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MORALITY BEFORE KNOWLEDGE

The impact of mangrove forest density on marine debris accumulation: Implications for ecosystem health and sustainable coastal management

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ABSTRACT

Background: Marine debris refers to all solid materials resulting from human activities that are found in aquatic environments, such as oceans, seas, and coastal areas. These materials directly threaten aquatic ecosystems' health and productivity and require specific actions to prevent and mitigate their negative impacts. In mangrove ecosystems, the density of mangrove vegetation may influence the accumulation of marine debris. This study investigates the relationship between mangrove density and the abundance and types of marine debris around Kassikebo Pier, Pangkep Regency**. Methods:** The research employed the parallel line method for sampling marine debris and a 10 m x 10 m transect for assessing mangrove density. The study was conducted across three stations with varying mangrove densities: sparse, medium, and dense. The abundance and percentage mass of debris were calculated based on size and type. Physical oceanographic parameters were also measured, such as current direction, velocity, and tidal patterns. The mangrove species were identified, and their densities were analyzed to determine their correlation with marine debris abundance. **Findings**: The study revealed that macro-sized debris dominated across all stations. At Station 1 (sparse mangrove density), the abundance of macro debris was 0.45 pieces/m^2 and 7.97 grams/m^2; at Station 2 (medium density), it was 0.66 pieces/m^2 and 14.75 grams/m^2; and at Station 3 (dense mangrove density), it was 1.05 pieces/m^2 and 21.48 grams/m^2. Plastic was the most dominant type of debris at all stations. The mangrove species identified in the area included Avicennia alba, Avicennia marina, and Rhizophora mucronata, with Avicennia alba being the most abundant. **Conclusions:** The study found a positive correlation between mangrove density and the abundance of marine debris, indicating that denser mangroves tend to trap more debris. **Novelty/originality of this article:** his research highlights the link between mangrove density and marine debris accumulation, stressing the need for plastic waste management in mangrove-rich areas. It offers recommendations for local governments and communities to adopt the 3R approach.

KEYWORDS: marine debris; plastic debris; mangrove; Kassikebo port; Pangkep.

1. Introduction

Waste has been one of the significant challenges to the global environment for decades. However, special attention is now focused on marine debris, especially plastics, which have spread to various aquatic ecosystems and significantly impact environmental quality. Marine plastic debris pollutes aquatic habitats and seriously threatens the sustainability of marine ecosystems. According to research by Jambeck et al. (2015), the proportion of plastic waste polluting the ocean is estimated to range from 1.7% to 4.6%, with an estimated 12.7

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million tons of plastic entering the world's oceans in 2010. This problem is becoming more severe in countries with large populations and rapid economic growth, including Indonesia. As the largest archipelago in the world, Indonesia ranks as the second largest contributor of marine plastic debris after China (Jambeck et al., 2015). With 17,504 islands and more than 54,716 kilometres of coastline, Indonesia faces enormous challenges in managing marine debris that mostly comes from land-based activities, such as household, industrial, and agricultural waste, as well as marine activities, such as fisheries and transportation (Purba et al., 2019). In addition, ocean currents also carry waste from neighbouring countries, exacerbating the accumulation of marine debris in Indonesian waters. The main challenge in marine debris management in Indonesia is the suboptimal management of land-based waste, the primary pollution source.

Marine debris, known as marine litter, is solid material from human activities found in marine, oceanic or coastal waters (Löhr et al., 2017; Purba, 2019; Hibatullah & Mutaqin, 2024). It can be plastic, metal, glass, fabric or other materials that do not biodegrade and can directly impact ecosystems. Ecologically, marine debris can pollute habitats, reduce biodiversity, and disrupt aquatic food chains. Physically, it can be carried by currents and winds to locations far from its origin, making it a transnational problem that requires a global solution. While the issue of marine debris pollution has been widely discussed, there is limited quantitative research on pollution levels, particularly in mangrove ecosystems. Mangrove ecosystems are important as a transition zone between land and ocean. Ecologically, mangroves provide a habitat for various species, such as fish, shrimp and molluscs. Physically, mangrove roots retain sediment, protect the coast from abrasion, and reduce the impact of flooding (Karimah, 2017). However, accumulated marine debris, especially macro debris, can become trapped in mangrove roots like pneumatophores, potentially covering the sediment surface and inhibiting the regeneration of mangrove seedlings. This impact damages the ecological function of mangroves and threatens the habitat of organisms that depend on the ecosystem (Paulus et al., 2020).

Pangkajene and Islands Regency, South Sulawesi Province, is one of the areas that has relatively good mangrove ecosystem potential. This region's area of mangrove ecosystems reaches around ± 267.70 hectares spread along the coastline (Pangkajene and Islands Regency in Figures, 2016). However, the utilization of mangroves by local communities, both for subsistence purposes such as fisheries and ponds, as well as for commercial purposes such as mangrove crabs, puts pressure on the ecosystem. In addition, simple jetties and harbours in the region are also potential points of marine debris accumulation due to human activities. This study focused on Kassikebo Pier, Pangkajene and Islands Regency to identify the distribution, composition and amount of marine debris in mangrove ecosystems with different density levels. The study site included three observation stations: low-density mangroves near residential areas, medium-density mangroves in aquaculture areas, and high-density mangroves around river mouths. With this approach, the study aims to provide comprehensive quantitative data for the sustainable management of mangrove ecosystems. In addition, this research is expected to provide recommendations for mitigation strategies for the impacts of marine debris, both through community-based management and policy approaches involving various stakeholders.

2. Methods

2.1 Time, place, and procedures

This research was conducted from July 2021 - April 2022 and data collection was carried out on September 25-27, 2021 which is located around Kassikebo Pier, Ma'rang District, Pangkajene and Islands Regency, South Sulawesi. This study focused on Kassikebo Pier, Pangkajene and Islands Regency to identify the distribution, composition and amount of marine debris in mangrove ecosystems with different density levels. The region consists of 13 sub-districts, namely Liukang Tangaya, Liukang Kalmas, Liukang Tupabbiring, Liukang Tupabbiring Utara, Pangkajene, Minasatene, Balocci, Tondong Tallasa, Bungoro, Labakkang, Ma'rang, Segeri, and Mandalle. Research location map can be seen in Figure 1.

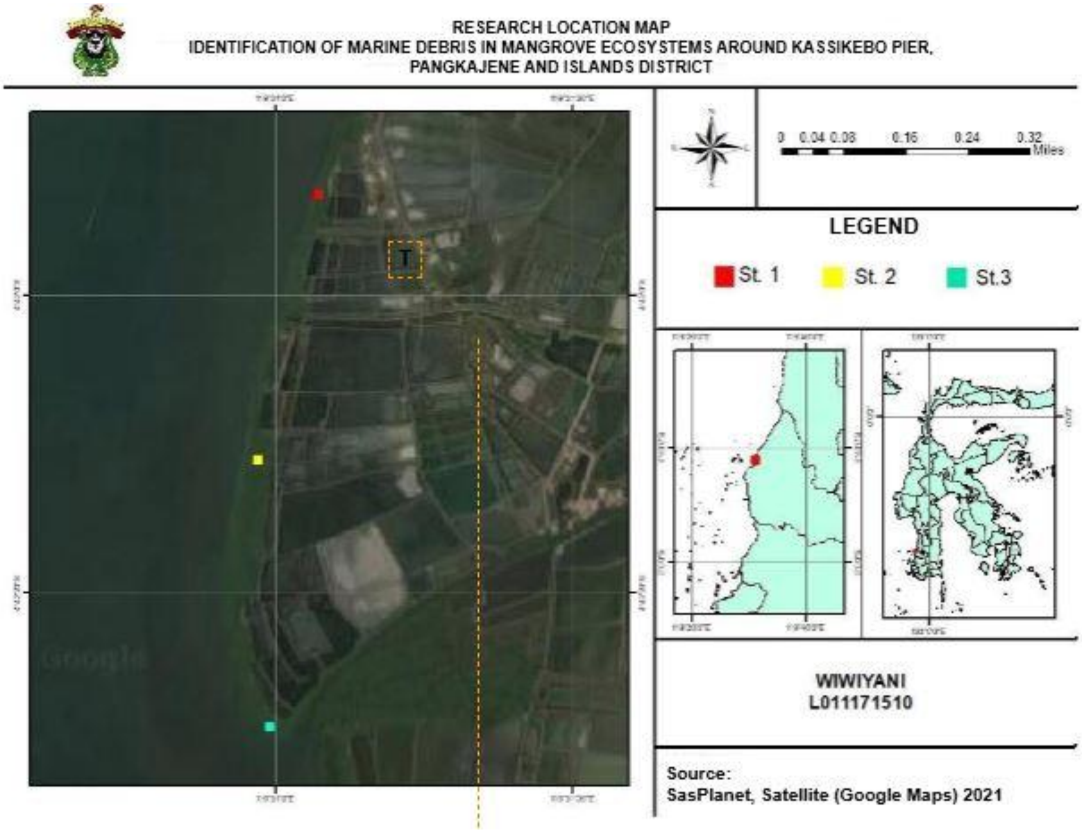

Fig 1. Research location

The research procedure was carried out in several stages. The first stage is the preparation stage. The preparation stage includes literature study related to the research title and preparation of research proposals, consulting with the supervisor, conducting an initial survey to obtain an overview of the research location, and preparing tools and materials that will be used during the research.

Fig. 2. Station sampling location

Station 2 is situated in an area with moderate-density mangroves, surrounded by aquaculture farms and seaweed cultivation areas managed by the local community. The activities at this station, such as aquaculture and the farming of seaweed, contribute to waste distribution due to the organic and inorganic materials used in these practices. The mangrove ecosystem here acts as a buffer, helping to filter pollutants; however, the medium density of mangroves might limit its effectiveness. Additionally, water currents from nearby farms may carry waste into the mangrove zone, further affecting its ecological balance. This location is shown in Figure 3.

Fig. 3. Station 2 sampling location

Station 3 is located in high-density mangroves near the river mouth, a site that is relatively far from residential areas but still impacted by human activities. This station experiences some waste distribution due to seaweed cultivation managed by local communities, even though it is distant from direct anthropogenic sources such as settlements or docks. The high density of mangroves at this location provides a significant natural barrier, potentially reducing the impact of pollutants and supporting a healthier ecosystem. Despite this, waste may accumulate due to the estuary's function as a convergence point for materials carried by river flow. This site is depicted in Figure 4.

Fig. 4. Station 3 sampling location

The third stage in this research is mangrove data collection. Data was collected using the transect method (line transect), where the transect line was drawn perpendicularly from the coastline to the observation station and adjusted to the extent of the mangrove growth area. Transect lines are made along 30 meters with a width of 10 meters, or the conditions in the field are adjusted. On each transect made, a plot measuring 10 m x 10 m is formed for tree-level observations (Saru, 2020). Identification of mangrove species was carried out by recording the names of known ones or by taking pieces of twigs complete with flowers and leaves for further identification based on mangrove identification books (Nurhayati & Saparuddin, 2022). In addition, the number of mangrove species was counted, and mangrove stem diameters were measured for the tree category, i.e. woody plants with a diameter ≥ 4 cm (Saru, 2020). Mangrove stem diameters greater than 4 cm were counted as one stand for mangrove species density calculations. Data were collected three times during low tide conditions, with transects stretched perpendicularly from the shoreline to the mainland (pond). The distance from the shoreline to the transect is 1-2 meters long or adjusted to field conditions, as shown in Figure 5.

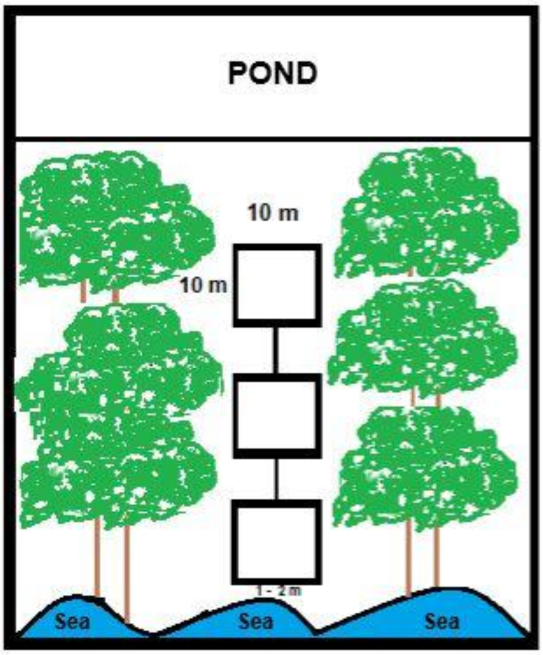

Fig 5. Transect sketch of data collection of mangrove vegetation (Saru, 2013)

The fourth stage was data collection and identification of marine debris. This process was carried out at the same location as the mangrove data collection, using a 10 m x 10 m plot that stretched perpendicularly from the shoreline towards the land (pond). The distance from the shoreline to the transect is about 1 meter. Garbage sampling was carried out three times during low tide conditions, with the parallel line principle at each observation station can be seen in Figure 6.

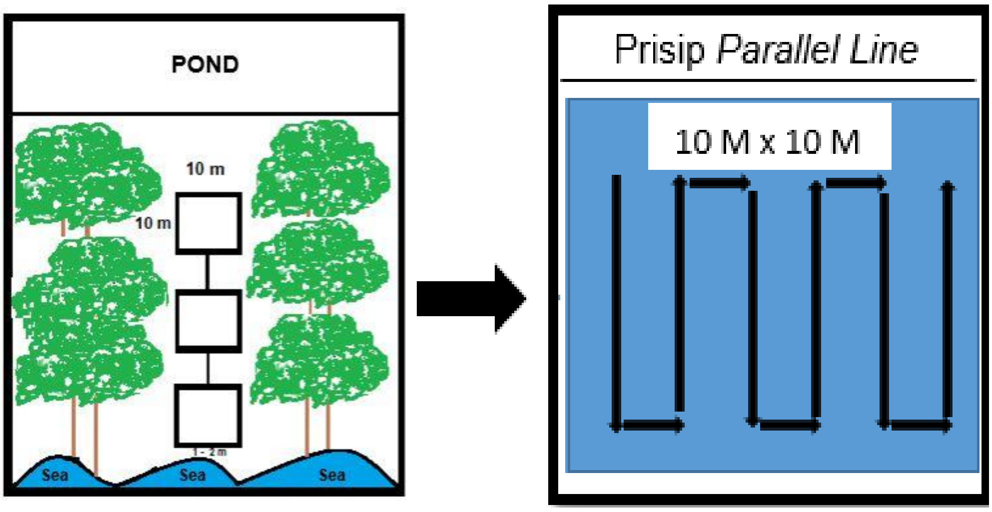

Fig. 6. Sketch of marine debris data collection transect (Opfer et al., 2012)

Samples of marine debris collected from each site were placed in trash bags. These samples were then dried, documented and characterized based on the debris classification by Cheshire et al. (2009) (Table 1). The mass of waste was weighed using a digital scale, and the length of each type of waste was measured with a ruler and meter. These measurements were taken to categorize the size of marine debris based on the classification proposed by Lippiatt et al. (2013) which distinguishes debris size into mega and macro categories. The fifth stage was the measurement of physical oceanographic parameters. Supporting data obtained included measurements of current direction, speed, and tidal data. Current speed was measured using a current kite placed in the waters around the data collection station. The current direction was determined using an aiming compass. A stopwatch was activated while releasing the current kite until the 10-meter rope was fully stretched. After that, the time to stretch the rope was recorded, and the current direction was determined using a compass. Tidal data was obtained from secondary data through the Geospatial Information Agency (BIG). The data were accessed through the BIG website by entering the research location's date, month, year, and geographical coordinates (latitude and longitude). Once the data was downloaded, analysis was carried out using an Excel application to process the tidal data. Overall, each data collection stage was designed to ensure the accuracy and relevance of the data in analyzing the relationship between mangrove ecosystems, marine debris abundance, and oceanographic conditions at the study site. This supports more in-depth research on anthropogenic impacts on coastal environments.

2.2 Data Processing

Data processing used to determine the abundance of marine debris (K) using the following Equation 1. The total waste abundance (K) is measured either in terms of the number of waste pieces per square meter (pieces/m^2) or by weight in grams per square meter (g/m^2). This value is calculated by considering the total amount of waste (n), which can be recorded as the total number of waste pieces or the total weight in grams, depending on the study's focus. The calculation also takes into account the total sampling area (A), measured in square meters (m^2), to determine the waste density within the specified area. This approach provides a standardized method for assessing waste abundance in environmental studies.

$$K = \frac{n}{a} \qquad \text{(Eq. 1)}$$

Data processing used to determine the density of mangrove species (Di) with the use of the following Equation 2. The density of mangrove species (Di) is expressed in terms of the number of trees per square meter (trees/m^2). This measurement is obtained by calculating the total number of trees of the i-th species (ni) within a designated sampling area (A), which is measured in square meters (m^2). This method helps determine the concentration of specific mangrove species in a given area, providing valuable data for ecological studies and conservation efforts.

$$Di = \frac{ni}{A} \qquad \text{(Eq. 2)}$$

$$v = \frac{s}{t} \qquad \text{(Eq. 3)}$$

Equation 3 describes the calculation of current velocity (V), which is measured in meters per second (m/sec). It is determined by dividing the current overpass travel distance (s), measured in meters, by the time taken (t) in seconds. This formula provides a straightforward way to assess the speed of water flow, which is essential for hydrodynamic studies and environmental assessments.

2.3 Data Analysis

The mean debris abundance at the three stations was statistically tested using the One-Way ANOVA method to determine whether there were significant differences in debris abundance among the stations. This method allows for the comparison of multiple groups – in this case, the three stations categorized by mangrove density: low, moderate, and high. The analysis aimed to evaluate how variations in mangrove density and anthropogenic activity at each station contribute to differences in debris accumulation.

Additionally, the relationship between mangrove density and marine debris abundance was assessed using the Pearson Correlation analysis. This statistical approach was employed to identify and quantify the strength and direction of the linear relationship between the two variables. A positive correlation would suggest that higher mangrove density is associated with increased debris accumulation, potentially due to the mangrove structure's ability to trap and retain waste. Conversely, a negative correlation would indicate that higher mangrove density reduces debris abundance, possibly due to the filtering capacity and ecological balance maintained by dense mangroves.

3. Results and Discussion

3.1 Site overview

This research location is around Kassikebo Pier, Talaka Village, Ma'rang Sub-district, Pangkajene and Islands Regency, South Sulawesi Province. Pangkajene and Islands Regency have an area of approximately 1,112.29 km^2 (Pangkajene and Islands Regency in Figures, 2016). The region consists of 13 sub-districts, namely Liukang Tangaya, Liukang Kalmas, Liukang Tupabbiring, Liukang Tupabbiring Utara, Pangkajene, Minasatene, Balocci, Tondong Tallasa, Bungoro, Labakkang, Ma'rang, Segeri, and Mandalle. Most of the Pangkajene and Islands Regency area is a coastal area with a coastline length of around ± 250 km, which is equipped with simple ports and docks to support the economic activities of coastal communities (Pangkajene and Islands Regency in Figures, 2016). Kecamatan Ma'rang, the research location, has an area of approximately 75.22 km^2. Administratively, the sub-district consists of 6 villages, one of which is Kelurahan Talaka. Kelurahan Talaka is approximately 30 km from the capital of Pangkajene and Islands Regency. Most of the area of Kecamatan Ma'rang is lowland, which is used for agricultural and plantation activities. In contrast, the coastal area is used for marine fisheries and aquaculture activities (Pangkajene and Islands Regency in Figures, 2016). Administratively, Ma'rang Sub-district is bordered by Segeri Sub-district to the north, Segeri and Bungoro Sub-districts to the east, Labakkang Sub-district to the south, and Liukang Tupabbiring Sub-district to the west.

The study was conducted at three observation stations, each representing a different level of mangrove density. Station 1 was located in a low-density mangrove area near settlements and aquaculture areas. Station 2 is located in a medium-density mangrove area, also in the aquaculture area. Station 3 was located in a high-density mangrove area around a river mouth. Each station point was selected to provide a comprehensive picture of the relationship between mangrove density, marine debris distribution, and other environmental parameters. This location was selected based on the characteristics of the Pangkajene and Islands Regency's strategic coastal area, which reflects the varied conditions of the mangrove ecosystem. With observations focused on three locations, this study explores the relationship between ecological factors, marine debris distribution, and the potential for sustainable coastal management.

3.2 Marine debris abundance and composition

The total number of mega debris items recorded across the study site, comprising three stations, amounted to 14 pieces. Station 3 exhibited the highest abundance of mega debris, with a total of 7 pieces, likely attributed to its location in high-density mangroves at the river mouth, which may act as a natural trap for debris carried by water currents. Station 1 had the second-highest amount of mega debris, with 4 pieces, potentially influenced by its proximity to residential areas and the Kassikebo Pier, where anthropogenic activities could contribute to waste deposition. Station 2, characterized by moderate mangrove density and aquaculture activities, recorded the lowest amount of mega debris, with only 3 pieces. The distribution of total mega debris across the three stations is depicted in Figure 7, highlighting variations influenced by environmental and human factors. Total mega debris can be seen in Fig 7.

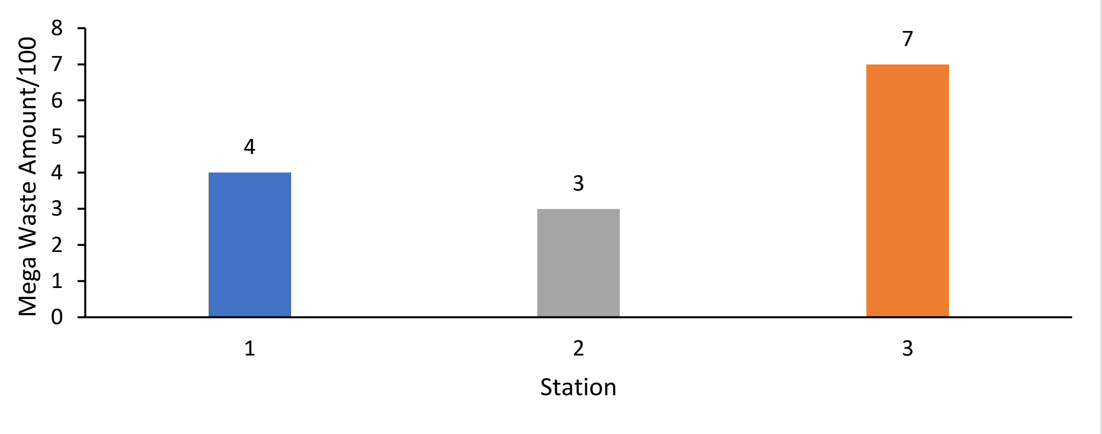

Fig. 7. Mega trash

The results obtained at the research site with the total amount of macro-waste at the three observation stations amounted to 649 pieces with a weight of 13,267 kg. The macro-waste category is dominated by plastic waste with a total of 429 pieces (66%) with a total weight of 5,148 kg (39%). Followed by wood waste which has a total of 150 pieces (23%) with a total weight of 4,955 kg (37%). The third highest amount of waste is other materials which has a total of 49 pieces (8%) with a weight of 0.250 kg (2%). The fourth highest amount of waste is fabric with a total of 6 pieces (1%) weighing 0.664 kg (5%). The fifth highest amount of waste is glass and ceramics with 5 pieces (1%) weighing 1.975 kg (15%). The sixth highest amount of waste was foam plastic with 4 pieces (1%), and paper and cardboard with 3 pieces, each weighing <0.100 kg. Rubber waste with 2 pieces and metal waste with the lowest amount of 1 piece weighing >0.110 kg (1%).

The overall results of the average abundance and composition of the amount of waste in the macro waste category at each station, the results obtained are station 1 of 0.45 ± 0.14 pieces / m2 with the percentage of the composition of the highest amount of plastic waste of 50%, station 2 obtained at 0.66 ± 0.17 pieces/m2 with the percentage of the composition of the highest amount of plastic waste of 68%, and station 3 obtained at 1.05 ± 0.32 pieces / m2 with the percentage of the composition of the highest amount of plastic waste of 72%. The overall results of the average abundance and weight composition of waste in the macro-waste category at each station obtained results namely station 1 of 7.97 ± 3.53 grams / m2 with the highest percentage of weight composition, namely plastic type waste of 35%, station 2 obtained at 14.75 ± 4.60 grams / m2 with the highest percentage of weight composition, namely plastic type waste of 37%, and station 3 obtained at 21.48 ± 9.05 grams / m2 with the highest percentage of weight composition, namely plastic type waste of 43%. Statistical test results for the abundance of the number and weight of macro-waste using the One Way Anova Test obtained a significant value of $P > 0.05$ or there was no significant difference in the abundance of the number and weight of waste between stations.

3.3 Mangrove density and thickness

Based on the results of the study found 3 types of mangroves that exist in the study site, namely Avicennia alba, Avicennia marina, and Rhizophora mucronata. The average density of mangrove species for each station obtained. At station 1 obtained mangrove Avicennia alba type with an average density value of 933 trees/ha and Avicennia marina 700 trees/ha which is included in the rare category. Station 2 obtained Avicennia alba mangrove with an average density value of 1300 trees/ha and Avicennia marina 500 trees/ha which is included in the medium category. While at station 3, Avicennia alba mangroves were obtained with an average density value of 2033 trees/ha and Rhizophora mucronata 600 trees/ha which included the tight category. Avicennia alba type is the most mangrove species found at each station. The thickness of mangroves at each station is station 1 is 32 meters, at station 2 is 54.8 meters, and station 3 is 51 meters. Where at station 3 there are many mangrove saplings. Average species density of mangroves at each station can be seen in Fig 8.

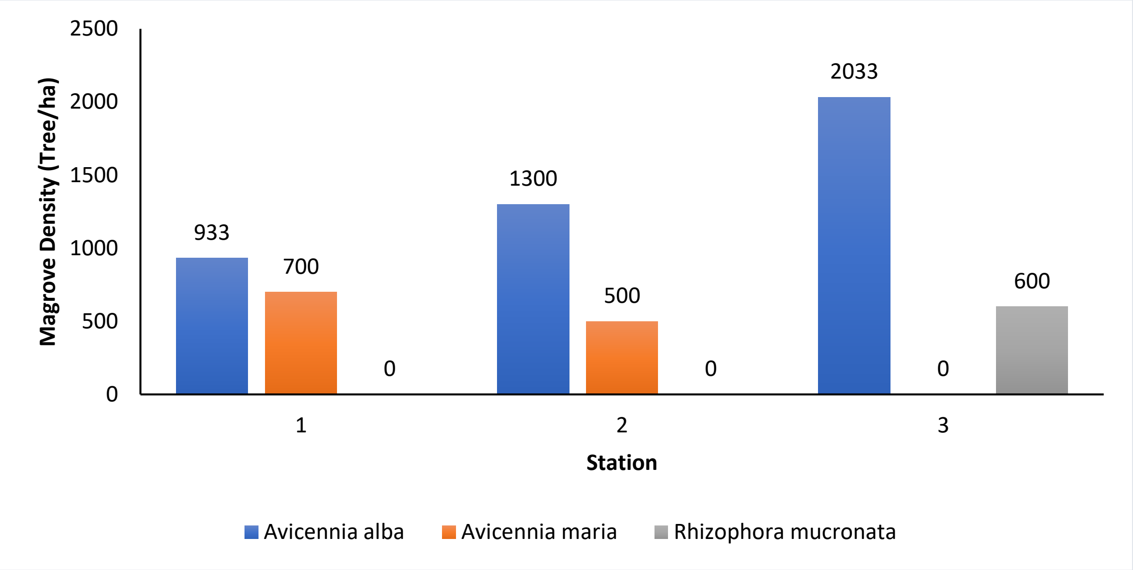

Fig. 8. Average species density of mangroves at each station

3.4 Relationship between mangrove density and marine debris abundance

The correlation analysis results between mangrove density and marine debris abundance revealed that the P-value (Significance) was greater than 0.05. This indicates that there is no statistically significant correlation between the abundance of debris and the density of mangroves. In other words, variations in mangrove density at the studied stations do not directly influence the amount of marine debris observed. These findings suggest that factors other than mangrove density may play a more dominant role in determining debris accumulation in the area. The results of the correlation between mangrove density and marine debris abundance obtained a fairly high value and positive value which is included in the strong category. The detailed results of the correlation analysis are presented in Table 1.

Table 1. Correlation results of mangrove density with marine debris abundance

		Waste Abundance	
		Total	Weight
Mangrove density	Correlation	0.610	0.496
	Significant	0.081	0.174
	N	9	9

3.5 Physical Oceanographic Parameters

The distribution of marine debris is influenced by several physical oceanographic factors such as currents and tides. Both oceanographic parameters affect the process of distribution and accumulation of marine debris in a place. Based on data from the measurement of current velocity using current kites, data on current speed and direction were obtained. The highest value of the current speed parameter at station 3 is 0.09 m/s, while the lowest is at station 1, which is 0.06 m/s. The three research stations did not show a significant difference in the average speed value; all were included in the slow current category. This is by the grouping determined by Mason (1981) that the value for the movement of water is speedy (>1 m/s), fast (0.5 - 1 m/s), medium (0.25 - 0.5 m/s), slow (0.01 - 0.25 m/s) and very slow (<0.01 m/s). The direction of arrival of the current from the three stations is from the northeast. Average current speed and direction be seen in Table 2.

Table 2. Average current speed and direction

Station	Distance (m)	Time (s)	Current Velocity (m/s)	Directions
1	10	172	0.06	Northeast
2	10	148	0.07	Northeast
3	10	113	0.09	Northeast

The tidal data in the research area is derived from secondary data from BIG (Geospatial Information Agency). Based on the estimated data obtained, the double daily tides (semi-diurnal tide), where the tides and ebb around Kassikebo Pier occur 2 times in high and 2 times in low. The lowest tide occurs in the time range of 10:00 - 12:00 WITA. The range of the highest tide and lowest tide is 1.295 meters. It is estimated that the spread of marine debris occurs when heading towards low tide, high tide, and high tide. Garbage data was collected during low tide conditions towards the tide, namely at 13.00 WITA. Marine debris collection at the three stations was carried out at station 3 on the 25th and stations 1 and 2 on September 26, 2021. Tidal and ebb conditions affect current conditions in terms of transporting waste. Tidal graph can be seen in Figure 9.

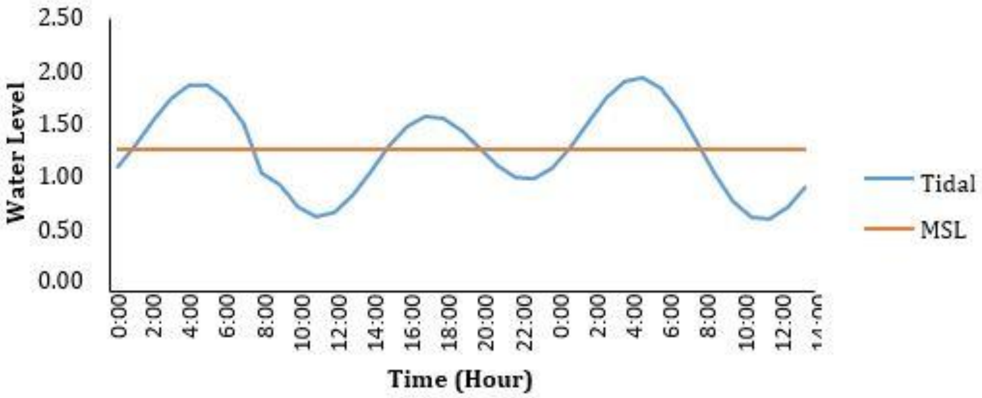

Fig. 9. Tidal graph

3.6 Marine debris abundance in mangrove ecosystems

Mega-sized waste was only found in small amounts in the study sites, both in Stations 1, 2, and 3. The total mega-waste identified in the three stations reached 14 pieces, mainly wood-type waste. This number is relatively low compared to macro-sized waste, as Silmarita and Fauzi (2019) reported that macro-sized waste is more dominant than mega-sized waste in various research locations. The mega-waste found in the study site is thought to come from community activities on land, given the presence of aquaculture areas and seaweed cultivation sites around the area. This aligns with Bamford (2013) statement that anthropogenic activities are the primary source of marine debris. Wood-type waste that dominates the mega waste category generally comes from mangrove tree branches. This result is consistent with the research of Hafizd et al. (2020), which showed that on Belacan beach, large pieces of wood and tree branches were evenly distributed on the coast with an average size of more than 1 meter, categorized as mega waste. This wood waste is also thought to be influenced by local community activities, such as seaweed cultivation, aquaculture activities, and houses and huts around the study site. This waste from the land is most likely carried from the coast to the sea by the flow of rainwater or the practice of dumping waste directly into the coastal area. In contrast, macro-waste was found in much larger quantities, totalling 649 pieces and weighing 13,267 kg. This finding is consistent with the research of Tahir et al. (2019), who reported that macro waste is the most abundant waste category in various research locations, including in Makassar and Takalar cities. Costa et al. (2011) also noted that the abundance of microplastics in mangrove sediments on the Northeast Coast of Brazil reached 70%. Santos et al. (2009) showed that styrofoam was the second largest macro-waste composition, with a proportion of 14%.

The dominance of plastic waste in the macro category is influenced by its physical properties, especially its low density, making it easier to be transported by water currents and wind (Ryan et al., 2009). NOAA (2015) also reported that plastic is the most common type of marine debris found worldwide and has the most significant impact on marine organisms. Thiel et al. (2013) added that the main components of plastic waste commonly found include plastic bags, fishing equipment, and food and beverage containers, with more than 80% stranded on beaches and surrounding areas. The most common types of plastic found at the research location were plastic bags and food containers. This result is consistent with Kadac-Czapska et al. (2023) and Muhib et al. (2023) research, which states that the dominant type of plastic is PL05, including beverage equipment, fast food containers, and the like. This plastic waste generally comes from community disposal in the island area or river flow that carries waste to the sea. This research emphasizes the importance of plastic pollution mitigation strategies through community-based waste management and stricter environmental policies to reduce the impact of plastic waste on coastal ecosystems, especially mangrove ecosystems.

This study's results show no difference in the average abundance of number and weight among the three stations ($P > 0.05$), but there is a difference in the abundance of the highest number and weight at station 3. The results of the abundance of the number and weight of marine debris in the macro-waste category at station 1 were obtained at 0.45 ± 0.14 pieces/m2 with the highest percentage of the composition of the number of plastic waste types by 50%. The results of the abundance of waste weight obtained amounted to 7.97 ± 3.53 grams / m2, with the percentage of the composition of the highest amount of the type of plastic waste of 35% consisting of 2L bottles, food containers, and transparent and opaque plastics. The location is closest to the Kassikebo pier, a crossing point to neighbouring islands such as Salemo Island and Sagara Island.

Station 2 had the highest abundance of 0.66 ± 0.17 pieces/m2 with the highest percentage composition of plastic waste at 68%, and the abundance of waste weight was 14.75 ± 4.60 grams/m2 with the highest percentage composition of plastic waste at 37%. The location of this study is far from community settlements but is around the area of aquaculture and seaweed cultivation by the local community. Seaweed cultivation activities around the data collection area use the floating method. In contrast, the constraints of this cultivation method are the fragility of plastic bottles and ropes used due to direct sun exposure and the ease of being carried by wind, currents, and tides so that they quickly bring plastic bottles and ropes to the coastal area. The data collection and observations at station 2, the local community's aquaculture and seaweed cultivation activities, are considered the main factor in the spread of marine debris and show that wood waste is the second highest waste after plastic. Wood waste still dominates for the second highest waste after plastic waste in stations 1, 2, and 3, which means that wood waste is quite dominant in coastal areas. This is to the statement of Paulus et al. (2020), which states that plastic is a widespread waste problem because it is a material that is difficult to decompose and is resistant to various environmental conditions. Meanwhile, Zhukov (2017) explains that plastic is a waste material that is distributed and fills all parts of the coast and ocean due to high human activity and population. Plastic is important because it is used for daily economic needs, especially in countries with large populations and consumption, such as Southeast Asia (Paulus et al., 2020).

At station 3, the highest abundance of plastic waste was 1.05 ± 0.32 pieces/m2, with the highest percentage of plastic waste composition of 72% and the highest abundance of plastic waste weight of 21.48 ± 9.05 grams/m2 with the highest percentage of plastic waste composition weight of 43%. This research location is also far from residential areas but close to seaweed cultivation areas and river estuaries, the most significant contributing sources of marine debris. The research also characterises the location by the characteristics of coloured garbage found at this station. The abundance of the number, weight, and composition of waste in the macro waste category at each station had the highest abundance values in densely populated areas and close to river estuaries (Isobe et al., 2019; Nguyen et al., 2024). This shows that the accumulation of macro waste comes from the upstream part of the estuary. Station 3 has the fastest current movement compared to stations 1 and 2, with a current velocity value of 0.09 m/s. The current velocity data was collected during high tide conditions where the wind blows from the southwest to the northeast. This tidal movement pattern is thought to be the spread of marine debris in the research location during high tide to low tide conditions so that the garbage goes to the mangrove ecosystem and settles during low tide and low tide conditions. Tides can also affect the accumulation of garbage in a place due to high waves and have the potential to stir up garbage in the water column or settle on sediments or substrates to the surface so that currents easily carry it and accumulate somewhere. This differs from the current pattern in Takalar, South Sulawesi. When heading towards the tide, the current tends to head north, while at the time of the ebb, the current tends to head south. Marine debris is thought to be carried by the river flow and experience accumulation in the estuary area (station 3), which is thought to be caused by a decrease in current speed. This is the cause of the high abundance of garbage at station 3. In addition, the presence of river flow at station 3 is thought to be the primary source of garbage entering the waters.

3.7 Relationship between mangrove density and marine debris abundance

Based on the observations in the field, the average density of mangrove species for each station, Station 1 has a mangrove density with a sparse category near the crossing pier to the surrounding islands such as Salemo island and Sagara island. This area is also often visited, and there are several houses around the pier, so activities like this allow the spread of waste at this station. Station 2 has a mangrove density with a moderate category, is near the aquaculture area, and has seaweed cultivation activities by the local community. Station 3 has a mangrove density with a dense category, which is close to the seaweed cultivation area and is in the river estuary area. The mangroves at the station grow well, so the distribution still has the potential to accumulate at this location. Avicennia alba is the type of mangrove that is most commonly found at each station; this is in accordance with the results of research by Hastuti et al. (2014) that mangrove vegetation, especially Avicennia marina and Avicennia alba, can trap macro debris through the shape of its roots. Avicennia marina has a root shape like a chicken claw with many breath roots. This root shape can trap macro debris that enters the mangrove ecosystem. The higher the density of Avicennia marina trees, the higher the abundance of macro debris.

In contrast to the type of Rhizophora mucronata, which has a stick root shape, it is evident that this stick root is less able to trap macro debris. This is reinforced by the explanation by Ryan et al. (2009), which states that the problem of plastic waste contained in mangrove ecosystems is that the composition of plastic-type waste is more dominant than the density of other types of marine debris, so it is easily transported to any area. Yin et al. (2019), in their research in Penang, Malaysia, explained that along the mangrove area, which is related to waste, mangrove trees and root structures efficiently hold waste from land waste to the sea or vice versa. Mangroves can sort the accumulation of garbage to be deposited or released, especially at the highest tide conditions, into the water column. Based on the Pearson Correlation analysis results between mangrove density and marine debris abundance, a reasonably high correlation value was obtained with a positive relationship direction. This indicates that the abundance of marine debris tends to increase as mangrove density increases, although this relationship is not statistically significant. The analysis showed a significance value of ($P > 0.05$), meaning there is no significant relationship between the two variables. However, the correlation values were 0.610 for litter abundance and 0.496 for litter weight abundance, respectively, which fall into the moderately strong and positive relationship category. This means that the denser the mangrove ecosystem, the greater the likelihood of marine debris being trapped in the area, both in number and weight.

These results align with research by Debrot et al. (2013) conducted in the mangrove area of Lac Bay, Bonaire Island, the Netherlands, in October 2010. The study found that mangroves in the region function as natural traps for marine debris, with the main composition being plastic (39%) and wood (40%). This process is influenced by factors such as wind, currents and tides. In addition, Ivar do Sul et al. (2014) research showed that plastic bags are more easily trapped and persist in mangrove ecosystems than other types of waste. Plastic waste can last for six months or more (March-September), and the dynamics of ocean currents and tides strongly influence its presence. Martin et al. (2019) also found that the mass of plastic waste trapped in mangrove ecosystems was higher than that of sandy beaches. This finding reinforces the hypothesis that mangroves serve as natural traps for marine debris and act as physical barriers that prevent anthropogenic debris from spreading further into the marine environment. In summary, the results of this study support the view that mangrove ecosystems have a dual role: as traps for marine debris, particularly plastics, and as natural barriers that prevent debris from spreading to larger water areas. However, while the relationship between mangrove density and marine debris abundance is strong, further research is needed to explore the mechanisms underlying this relationship, including the influence of environmental variables such as current type, topography and human activity patterns.

4. Conclusions

Based on the results of the study and the objectives to be achieved in this study, it can be concluded that the most dominant types of marine debris found at Kassikebo Pier are plastic waste and macro-sized wood, with a total of 429 pieces and 150 pieces and weighing 5.148 kg and 4.955 kg respectively. Mangrove species found at the research site include Avicennia alba, Avicennia marina, and Rhizophora mucronata, where Avicennia alba is the most common mangrove species found at each station. Mangrove density positively correlated with marine debris abundance, although the relationship was not statistically significant. This suggests that denser mangrove ecosystems tend to retain more marine debris.

The results of this study are expected to be a reference for the Pangkep Regency Government to improve waste management efforts, especially plastic waste around Kassikebo Pier. In addition, strategic steps such as encouraging the community to apply the principles of reuse, reduction, and recycling in the use of plastic products are essential to reducing the burden of marine pollution in the area. Furthermore, the results of this study also emphasize the importance of sustainable mangrove ecosystem management. Local governments, communities and related institutions should consider integrating marine debris management strategies into mangrove conservation plans. Public education and awareness programs on the impacts of marine debris on coastal ecosystems, including mangroves, need to be improved to create synergies for environmental conservation and sustainable natural resource management. Thus, this study provides scientific contributions and practical inputs that can support mangrove ecosystem management policies and marine debris reduction in the Kassikebo Pier area. Further research with a broader area coverage and multidisciplinary approach is recommended to gain a more comprehensive understanding of the dynamics of the relationship between mangrove density and marine debris distribution.

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Author Contribution

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