as strengthening cooperation with relevant stakeholders. These efforts are essential to support the success of programs, including collaborative efforts to provide waste transport equipment and educate the public about responsible waste disposal and sustainable management practices.

Marine Debris Pollution Disturbance

The Karimunjawa and Kemujan Islands are vulnerable to environmental pollution, which ultimately has negative impacts on mangrove ecosystems and various organisms living within them. Indirectly, this vulnerability affects the balance of the mangrove ecosystem and various species that are dependent on it. Mandura [23] indicated that waste disposal into mangrove habitats has damaged many prop roots along the coast, thereby hindering mangrove tree growth. Additionally, marine debris can accelerate the invasion of alien species associated with marine debris, which can then spread to new habitats. Mangroves are coastal ecosystems that can capture and store waste because of their position between land and sea. Mangrove roots can also lead to significant accumulation of debris. *Rhizophora* sp., which grows on muddy sand substrates, is the most common type of mangrove found in the area. In addition to examining various mangrove types, this study also observed diverse aquatic biota within the mangrove ecosystems. The total number of biota detected across the six research stations was 434. Some biota samples found at the study locations included *Anadara* sp., *Vexillum* sp., *Nerita* sp., *Littoria* sp., *Terebralia sulcata*, *Scylla serrata*, and *Panulirus* sp. Information regarding benthic biota density at the study locations is shown in Table 3.

Table 3. Types and benthic biota densities at the study locations.

Category	Legon nipah	Ujung gelam	Ujung jelamun	Mrican	Legon lele	Lumbung
Anadara sp.	340	280	240	200	260	140
Vexillum sp.	200	300	220	200	240	160
Nerita sp.	400	360	300	260	340	200
Littoria sp.	360	340	240	220	280	180
Terebralia sulcate	320	300	260	240	280	220
Scylla serrata	240	160	100	60	120	40
Panulirus sp.	80	0	0	0	0	0
Total	1,940	1,740	1,360	1,180	1,520	940

[a]Explanation = Density (ind $100m^{-2}$).

Table 3 shows that the largest benthic biota count was found in Legon Nipah, reaching 1,940 ind 100 m^{-2}, whereas the lowest aquatic biota count was recorded in Lumbung, reaching only 940 ind 100 m^{-2}. The abundance of benthic biota on the edge of the nipah lagoon was due to a significantly lower amount of trash compared to that found on the barn shore. In addition, this condition is influenced by the presence of a small active pier on the barn shore, thereby contributing to an increased volume of marine debris. At each location, the most common biota was *Nerita* sp., where Legon Nipah had the highest population at 400 ind 100 m^{-2}, whereas *Panulirus* sp. was the least common, with a density of 80 ind 100 m^{-2}. Significant benthic biota, particularly from the gastropod class, such as *Nerita* sp., were found at research locations with muddy sandy substrate covered by mangrove vegetation. Noersativa et al. [24] has also shown that gastropods are generally found in muddy areas with a sufficient availability of organic materials.

A high density of gastropods indicates a strong ability to adapt to their habitat. This suggests that gastropods have a high reproductive capacity. According to Nybakken [25], organisms with high densities tend to dominate larger areas, giving them the opportunity to grow. Hartoni et al. [26] also concluded that gastropods exhibit stability and can adapt to environmental changes in mangrove ecosystems, which indirectly affects their abundance. The discovery of these biota in research locations on muddy substrates and their influence on waste pollution shows their resilience to suboptimal environmental conditions. The presence of crustacean biota demonstrates their ability to survive under suboptimal environmental conditions. According to Kantharajan et al. [27], marine debris found in water bodies can affect the availability of marine habitats for fauna groups, such as mollusks and crabs. This was demonstrated by the significant finding of the mangrove crab species (*Scylla serrata*). Pratiwi and Rahmat [28] explained that crabs have a strong ability to adapt to environmental change. Crustacean groups, such as *Scylla serrata*, have excellent adaptation capabilities, allowing them to thrive in various mangrove habitats [29].

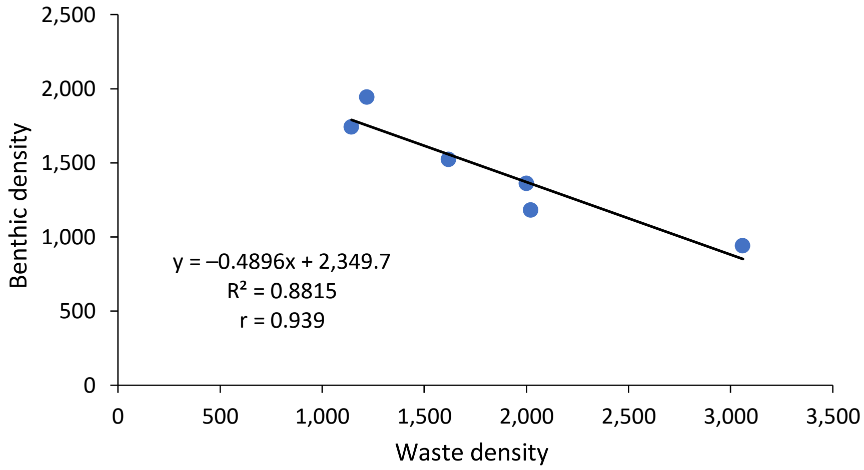

Figure 4. Correlation between marine litter weight and benthic biota.

The results of this study also indicated that locations with higher biota densities usually have relatively low amounts of marine litter, whereas locations with lower biota densities tend to have higher amounts of marine litter. To measure the impact of the independent variable waste on the dependent variable, benthos, regression, and correlation analyses were conducted on six pairs of data representing each research station (n = 6). The analysis results yielded a model depicting the relationship between waste quantity and benthic presence, represented by the equation $y = -0.4896x + 2,349.7$ (Figure 3).

Figure 3 shows the extent of the impact of marine litter variables on benthic biota density, as reflected by the coefficient of determination (R^2) of 0.881. The correlation coefficient (r) was –0.939, indicating an inverse relationship between litter density and benthic density within the mangrove ecosystem. In the context of correlation, a positive value indicates a direct relationship between two variables, meaning that if one variable increases, the other tends to increase, and vice versa if one variable decreases, the other also tends to decrease [30]. Therefore, these results indicate that as litter density increases, benthic density within the mangrove ecosystem decreases. Reinforcing the above statement, the ANOVA test results yielded a significant value for benthic quantity and density of 0.173. The null hypothesis (H_0) was accepted when the significance value was greater than 0.05. This indicates that benthic density in stations affected by litter tended to be lower than that in stations unaffected by litter.

Conclusion

The results of this research can be concluded that the identified litter at the research sites includes various types, such as plastic litter, metal, glass, rubber, organic waste, and others. The dominant litter types at each research station were plastic and macro-debris. Lumbung Beach had the highest litter quantity. In terms of waste weight, Lumbung Beach on the west side of Karimunjawa Island and Mrican Beach on the west side of Kemujan Island showed higher levels of waste than the other locations. The impact of marine litter is the reduction in benthic biota density at the affected research locations owing to litter abundance. Legoh Nipah had the highest benthic biota density, whereas Lumbung Beach had the lowest benthic biota density among the study sites.

Author Contributions

ADR: Conceptualization, Methodology, Software, Investigation, Review, Supervision; **TK**: Conceptualization, Methodology, Software, Investigation, Review, Supervision; **ERF**: Writing- Review & Editing.

Conflicts of Interest

There are no conflicts to declare.

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