



Accumulation, Composition, Density, and Volume of Marine Litter on Palu Bay

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Abstract

Marine litter poses an increasing threat to the coastal ecosystem of Palu Bay, Indonesia, driven by contrasting land-based human activities. This study assessed the accumulation, composition, density, and volume of macro-debris (>2.5 cm) at four coastal stations representing residential, river-influenced, and tourism-dominated areas. Surveys were conducted from June to September 2025 using a line transect method. The results showed marked spatial differences in marine litter characteristics. Residential and river-influenced sites (Baiya and Mamboro Beaches) recorded the highest debris weights (4003.67–4378.22 g/m²), dominated by heavier household waste transported via river systems. In contrast, tourism areas (Taman Ria and Kampung Nelayan Beaches) exhibited lower debris weights (1697.67–1892.37 g/m²) but significantly higher item densities (14.46–17.28 items/m²) and volumes, reflecting the dominance of lightweight, single-use plastics from recreational activities. Plastic debris dominated all stations, exceeding 94% in tourism zones. These findings demonstrate a clear dichotomy in litter sources and characteristics between tourism and residential areas, underscoring the need for targeted management strategies. Effective mitigation should prioritize single-use plastic restrictions, adequate waste facilities, and visitor awareness in tourism areas, alongside improved household waste collection and riverine waste control in residential watersheds. Such source-specific approaches are essential for sustainable coastal management in Palu Bay and comparable semi-enclosed bays.

Keywords: marine debris; macroplastics; coastal pollution; river inputs; tourism impact.

1. INTRODUCTION

Coastal and marine ecosystems are vital for supporting human life. The population residing within 100 km of the coast is substantial, estimated at 2×10^9 people—approximately three times the global average population density (1.2 billion in 2002) [1] and is projected to increase by 50% by 2030 [2]. A significant portion of humanity inhabits areas within 10 meters above sea level [3]. Consequently, the burden on these coastal and marine environments from human activities is intensifying [4]. Nearly half (43.3%) of all protected coastal areas worldwide are exposed to intense human pressure [5], underscoring the high vulnerability of coastal zones to anthropogenic activities [6]. Conversely, coasts and oceans provide essential resources for human needs [7], [8], including a significant portion of global food from fisheries [9].

The pressure on coastal and marine environments is further exacerbated by the increasing input of waste from human activities and natural processes. Land-based waste is transported to estuaries and drifts into the ocean. This debris, once in the marine environment, is carried by currents and is collectively termed "marine litter" [10]. Marine litter is defined as any persistent, manufactured, or processed solid material discarded, abandoned, or lost in the marine and coastal environment. It includes items deliberately discarded, accidentally lost, or transported from land via rivers, drainage systems, or sewage networks, eventually carried by water currents and wind [11]. Common examples include plastic, wood, metal, glass, rubber, clothing, paper, and other solid refuse.

Marine litter is a pressing issue in the coastal area of Palu Bay. The amount of debris increases annually due to population growth [12], yet there is no clear indication of implemented marine litter management strategies. The origin, distribution, type, and volume of marine litter are often difficult to predict. This study



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aims to scientifically observe the phenomenon of marine debris distribution. The research focuses on macro marine debris (size > 2.5 cm to 1 m) [13], [14] along the coast of Palu Bay across four (4) observation stations. The plastic waste was collected, weighed, measured, and identified by type and potential source.

This study aims to analyze the types, weight, and density of marine litter on the coast of Palu Bay. Research on marine debris remains scarce compared to other coastal management studies. This research estimated the accumulation, composition, density, and volume of marine litter on Palu Bay. The findings are expected to provide evidence-based recommendations for marine litter management to policymakers, serving as a reference for developing more effective and sustainable coastal management policies.

2. METHODS

2.1. Study Location

This study was conducted at four observation stations along the coast of Palu Bay. Station 1 was located in Baiya Village and Station 2 in Mamboro Village, both representing residential and riverine-influenced areas on coastal areas. Station 3 was situated at Taman Ria Beach and Station 4 was located at Kampung Nelayan Beach both representing tourism area. Field observations were conducted from June to September 2025. These stations were selected to represent different coastal characteristics influenced by marine debris. The locations of the study stations are shown in Figure 1.

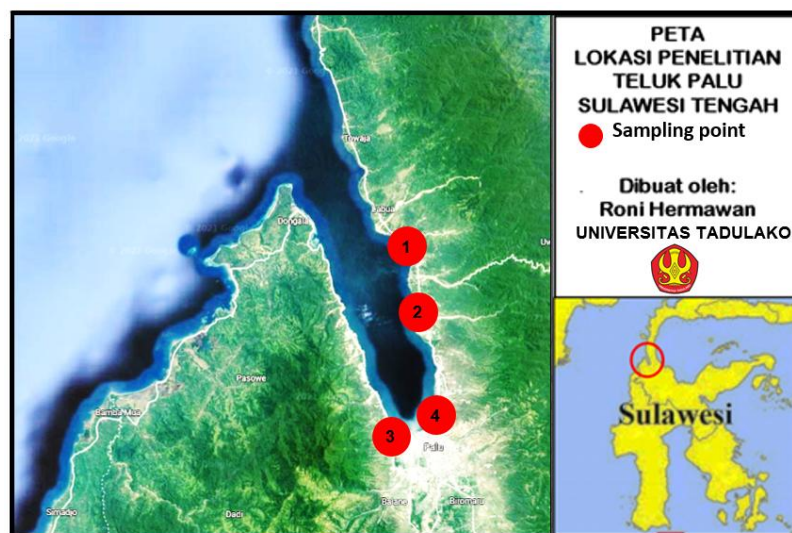


Figure 1. Study Location

2.2. Marine Debris Data Collection Technique

Debris data were collected using the line transect method to identify the type, weight, quantity, and volume of the debris. The size of the debris observed had a cross-sectional area of >2.5 cm, classifying it as macro-debris [15].

2.3. Beach Litter Sampling

Beach litter consisted of marine debris stranded on the shore by currents or waves. The observation stations, located in beach tourism areas, were dominated by remnants of food and beverage packaging. Litter sampling was performed using a transect sampling method. Sampling (Figure 2) was conducted within a 5-meter wide transect, with the length following the width of the beach. Observations were carried out during the lowest low tide in the intertidal zone. The length of the beach observed was 50 m, in accordance with [15]. All solid marine debris was collected, cleaned, and gathered into large sacks or plastic bags. Subsequently, the debris was sorted by type and according to the predetermined locations. The quantity, type, and weight of the solid marine debris were then analyzed [7], [13], [16].

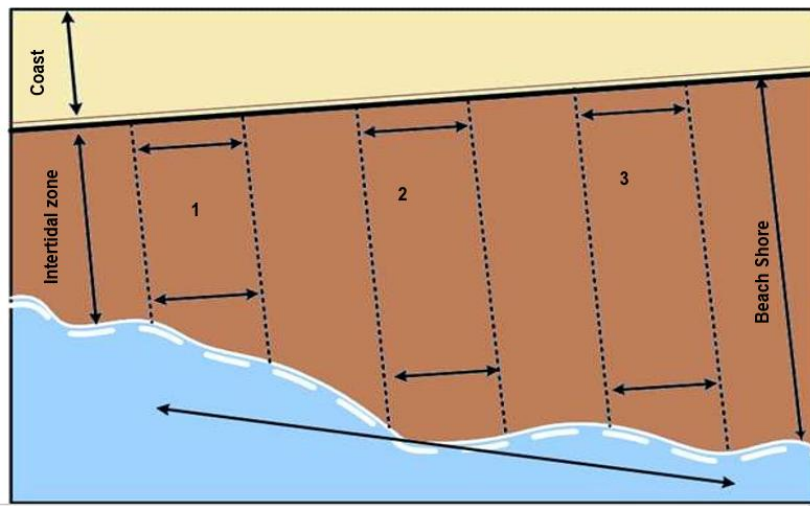


Figure 2. Transect Sampling Method

2.4. Data Analysis

The analysis was conducted to determine the composition and density of the marine debris. Sample analysis was performed using the following formula [13]:

- a. Marine litter weight (g/m^2)

$$\text{Marine litter weight } (\text{g}/\text{m}^2) = \frac{\text{Marine debris weight } (\text{g})}{\text{area } (\text{m}^2)} \quad (1)$$

- b. Density (item/m^2)

$$\text{Density } (\text{item}/\text{m}^2) = \frac{\text{Number of objects counted } (\text{item})}{\text{area } (\text{m}^2)} \quad (2)$$

- c. Marine debris volume was measured directly and averaged

3. RESULTS AND DISCUSSION

Interesting variations in macro-debris were observed between the observation stations in Palu Bay. Based on the weight per unit area (g/m^2), the highest value was recorded at Station 2 in Mamboro Village, with an average marine debris weight of $4378.22 \text{ g}/\text{m}^2$, followed by Station 1 at Baiya Beach at $4003.67 \text{ g}/\text{m}^2$ (Figure 3). Lower debris weights were found at Station 3 Taman Ria Beach tourism area and Station 4 Kampung Nelayan Beach tourism area, which were measured at $1697.67 \text{ g}/\text{m}^2$ and $1892.37 \text{ g}/\text{m}^2$, respectively.

A different pattern was observed in the item density per square meter (items/m^2) (Figure 4). A much higher density was shown at Station 4 was $17.28 \text{ items}/\text{m}^2$ and Station 3 was $14.46 \text{ items}/\text{m}^2$ compared to Station 1 was $6.82 \text{ items}/\text{m}^2$ and Station 2 was $7.23 \text{ items}/\text{m}^2$. This discrepancy indicated that the debris at the tourism areas of Stations 3 and 4 was dominated by lighter but more numerous items, whereas the debris at Stations 1 and 2 likely consisted of heavier and more compact materials. These findings were supported by the volumetric data per meter square (m^3/m^2) (Figure 5), which showed the highest debris volume at Station 4 was $0.48 \text{ m}^3/\text{m}^2$ and Station 3 was $0.45 \text{ m}^3/\text{m}^2$, demonstrating that the debris at these stations had a higher volume but was lighter than station 1 ($0.22 \text{ m}^3/\text{m}^2$) and station 2 ($0.19 \text{ m}^3/\text{m}^2$). The weight and volume of the debris were determined significantly by its type; Stations 3 and 4 were dominated by plastic debris types that had a larger volume but a lighter weight.

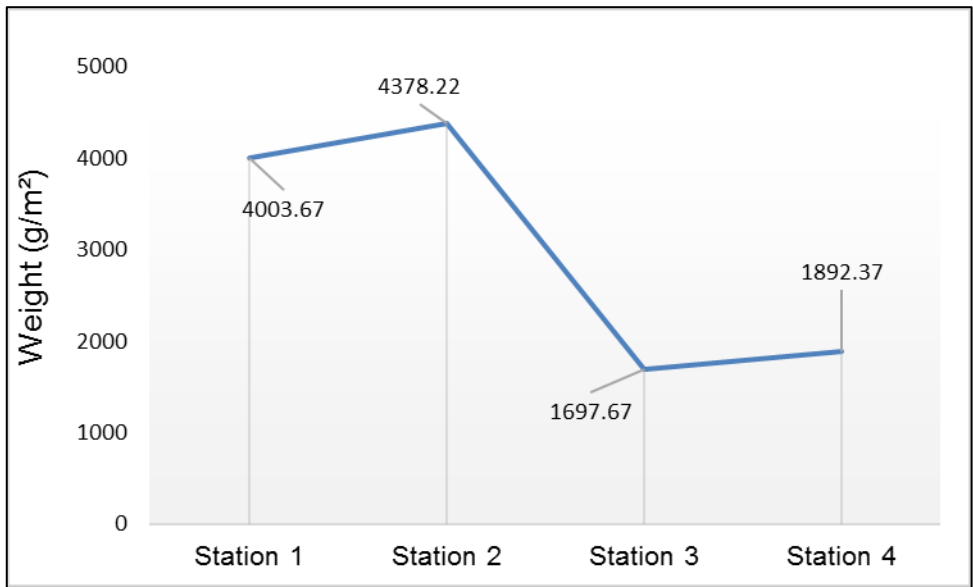


Figure 3. Average Marine Debris Weight (g/m²)

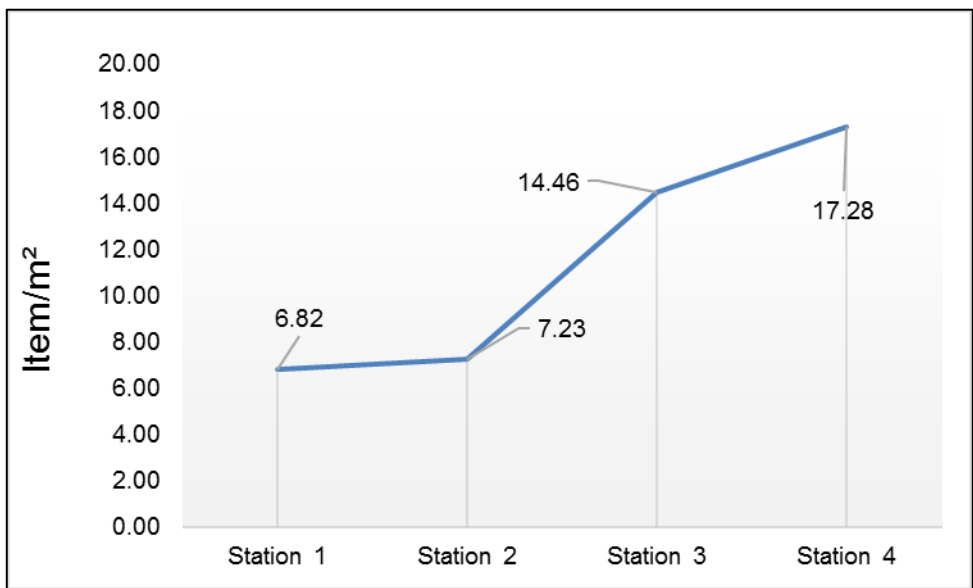


Figure 4. Average Marine Debris Item Density (item/m²)

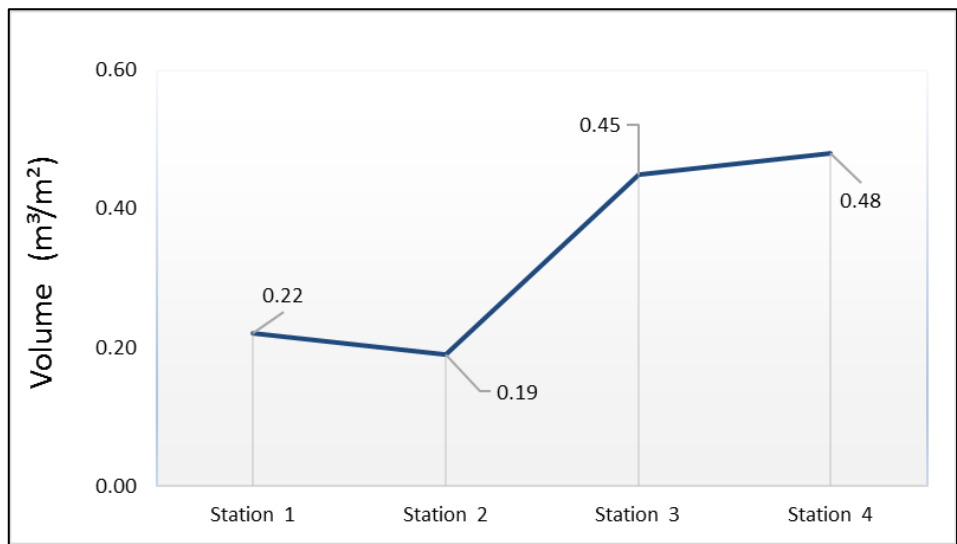


Figure 5. Average Marine Debris Volume (item/m³)



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Debris composition was dominated by plastic material at all stations, albeit with different types and sources. At the beach tourism areas of Stations 3 and 4, plastic debris had a very high percentage (Table 1 and Figure 6), at 94.31% and 95.35%, respectively. This debris was predominantly composed of snack wrappers, plastic straws, plastic spoons, plastic cups, and various plastic beverage bottles, remnants of tourist activities around the observation stations.

Station 3 is a coastal tourism area at the head of Palu Bay and is adjacent to the Palu River estuary. Palu Bay terminates at the estuary of the Palu River, with Palu City itself being bifurcated by this river (Figure 1). Activities occurring around the Palu River if not managed properly, will ultimately impact its estuary, rivers are a primary pathway for land-based waste to enter the marine environment [17], [18], [19], [20]. Inadequate waste management of community activities along the river will consequently affect the sea [21], [22], [23], [24]. Riverine waste is ultimately deposited in estuaries, riverbanks, coastal shores, the water surface, and the seafloor [16], [25], [26], [27], [28].

Observations at Station 4, the coastal tourism area of Kampung Nelayan showed that the waste originates predominantly from tourism activities, the majority of tourists were local visitors. Kampung Nelayan Beach is a popular local destination due to its proximity to Palu City. Despite the presence of littering prohibition signs and trash bins in several locations, non-compliance among tourists remains prevalent. The percentage of plastic waste was 95.35% (Table 1) recorded at this station consists entirely of plastic remnants, plastic packaging, bottles, cups, spoons, straws, bags, rubber, lighter, diapers, and other items. Tourist activity increase significantly during holidays and weekends. The beach offers various attractions, such as swimming, shoreline cafés, restaurants, accommodations, street vendors, and tourist boats. Coastal tourism is a contributor to marine debris [29], [30]. Conversely, tourism is highly susceptible to the impacts of waste, as visitors inherently prefer clean, litter-free environments [31], [32]. Therefore, maintaining tourism locations free from both natural and anthropogenic debris is essential [33], [34], [35]. Clean beaches enhance visitor comfort and increase tourist visits, which in turn supports the local economy [36], [37].

Table 1. Type of Marine Debris

Sampling Point	Plastic (%)	Metal (%)	Glass (%)	Paper (%)	Fabric (%)	Rubber (%)	Proceed Wood (%)
Station 1	68.56	2.51	3.82	3.72	1.13	1.52	18.74
Station 2	75.23	1.73	2.34	2.16	1.98	7.44	9.12
Station 3	94.31	0.20	1.46	1.98	0.31	1.74	0
Station 4	95.35	0.65	0.73	2.02	0.49	0.76	0

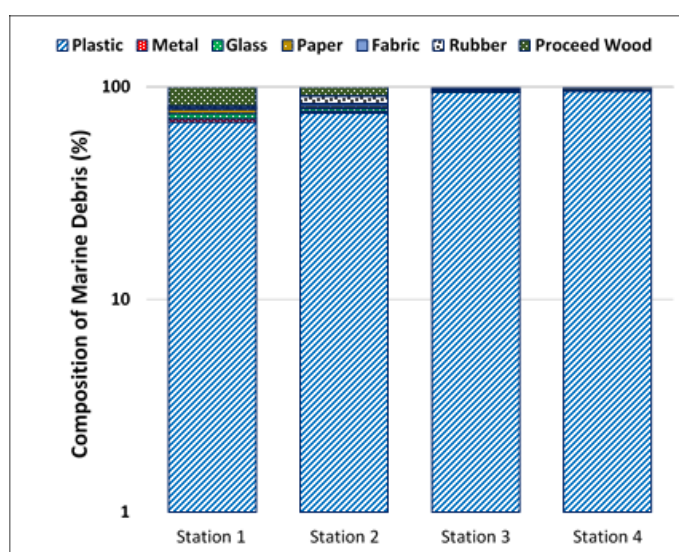


Figure 6. Composition of Marine Debris (%)

At Station 1 Baiya Beach and Station 2 Mamboro Beach, the percentage of plastic debris was slightly lower, at 68.56% and 75.23%, respectively. The plastic debris at Stations 1 and 2 was dominated by household waste, such as glass, cloth, tire, detergent packaging, plastic bags, sacks, nylon ropes, baby diapers, plastic baskets,



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plywood and various other plastic packaging fragments, suspected to originate from household activities carried by river flow or from nearby settlements.

Station 1 on Baiya Beach was located adjacent to a residential area. In addition to housing, the vicinity also features an oil processing industry, warehouses, dormitories, a port, a military zone, and a fishing community. The range of community activities in Baiya Village is highly diverse, with only a small proportion of the population working as full-time or part-time fishermen. Consequently, only a minority of the Baiya community actively concerns itself with the coastal environmental condition. Following the 2018 tsunami disaster, a significant number of residents have been reluctant to return and resume livelihoods as fishermen. They predominantly choose to reside and seek employment away from the coastline [37], [38], [39] or engage in fishing only as a secondary occupation. This condition has led to diminished community attention and commitment towards maintaining the condition and cleanliness of the marine environment.

Field observations at Station 1 showed the presence of household waste, which was either discarded directly or burned along the shoreline. The Palu City government and Baiya Village authorities have actually prohibited residents from dumping or burning waste through *Peraturan Daerah Kota Palu Nomor 11 Tahun 2013 tentang Pengelolaan Sampah*. However, inadequate waste collection fleet capacity results in incomplete service coverage across all areas, including the Baiya Beach region.

The dominance of plastic debris, exceeding 90% in the tourism areas, indicates a weak waste management system and low environmental awareness among visitors [40], [41]. The item density per unit area at Stations 3 and 4, despite a lower total weight, reflects the characteristic of lightweight and numerous packaged plastic waste. Therefore, different management strategies are required, such as the provision of adequate waste bins, a ban on single-use plastics in tourism areas, and educational programs for tourists. For Stations 1 and 2, the key approach lies in improving household waste management in the river basins flowing into Palu Bay.

Marine debris distribution in Palu Bay showed clear spatial differences linked to land-based activities. Residential and river-influenced areas (Stations 1 and 2) recorded the highest debris weights (4003.67–4378.22 g/m²), reflecting the accumulation of heavier household waste transported by river systems. In contrast, tourism areas (Stations 3 and 4) exhibited lower debris weights (1697.67–1892.37 g/m²) but higher item densities (14.46–17.28 items/m²) and volumes (0.45–0.48 m³/m²), indicating dominance of lightweight, single-use plastics from recreational activities. These contrasting patterns highlight distinct debris sources and emphasize the value of integrating weight, density, and volume metrics for targeted coastal management.

4. CONCLUSION

This study demonstrates distinct marine debris profiles in Palu Bay, directly linked to land-based activities. Tourism areas Stations 3 and 4 are polluted by high densities of lightweight, single-use plastics from visitors, highlighting inadequate waste management and low environmental awareness. In contrast, residential zones Stations 1 and 2 accumulate heavier, household-sourced debris, transported via river systems and exacerbated by insufficient waste collection services.

Effective mitigation requires targeted strategies: enforcing single-use plastic bans and improving tourist facilities in coastal resorts, while enhancing household waste management and riverine cleanup programs in residential watersheds. Sustainable coastal health in Palu Bay depends on these prioritized, source-specific interventions. These contrasting debris profiles highlight the need for source-specific management strategies. The findings are applicable to other semi-enclosed bays with similar urbanization, riverine inputs, and tourism pressure, supporting targeted interventions for effective and sustainable coastal debris management.

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