Characteristics of anthropogenic solid waste in some mangrove ecosystems of East Java, Indonesia

Catur Retnaningdyah[1*], *Viky* Vidayanti[1]

[1]Biology Department, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya, Malang, Indonesia

Abstract. Some mangrove ecosystems in East Java, Indonesia have a serious problem, i.e. the degradation of ecosystem quality caused by anthropogenic solid waste pollution dominated by macroplastics from human activities in the surrounding area. This study aimed to evaluate the characteristics of anthropogenic solid waste trapped in the mangrove ecosystem and its impact on changes in the qualities of water and sediment. This research used the ex post facto method in ten mangrove ecosystems of East Java with different anthropogenic activities including Trenggalek (Cengkrong), Malang (Gedangan and Kondang Merak), Pasuruan (Penunggul), Probolinggo (Pantai Duta), Situbondo (Dubibir and Blekok), Surabaya (Gunung Anyar and Medokan Ayu) and Banyuwangi (Alas Purwo National Park/APNP). At each location, anthropogenic solid waste was monitored, including plastic, metal, glass, rubber, paper, cloth, and other waste, by making three plots with each size of 5 x 1 m^2. The research results showed that the density ratio of plastic to non-plastic anthropogenic waste in ten mangrove ecosystems in East Java was 55:45. The mangrove ecosystems in Dubibir, Penunggul, and Cengkrong have moderate anthropogenic solid waste. The mangrove ecosystems in Kondang Merak, Gedangan, Duta, Medokan Ayu, and Gunung Anyar have low to moderate anthropogenic solid waste densities. The mangrove ecosystem in APNP has the lowest anthropogenic solid waste density. Based on the results of data analysis, it can be seen that high human activity will have an impact on increasing anthropogenic solid waste. Thus, solid waste management in the mangrove ecosystem is needed to control human activities around the mangrove ecosystem. Sampling was carried out in 11 mangrove ecosystems of Sawahmulya.

1 Introduction

Mangrove ecosystems are riparian ecosystems that are located between terrestrial and marine environments. In East Java, mangrove ecosystems are widely distributed along river estuaries and coastal areas on both the southern and northern coasts [1, 2]. The total mangrove area along East Java's southern and northern coasts is approximately 18,253.87 hectares [3].

* Corresponding author: catur@ub.ac.id

However, this ecosystem has been degraded due to anthropogenic activities, including land-use changes for settlement, agriculture, aquaculture, industrial development, and illegal logging for firewood, charcoal, or commercial purposes. This degradation reduces species diversity within the mangrove ecosystem, leading to declines in ecosystem stability and the loss of critical habitats for mangrove-associated biota [4, 5].

A critical issue affecting nearly all ecosystems, including mangrove ecosystems in East Java, is solid waste pollution, predominantly from anthropogenic activities. Solid waste encompasses materials in the form of plastics, metals, glass, rubber, paper, wood products, textiles, and other miscellaneous debris [6-8]. Research findings indicate that the most prevalent type of marine debris in the coastal area such as at West Bali National Park, was plastic waste, comprising 92% of the total domestic solid waste. This includes 44.8% soft plastics, 30.8% foam, 12.4% hard plastics, 3.4% plastic straps, and 0.5% fishing-related debris [9].

Plastic macro-waste, such as bottles, bags, and packaging materials, as well as microbeads released from personal care products and cosmetics, can degrade through processes like UV photooxidation, driven by high-energy wavelengths, followed by thermo-oxidation influenced by temperature and oxygen availability. This degradation breaks down plastic into microparticles or fragments measuring 100 nm to 5 mm, known as microplastics [10-14]. Microplastics (MPs) in ecosystems can profoundly impact soil, water, and air quality due to their persistence and tendency to accumulate within various environmental matrices. MPs can also accumulate in the tissues of organisms inhabiting these ecosystems, resulting in detrimental impacts on their behavior, growth, reproduction, tissue integrity, and physiological functions [15-20].

Given the essential conservation functions of the mangrove ecosystem—including coastal protection against waves, storms, floods, and abrasion, as well as the prevention of seawater intrusion, and roles as a trap, sediment stabilizer, nursery ground, and feeding ground supporting both aquatic and terrestrial biota [21, 22]—it is imperative to evaluate anthropogenic waste in various mangrove ecosystems across East Java. Such an evaluation will serve as a critical foundation for developing effective waste management strategies to preserve and enhance the ecological integrity of East Java's mangrove ecosystems.

2 Materials and methods

2.1 Study site

Sampling for the study was conducted in ten selected mangrove ecosystems across East Java which have different environmental quality and anthropogenic activities included in Trenggalek (Cengkrong), Malang (Gedangan and Kondang Merak), Pasuruan (Penunggul), Probolinggo (Duta Beach), Situbondo (Dubibir and Blekok Beach), Surabaya (Gunung Anyar and Medokan Ayu), and Banyuwangi (Alas Purwo National Park/APNP or TNAP). Water quality assessments were conducted at the Laboratory of Ecology and Tropical Ecosystem Restoration Laboratory and the Microbiology Laboratory of the Department of Biology at the Faculty of Mathematics and Natural Sciences, Brawijaya University, Malang.

This ex post facto study aimed to evaluate the characteristics of anthropogenic waste—specifically the composition and quantity of waste—accumulated in the mangrove ecosystem, as well as to compare macroplastic waste with other waste types. The independent variables in this study included environmental conditions, which were assessed based on naturalness and hemeroby index values. Sampling in each selected mangrove ecosystem was conducted randomly at three adjacent sites as replication to enhance data reliability.

Fig. 1. Ten mangrove ecosystems as the sampling locations for the research.

2.2 The technique for measuring macro-anthropogenic waste in mangrove ecosystems and environmental factor analysis

The characteristics of anthropogenic waste observed in this study include the composition and types of waste trapped within the mangrove ecosystem at each sampling location. Sampling was conducted by establishing 5 x 1 m^2 plots during low tide, allowing for easy identification of waste types or composition and for measuring the weight of each waste type found. The density or weight of waste was calculated based on the quantity of each waste type per unit area. In this study, plastic waste categories included PETE (Polyethylene Terephthalate), HDPE (High-Density Polyethylene), V (Vinyl or PVC – Polyvinyl Chloride), LDPE (Low-Density Polyethylene), PP (Polypropylene), PS (Polystyrene), and other plastics (e.g., ropes, plastic sacks). Non-plastic waste types observed included cloth, glass, rubber, paper, toxic materials, diapers, life jackets, masks, and metal. This data was subsequently used to calculate the ratio of macroplastic waste to other types of anthropogenic waste trapped within the mangrove ecosystems of East Java.

In each selected mangrove ecosystem, observations of human activities and land-use quality were conducted. Land-use quality was assessed descriptively by observing the degree of naturalness and habitat disturbance, which were evaluated based on the Naturalness and Hemeroby indices [23, 24]. This approach aims to gather information on land-use patterns that may influence the quality profile and condition of mangrove vegetation.

2.3 Data analysis

The monitoring data were utilized to analyze the profile of macroplastic waste within the mangrove ecosystem, as well as to assess the human activity profile based on the Hemeroby and Naturalness indices. The outcomes of the profile calculations were then used as a foundation for categorizing the characteristics of macroanthropogenic waste across various mangrove ecosystems in East Java, employing biplot analysis through Principal Component Analysis (PCA). The findings of this study are anticipated to provide a basis for recommendations regarding the management of macroanthropogenic waste in the mangrove ecosystems of East Java.

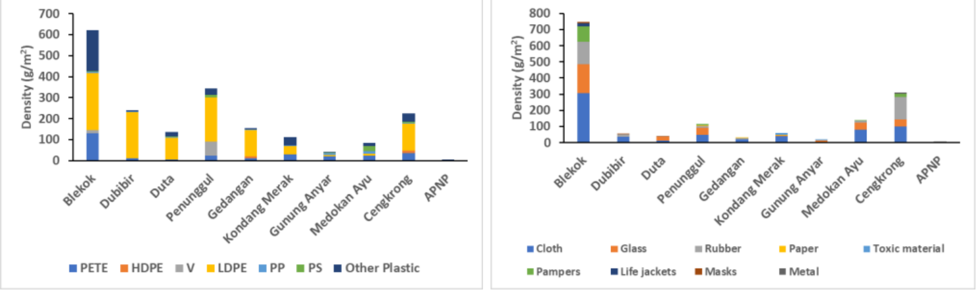
3 Results and discussions

3.1 Composition and density of macroanthropogenic waste in some mangrove ecosystems in East Java

In the ten monitored mangrove ecosystems in East Java, the composition and density of anthropogenic waste exhibited significant variability. This waste is likely sourced from upstream areas and transported by river currents to the estuary, where it becomes deposited within the mangrove ecosystem. The study results indicated that macroanthropogenic waste, comprising various types and densities, was consistently present across all ten mangrove ecosystems in East Java (Fig. 2 and 3).

Among these ecosystems, the APNP mangrove ecosystem demonstrated the highest quality, characterized by the lowest plastic and non-plastic waste densities, measured at 3.35 g/m² and 6.9 g/m², respectively. In contrast, the Blekok mangrove ecosystem exhibited the highest density of plastic waste, recorded at 621.1 g/m². The Penunggul, Dubibir, and Cengkrong mangrove ecosystems showed moderate plastic waste densities, ranging from 223.9 to 343.9 g/m². Other mangrove ecosystems displayed lower densities of anthropogenic plastic waste, varying from 42.6 to 155 g/m² (Fig. 2a).

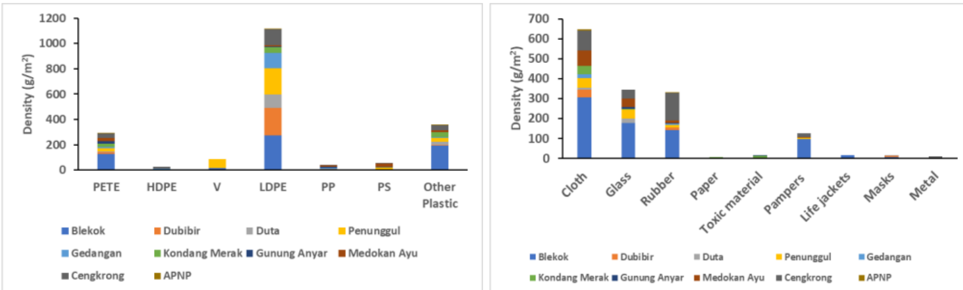
The highest density of non-plastic macroanthropogenic waste was also observed in the Blekok mangrove ecosystem, with a measurement of 747.3 g/m². In contrast, the Cengkrong, Penunggul, and Medokan Ayu mangrove ecosystems exhibited moderate non-plastic waste densities, ranging from 114.4 to 311.5 g/m². Other ecosystems demonstrated lower densities of non-plastic waste, with values between 18.5 and 58.8 g/m² (Fig. 2b).



(a) (b)

Fig. 2. Comparison of plastic (a) and non-plastic (b) macro waste composition and density between ten mangrove ecosystems in East Java. Notes: APNP (Alas Purwo National Park), PETE (Polyethylene Terephthalate), HDPE (High-Density Polyethylene), V (Vinyl or PVC – Polyvinyl Chloride), LDPE (Low-Density Polyethylene), PP (Polypropylene), PS (Polystyrene)

The types of anthropogenic plastic waste identified in the location research include PETE, HDPE, PVC, LDPE, PP, PS, and various other plastic types (Fig. 3a). Among these, LDPE exhibited the highest density across the ten mangrove ecosystems, measuring 1115.5 g/m², followed by PETE and other plastic types, which ranged from 292.3 to 352.8 g/m². The densities of other plastics, including HDPE, PVC, PP, and PS, were observed to range from 23.6 to 84.4 g/m². These findings are consistent with those reported by Yin et al. [25] and Kesavan et al. [26], who identified LDPE and PETE as the most prevalent types of macroplastics, followed by PP and PS. The majority of this plastic waste is attributed to food and beverage packaging, followed by household appliances, construction materials, and textiles [26-28].



(a) (b)

Fig. 3. Comparison of the density of each type of macroplastic (a) and non-plastic (b) waste in ten mangrove ecosystems in East Java. Notes: APNP (Alas Purwo National Park), PETE (Polyethylene Terephthalate), HDPE (High-Density Polyethylene), V (Vinyl or PVC – Polyvinyl Chloride), LDPE (Low-Density Polyethylene), PP (Polypropylene), PS (Polystyrene).

In addition to plastic waste, various types of non-plastic waste were found within the East Java mangrove ecosystem, including cloth, glass, rubber, paper, diapers, buoys, masks, iron, and hazardous materials such as medical infusion equipment (Fig. 3b). Notably, cloth, glass, and rubber displayed significantly higher densities, ranging from 331.6 to 647.7 g/m², with diapers ranking second at 126.9 g/m². Other non-plastic waste types, including paper, hazardous materials, buoys, masks, and iron, exhibited lower densities, ranging from 6.7 to 18.0 g/m².

Plastic waste within the mangrove ecosystem originates from various sources, including marine debris, tourism activities, fishing, aquaculture, and household waste [28, 29]. A significant portion of this waste is concentrated in mangrove areas that exhibit a depression-like morphology, accounting for 61% of the total, in contrast to the 33% found in areas leading directly to the open sea. The remaining 5% of waste is situated in the transition zone between land and the sea [30].

Plastic waste that becomes entangled in mangrove branches or roots complicates the cleaning process. Such debris can induce stress in the mangrove ecosystem, adversely affecting the health and survival of the mangroves. Specifically, plastic waste can obstruct respiratory roots, thereby hindering the respiration process. Furthermore, entangled plastic can cause physical damage and potentially lead to the mortality of mangrove seedlings [30-32].

3.2 Human activities and natural levels in some mangrove ecosystems in East Java

The density of waste in the mangrove ecosystem is significantly influenced by human activities surrounding the area. The level of human disturbance within the mangrove ecosystem can be assessed using the Hemeroby index and the degree of naturalness. Variability in human disturbance levels across the ten mangrove ecosystems in East Java is illustrated in Fig. 4.

According to the Hemeroby index, the mangrove ecosystem in APNP is categorized as Ahemerobik (1), indicating very low human activity and minimal anthropogenic impact. In contrast, the Duta, Gedangan, and Cengkrong mangrove ecosystems fall within the mesohemerobic category (3), which signifies moderate human activity. The Gunung Anyar and Medokan Ayu mangrove ecosystems are classified as β-euhemerobic (4), reflecting moderate to high levels of anthropogenic disturbance. Meanwhile, the Blekok, Dubibir, Penunggul, and Kondang Merak mangrove ecosystems are categorized as α-euhemerobic (5), indicating high levels of human activity. Some anthropogenic activities in this area are tourism, agriculture, and settlements. A higher hemeroby value corresponds to increased mechanical disturbance of the soil, direct mechanical disruption of vegetation, and chemical disturbance [24].

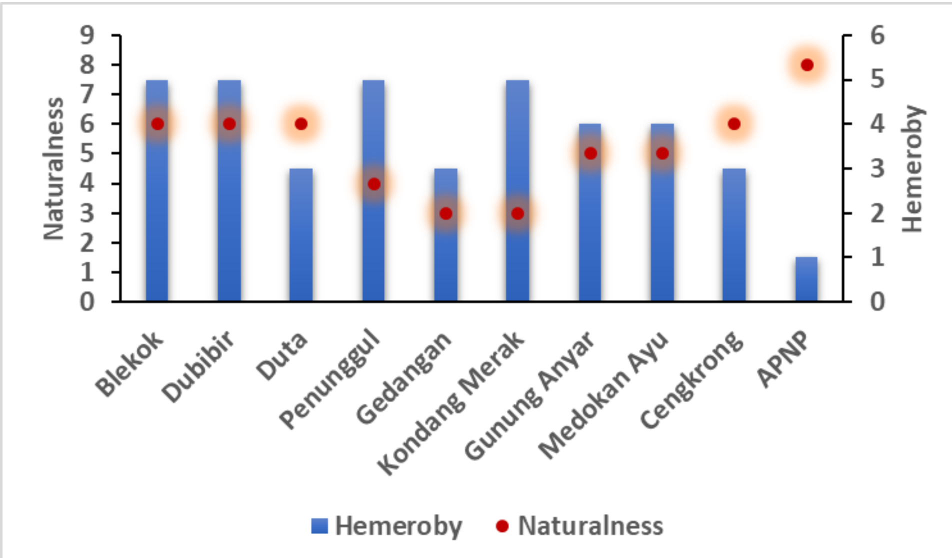


Fig. 4. Environmental quality in the mangrove ecosystem based on the Hemeroby and Naturalness indices. Note: APNP=Alas Purwo National Park.

Based on the naturalness index, the APNP mangrove ecosystem exhibits the highest level of naturalness, categorized as a sub-natural system, indicating that it remains largely unaltered [8]. In contrast, the Blekok, Dubibir, Duta, and Cengkrong mangrove ecosystems demonstrate fairly good naturalness, classified within the semi-natural system category, which retains its natural characteristics but is subject to restorative efforts [6]. The Gunung Anyar and Medokan Ayu mangrove ecosystems are the result of successful restoration efforts, well-managed by the Surabaya local government, and are classified as culturally self-maintained systems [5]. The Penunggul mangrove ecosystem falls under the culturally assisted system category [4], while the Gedangan and Kondang Merak mangrove ecosystems are categorized as highly intervened systems [3].

Several mangrove ecosystems exhibit low naturalness levels due to habitat fragmentation surrounding the mangrove areas, occurring at moderate to substantial degrees (Machado, 2004). Additionally, much of the land adjacent to these ecosystems has been converted into settlements, agricultural lands, and plantations, which significantly contribute to elevated pollutant levels entering the mangrove habitat. This includes anthropogenic waste, synthetic fertilizers, and pesticides [33, 34]. Mangrove vegetation plays a critical role in regulating water quality within the mangrove ecosystem; however, high levels of anthropogenic activity can adversely affect both water and sediment quality [35].

3.3 The grouping of mangrove ecosystem quality in East Java based on anthropogenic waste density

The results of the biplot analysis conducted using Principal Component Analysis (PCA) indicate that the Blekok mangrove ecosystem in Situbondo has the highest density of macroanthropogenic waste, comprising both plastic and non-plastic materials. Specifically, the types of plastic identified—such as PETE and LDPE—were found in the greatest quantities at this location. Furthermore, this area also exhibits the highest level of human activity, as determined by the Hemeroby index.

The analysis reveals a positive correlation between elevated human activity and increased waste density, encompassing both plastic and non-plastic waste (Fig. 5). PETE, a type of plastic known for its moisture resistance, is commonly utilized in the production of beverage bottles, food packaging (such as vegetable oil containers), and cosmetic packaging (including shampoo and lotion bottles). In contrast, LDPE is characterized by its flexibility and is frequently used for items such as plastic shopping bags, laundry bags, and food packaging.

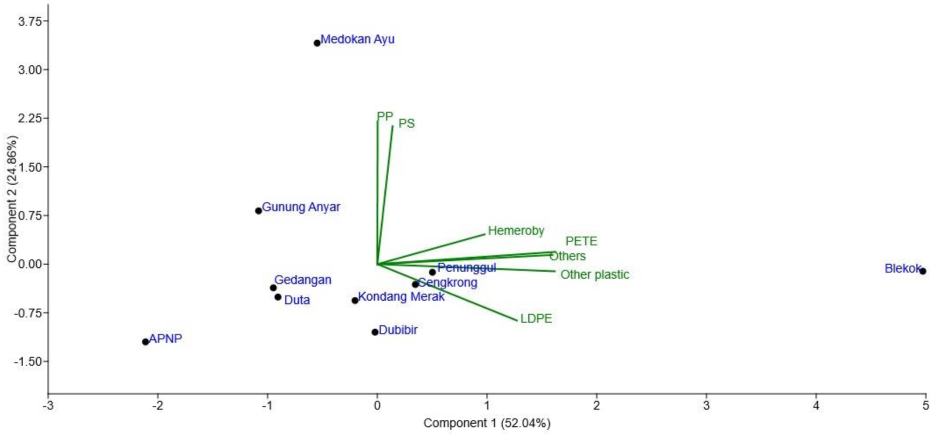


Fig. 5. Grouping of some East Java mangrove ecosystems based on the density of macroanthropogenic waste and human activities. Notes: APNP (Alas Purwo National Park), PETE (Polyethylene Terephthalate), LDPE (Low-Density Polyethylene), PP (Polypropylene), PS (Polystyrene), others (non-plastic waste)

The mangrove ecosystems in Dubibir, Kondang Merak, Cengkrong, and Penunggul exhibit moderate levels of macroanthropogenic waste, encompassing both plastic and non-plastic materials, with moderate to high levels of human activity. Conversely, the mangrove ecosystems in Gedangan, Duta, and Gunung Anyar demonstrate low to moderate densities of macroanthropogenic waste, including both plastic and non-plastic types. The density of anthropogenic waste, both plastic and non-plastic, in the mangrove ecosystems in Duta, Gedangan, and Gunung Anyar is lower than in the four mangrove ecosystems. Meanwhile, the mangrove ecosystem in Medokan Ayu has the highest density of PP and PS with low LDPE, while PETE, LDPE, and other plastic and non-plastic waste density is moderate.

The mangrove ecosystem in APNP exhibits the lowest density of anthropogenic waste, encompassing both plastic and non-plastic materials. This can be attributed to the fact that the National Park Area is a protected zone governed by the government, resulting in minimal to no human activity. The presence of waste in this region is likely the result of debris transported by currents during the ebb and flow of seawater.

The biplot analysis further illustrates that elevated human activity, as indicated by a high Hemeroby index value, correlates with an increase in both macroanthropogenic plastic and non-plastic waste. Consequently, effective waste management in the mangrove ecosystem should focus on regulating human activities in the surrounding areas to mitigate waste accumulation.

4 Conclusions

The density ratio of plastic to non-plastic anthropogenic waste across the ten mangrove ecosystems in East Java is 55:45. The Blekok mangrove ecosystem exhibits the highest levels of macroanthropogenic waste, predominantly in the form of plastic (particularly PETE, LDPE, and other plastic materials) and non-plastic waste. In contrast, the mangrove ecosystems of Dubibir, Kondang Merak, Cengkrong, and Penunggul display moderate levels of anthropogenic solid waste. The Medokan Ayu mangrove ecosystem is characterized by the highest densities of PP and PS plastics. Conversely, the mangrove ecosystems in Duta, Gedangan, and Gunung Anyar have low densities of anthropogenic solid waste, while the APNP mangrove ecosystem has the lowest density of such waste.

Data analysis reveals a clear relationship between high human activity and increased levels of anthropogenic solid waste. Consequently, effective solid waste management in the mangrove ecosystem is essential, necessitating the control of human activities in the surrounding areas. Furthermore, a higher Hemeroby Index correlates with increased densities of both plastic and non-plastic anthropogenic waste in the ten mangrove ecosystems of East Java. Further research is needed to provide a more comprehensive understanding of the dynamics of anthropogenic solid waste by incorporating temporal variation data such as seasonal differences.

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