

Microplastics in Landfill Environments: Distribution, Characteristics, and Risks from Gampong Jawa, Indonesia

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Abstract - Landfills are generally considered the ultimate solution for waste management. However, the degradation process of plastic waste in landfills causes the release of microplastic particles into the surrounding environment and threatens human health. The distribution and properties of microplastics in four environment matrices, soil, leachate, river water, and well water surrounding the landfill, are examined in this study. Sampling was conducted at the inflow and outflow areas of the leachate ponds., The soil at the top (0–5 cm) and bottom (5–20 cm), upstream and downstream surface water adjacent to the landfill, and community wells within a radius of fewer than 700 meters from the landfill. Microplastic analysis used a gradual extraction method with saturated NaCl for density separation, 30% hydrogen peroxide for organic matter degradation, and 0.05 M FeSO₄ as a catalyst. Physical character identification of microplastics using a microscope showed microplastic contamination at all study sites. The results showed an abundance of microplastics was found in well water samples (808 to 979 items/L), leachate (209 to 757 items/L), surface water (6.29 to 7.2 items/L), and soil (23,340 to 23,420 items/kg). Types of microplastics found consist of fragments, fibers, films, pellets, foam, and rods. The size of microplastics found ranged from 1.897 μm to 1,642.79 μm . Fourier Transform Infrared spectroscopy examination identified polyethylene terephthalate (PET) plastic compounds in soil and leachate materials. The high concentration of microplastics in well water indicates potential groundwater contamination from landfill activities that may impact the surrounding community. This study provides preliminary insights into how landfills may contribute to environmental microplastic contamination. It paves the way for further research to develop mitigation strategies.

Keywords: microplastic; landfills; leachate; groundwater; environmental pollution

Introduction

The extensive application of plastic stems from its beneficial characteristics: it is economical, light in weight, long-lasting, adaptable, cost-efficient, and thermally insulating. Plastic packaging has replaced cans and glass packaging because it is more practical and efficient (Rusman & Hidayati, 2022). However, its current production and use could be more sustainable. (Borrelle et al., 2020). In the last 50 years, plastic production has increased drastically by 20 times, global production has reached 9200 Mt, and more than 6900 Mt ends up in landfills (Geyer et al., 2017). As a result of the increasing use of plastic, the environmental impact is also increasingly widespread (Puthcharoen & Leungprasert, 2019). The international community has recognized the importance of addressing the problem of plastic waste in the ocean for the sustainability of marine ecosystems, which was then included in SDG 14 as one of the UN's global targets. (Walker & Fequet, 2023). A critical study shows that microplastic contamination impacts at least 12 SDGs directly and indirectly and can threaten global social, environmental, and economic sustainability. (Walker, 2019).

Microplastics are particles measuring less than 5 mm (Shi et al., 2022). Microplastics are formed from the fragmentation of larger plastic debris through chemical, physical, and biological processes and can be further degraded into nanoplastics. Based on their source, microplastics are classified as primary and

secondary. Essential microplastic are plastic particles that were at first 5 mm or smaller when they entered the environment, such as plastic pellets, microbeads, and microfibers from clothing (Friot & Boucher, 2017). Auxiliary microplastics are shaped from expansive plastic things that break down within the environment due to normal forms, such as water bottles, plastic sacks, utilized tires, angling nets, and others (Kovochich et al. 2021).

A study has revealed that microplastics act as vectors for various pollutants, including heavy metals, antibiotics, and pathogens. Smaller microplastic particles can adsorb more contaminants (Tumwesigye et al., 2023). When these contaminated microplastics are dispersed in the environment, they can contaminate ecosystems and enter the food chain through various exposure routes such as skin contact, food, and inhalation (Prata, JC; Da Costa, JP; Lopes, I.; Duarte, AC; Rocha-Santos, 2020). Several laboratory and animal studies have shown that exposure to micro- and nanoplastics can affect the human body. These effects include physical stress and damage, cell death (apoptosis and necrosis), inflammation, oxidative stress, and immune system disorders (Yee et al., 2021). Microplastics within the environment have been a concern for a long time. This microplastic is due to its gigantic dispersion and the potential hurt it poses to the environment (Z. Zhang et al., 2021). The presence of microplastics has been detected in various environmental matrices such as soil (S. Zhang et al., 2022), sediment (Zong et al., 2024), surface water (Kataoka et al., 2019), and groundwater (Fajaruiddin Natsir et al., 2021). Previous studies have generally focused on microplastic pollution in surface water and marine environments. However, few have investigated microplastic pollution on land, even though land is a much larger dumping ground for plastic pollution and releases 20 times more plastic onto land than into the ocean (Horton et al., 2017).

A study in Iran found the abundance of microplastics in the Bushehr Port adjacent to the landfill at 79.16 mg/L and PAE at 3.27 mg/L, and the average PAE level in microplastics was 48.33 µg/g. It proves that many microplastics and phthalate esters (PAEs) can be released into the environment around the landfill site (Mohammadi et al., 2022). Mismanagement of plastic waste paves the way for the release of microplastics, making landfills one of the main sources contributing to the release of microplastics into the environment (Sekar & Sundaram, 2023). Landfills that function as solid waste management sites have become a source of microplastic distribution. Degradation of plastic waste in landfills triggers the release of microplastics, which then spread to the surrounding area, contaminating soil and water sources, including groundwater and surface water. This condition threatens human health and the ecosystem because microplastics can absorb toxic substances (Singh et al., 2023).

Landfilling is the practice of dumping waste on land in a designated area. This method is commonly used to manage various types of waste, but it can cause significant environmental impacts. Environmental conditions in landfills, such as pH and temperature, which are constantly changing, can affect the waste degradation process and the quality of the surrounding soil and water (Nanda et al., 2021). Whether treated or not, leachate from landfills is known to contaminate environmental components such as soil and groundwater with various heavy metals and other toxic compounds. This groundwater contamination poses a major risk to communities that utilize groundwater resources around landfills and poses a threat to the ecosystem. In addition, several studies have reported the presence of hazardous plasticizers (plastic additives) in leachate, thus confirming landfills as a significant source of plastic pollution (Upadhyay & Bajpai, 2021).

In Indonesia, there are 532 landfills. The amount of waste generated from 169 regencies/cities throughout Indonesia is 19,517,172.98 tons/year. Managed waste is 13,040,691.26 tons/year (66.82%), while unmanaged waste reaches 6,476,481.72 tons/year or 33.18%. Plastic waste contributes 18.9% of the total (Kementerian Lingkungan Hidup dan Kehutanan, 2023). Plastic squandered in landfills experiences natural corruption into microplastics. Studies on microplastics in final waste processing sites still need to be completed. Hence, it is critical to conduct extensive research to determine microplastics' nature, attributes, and ultimate destination in waste processing facilities."(Su et al., 2019). Previous research has detected the presence of microplastics in landfills based on the age of the landfill (Su et al., 2019), in different ancient zones and dynamic landfills (Rahmani et al., 2023), as well as dynamic and closed landfills (He et al., 2019). This will look at the nearness of microplastics in landfills that have the status of transfer stations and their potential to release microplastics into the surrounding environment. This study aims to determine the distribution and properties of microplastics in landfill soil and leachate, as well as surface water and groundwater in the surrounding environment since landfills are repositories of plastic waste and can be a source of pollution and are dangerous to the environment.

Materials and Methods

Study Time and Location

Sampling was conducted in July-August 2024. Soil and leachate samples were collected from the Gampong Jawa landfill site in Banda Aceh City, Aceh Province, Indonesia. Banda Aceh is the capital of Aceh Province, which has an area of 61.36 km² and a population of 259,538 people. The Gampong Jawa landfill is located at 112°37'58 BT - 112°38'01 BT and 7°13'02 LS - 7°13'19 LS, which is geologically located near the mouth of the Krueng Aceh River. The distance between the landfill and the nearest river is only 30 meters, and between the landfill and the beach is 300 meters. Due to the increasing population of the city of Banda Aceh and limited land, since the end of 2018, the Gampong Jawa landfill has changed its function to become a transfer station, which is a temporary storage place for waste before being transported to the Blang Bintang Regional Landfill, Aceh Besar. The Gampong Jawa landfill has an area of ±21 Ha. The amount of waste entering the Gampong Jawa TPA is 250 tons/day. A total of 220 tons of waste is transported to the Blang Bintang Aceh Besar Regional TPA daily, using 8 (eight) trucks. Meanwhile ±30 tons/day of waste is managed at the Gampong Jawa landfill. In this study, the temporary waste storage area and the managed waste are referred to as the active zone (ST-1), while the area that has been stockpiled and is no longer stockpiled is referred to as the inactive zone (ST-2). The Gampong Jawa landfill has three leachate ponds; in this study, only the leachate pond inlet (ST-3) and leachate pond outlet (ST-4) were studied. The location of the Gampong Jawa landfill is ±30 meters from the nearest river (ST-5 and ST-6), 300 meters (ST-7), and 600 meters (ST-8) from the community houses.

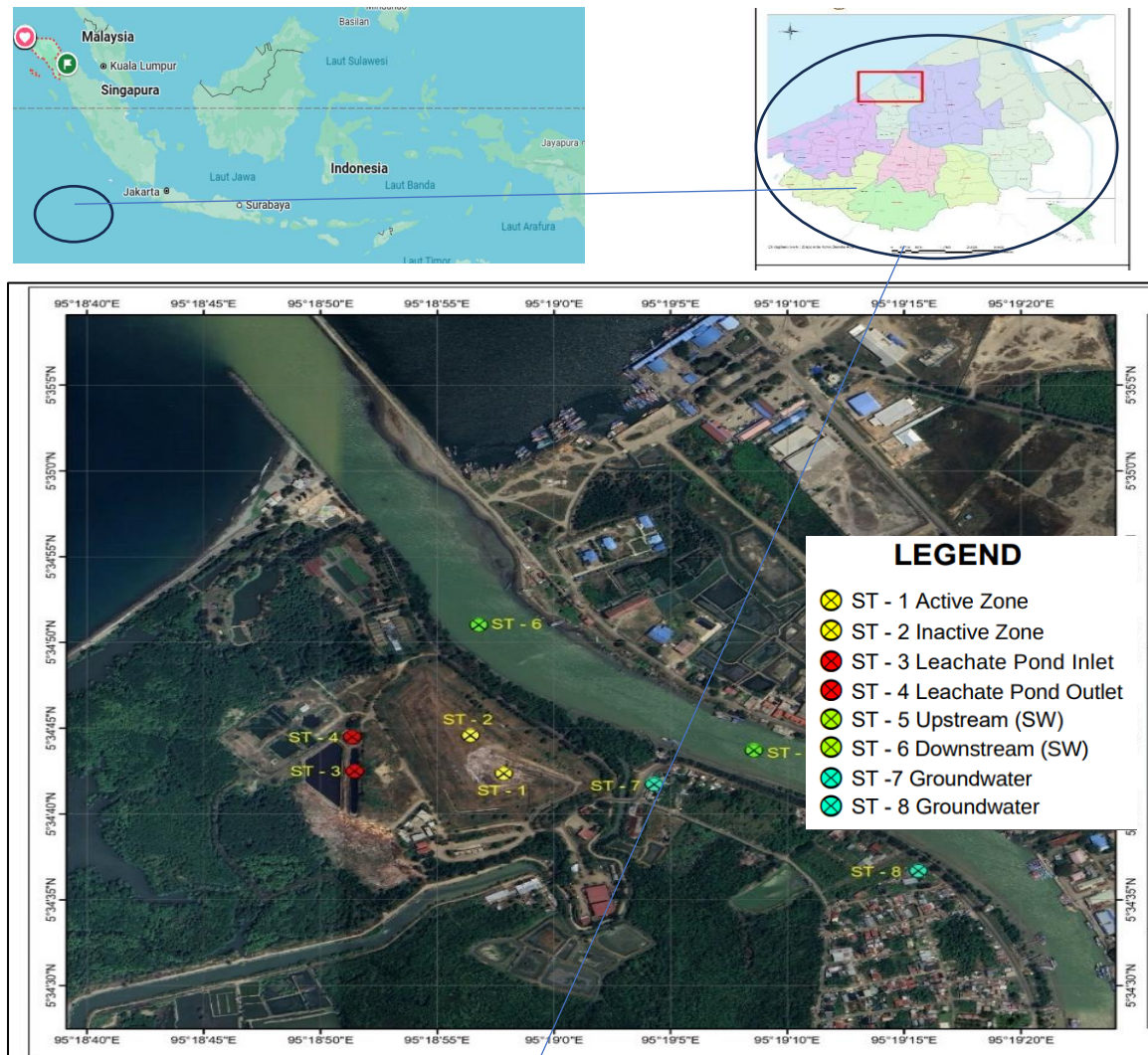


Figure 1. Study Location

Sample Collection

The study analyzed ten different samples, comprising four landfill soil samples alongside two samples each of leachate, surface water, and groundwater.. Soil samples were taken from the top (0-5 cm) and bottom (5-20 cm). Three hundred grams of soil at each location were collected using an iron shovel and then put into a glass container covered with aluminum foil.

A total of 1 liter of leachate and groundwater samples from residents wells were collected from each study location using an iron bucket, placed in a glass bottle, and then covered with a bottle cap coated with aluminum foil.

One hundred liters of surface water from each study location was collected from 30 cm below the water surface using a 20-liter iron bucket and then filtered with a plankton net. Furthermore, the filtered water was put into a glass bottle with a lid coated with aluminum foil.

All samples are then put into an ice box at temperature $\pm 4^{\circ}\text{C}$ (Efendy et al., 2024) and taken to the Marine Chemistry Laboratory, Faculty of Marine Affairs and Fisheries, Syiah Kuala University for further investigation.

Contamination Control

Sampling equipment was rinsed with distilled water and dried before use, and sample containers were washed thoroughly, rinsed with distilled water, and dried. No plastic products were used on sampling equipment and sample storage containers to avoid additional plastic contamination. We used aluminum foil to line the caps of bottles/sample storage containers. We put empty filter paper in petri dishes next to the sample processing area to avoid airborne contamination. Additionally we covered the samples with aluminium foil while they were being analyzed.

Microplastic Extraction

There is no standard method for determining microplastics. The analytical procedure used in this study followed the procedure of previous studies with modifications. As in previous studies, the soil sample analysis procedure was modified. The soil samples were first dried in an oven at a temperature of 70°C for 24 hours (Ding et al., 2019). The dried soil samples were then sieved using 2 mm sieves. Fifty grams of sieved soil were dissolved in 200 mL of saturated NaCl (Afrin et al., 2020), stirred for 15 minutes, and left for 24 hours.

Furthermore, the supernatant was filtered by vacuum filtration using filter paper with a 47 mm diameter pore size of $0.45\ \mu\text{m}$. After that, distilled water is used to rinse the filter paper in the filtering unit to eliminate any remaining salt (Rahmani et al., 2023). The filtered results were transferred to a beaker glass to destroy the organic material. The organic material was destroyed by adding 0.05 M Fe (II) and 30% H_2O_2 solution with a volume of 20 ml each. The sample was heated and homogenized at 60°C for 30 minutes (90 rpm). The sample that had lost its organic material was then filtered with a vacuum filtration unit using 47 mm diameter filter paper and a pore size of $0.45\ \mu\text{m}$ (Ding et al., 2019). A petri plate was used to hold the filter findings. Before extraction, the solid particles in the collected leachate were cleaned with distilled water after being filtered through a $50\ \mu\text{m}$ screen. There was a significant amount of organic matter in the leachate samples. This study's methodology is an adaptation of earlier studies. One technique for dissolving organic substances is chemical digestion. The filtered sample was dissolved with 30% H_2O_2 (Emplura) and 0.05 M Fe (II). Then, it was heated to 60°C for 30 minutes at a speed of 90 rpm (Rahman et al., 2024) and left for 48 hours. A vacuum filtration equipment was then used to filter the sample. Density separation was accomplished using saturated NaCl. After rinsing with saturated NaCl, the sample was centrifuged for 10 minutes at 1000 rpm and allowed to sit for two hours. A vacuum filtration device was then used to filter the supernatant using filter paper with a pore size of $0.45\ \mu\text{m}$ and a diameter of 47 mm. In a petri dish, filter paper is put on it and allowed to dry (Sekar & Sundaram, 2023). The collected samples were filtered with a $50\ \mu\text{m}$ sieve, μm for surface water and groundwater samples. Following a 48-hour treatment with 30% H_2O_2 to decrease dissolved organic matter, the particles retained in the filter were washed with distilled water. In addition, the sample is filtered using 47 mm-diameter filter paper with $0.45\ \mu\text{m}$ pores. A petri dish was then used to hold the filter paper while it dried at room temperature.

Visual Examination of Microplastics

The entire filter paper that has been desiccated from each study location and blank filter papers were observed at 4x and 10x magnification using a microscope (Primus Zeiss). This observation was conducted at the Marine Biology Laboratory, Faculty of Marine and Fisheries, Syiah Kuala University. Microplastic image observations used ZEISS ZEN microscopy software. Microplastic characterization was carried out

based on color, shape, and size. Microplastic forms are grouped according to their morphological characteristics: fragments, fibers, foams, pellets, rods, and films. For size, they are grouped into four groups, namely <100 μm , 100-500 μm , 500-1000 μm and >1000 μm .

Fourier Transform Infrared (FTIR) Analysis

To identify the polymers of the microplastics found, microplastics in the form of films, fibers, and fragments were selected from the study sites ST-1 and ST-4 because these forms are the most commonly found. This study used FTIR at the Multifunction Laboratory of the State Islamic University of Ar-Raniry. The absorption band of each polymer was obtained from the Spectrabase database, which is available online at John Wiley and Sons, Inc..

Results

Distribution of Microplastics

An abundance of microplastics was identified in this investigation in landfill soil, leachate, surface water, and groundwater samples. All study sites were detected to contain microplastics. Microplastics found from all study sites amounted to around 8,503 particles, which were counted and categorized visually. The concentration of microplastics in liquid samples will be represented in items/L, while microplastics in soil samples will be represented in items/Kg.

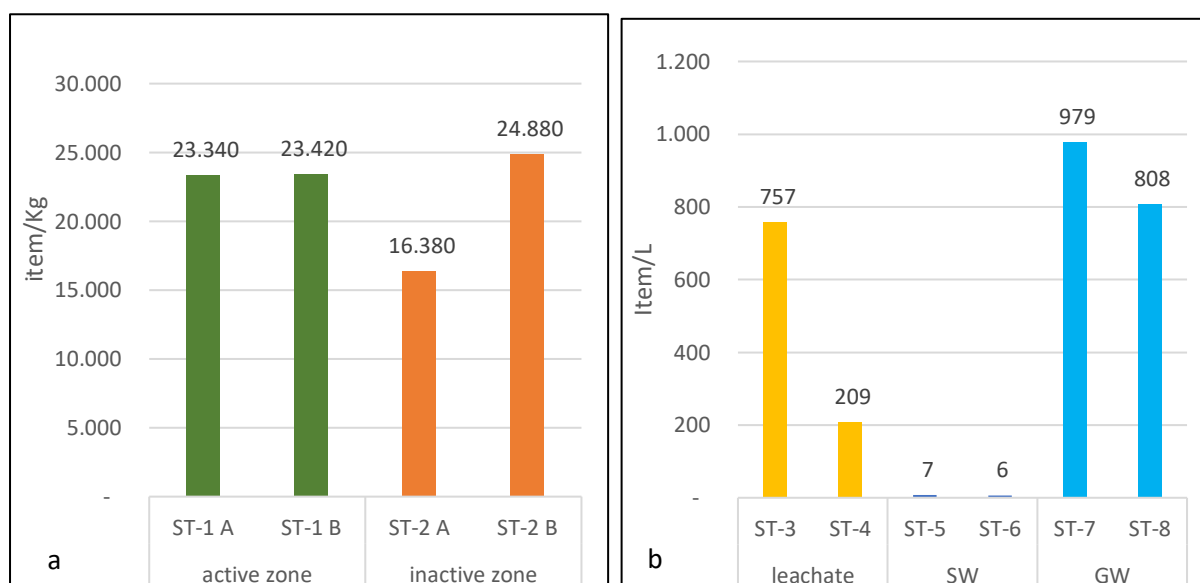


Figure 2. The abundance of microplastics in (a) Active and inactive zones, (b) leachate, surface water, and groundwater

Characterization of Microplastics

Shape

Based on its shape, the microplastics found in this study vary greatly. Fragments, films, fibers, foams, pellets, and rods are the microplastics identified. The shape of microplastics can provide information about their origin, such as fibers from textile scraps, foams, and fragments that may result from the decomposition of plastic items and films that come from packaging or plastic bags (Zhang et al., 2018). The varied shapes in this study indicate that the sources of microplastics come from various waste sources, environmental conditions of the landfill such as pressure from piles of waste, leachate movement, waste compaction activities, physical-chemical factors, exposure time, surface water flow, and groundwater.

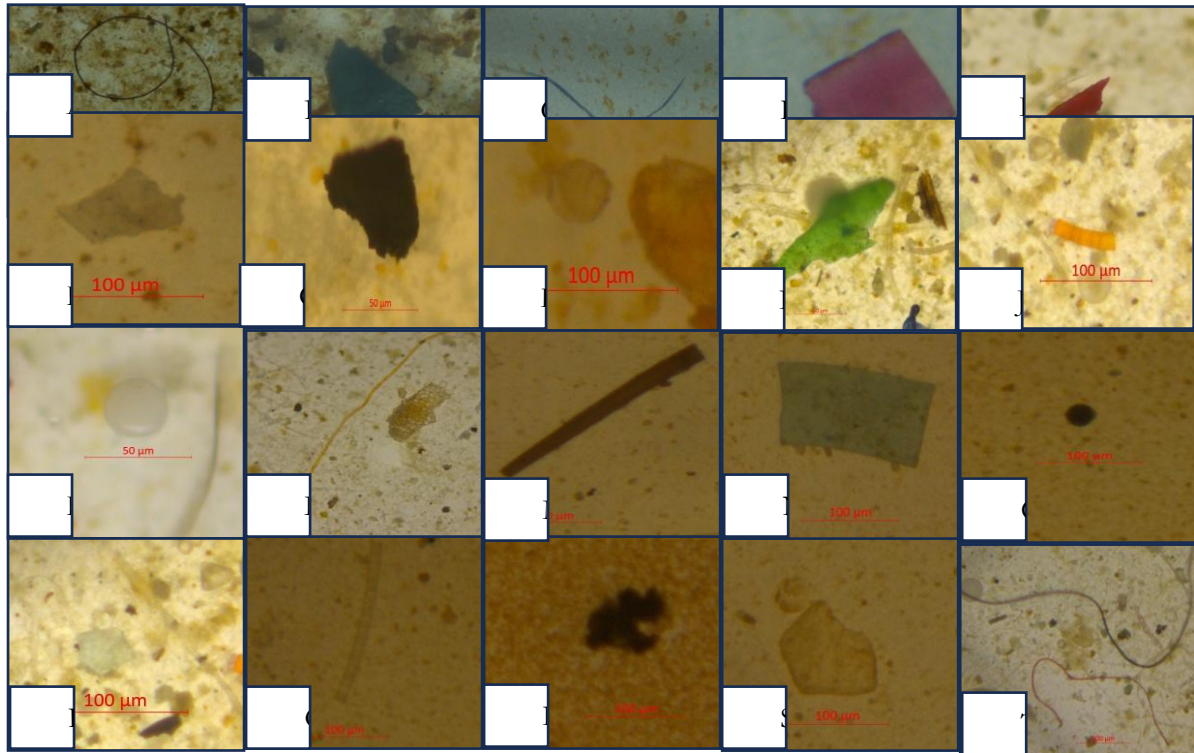


Figure 3. The study's microplastics in a range of colours and forms were collected from soil, leachate, surface water and groundwater, fiber (A, C, L, T), fragments (B, E, G, J, P, S), films (D, F I, N), pellets (H, O, K), foam (R), rods (M, Q)

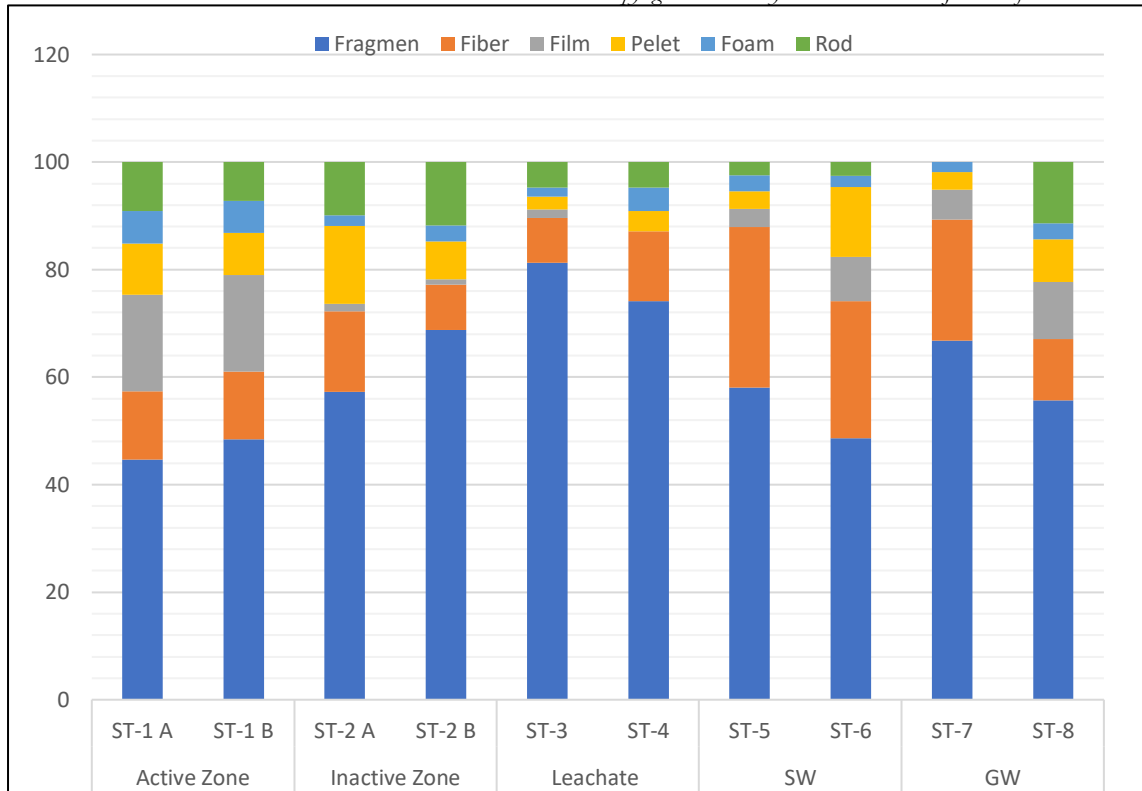


Figure 4. Distribution of microplastics by shape across all study sites.

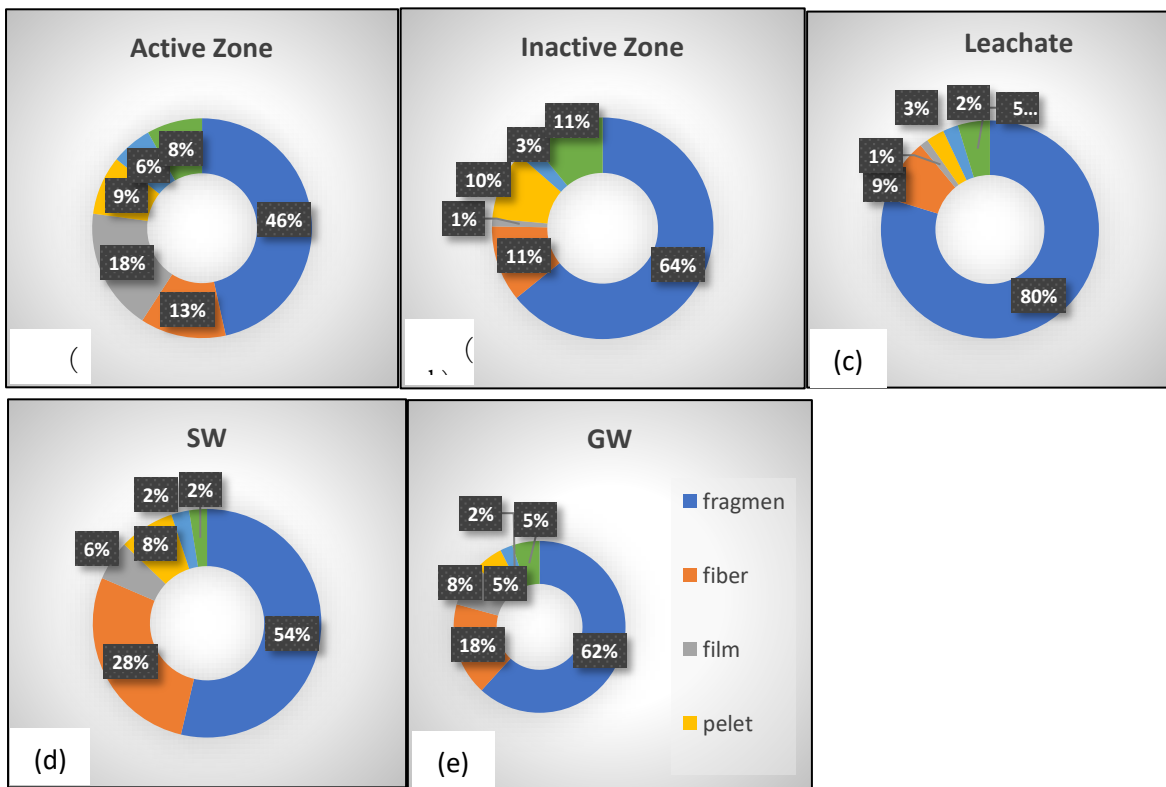
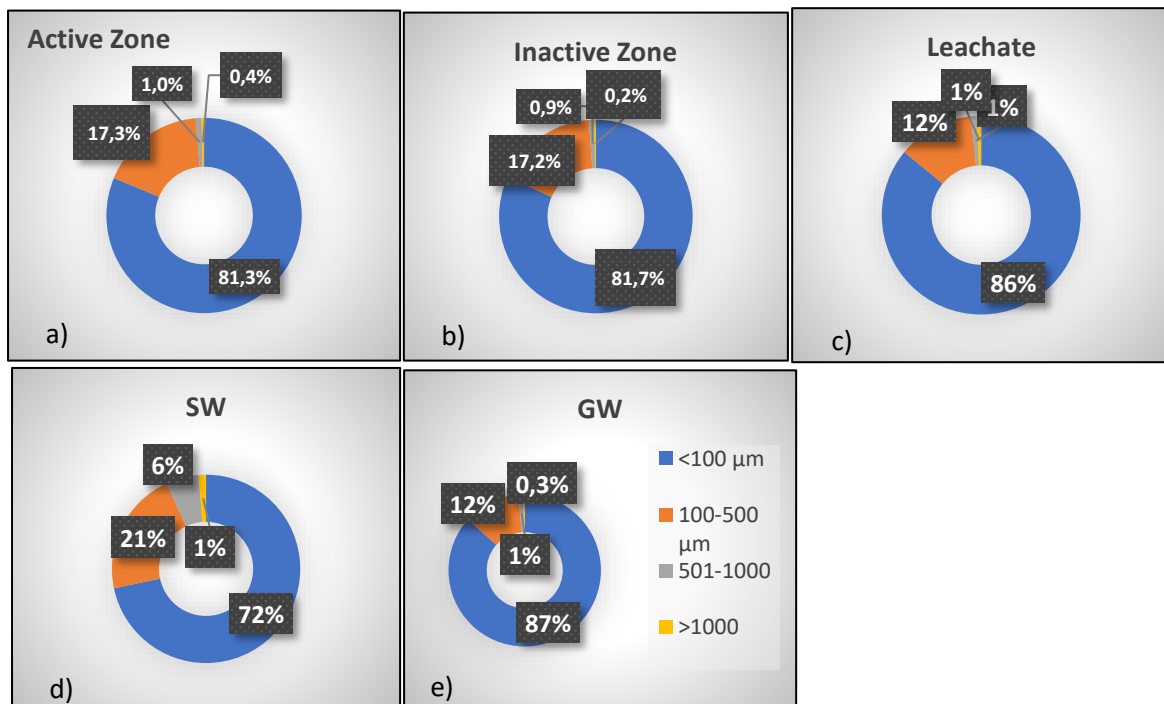
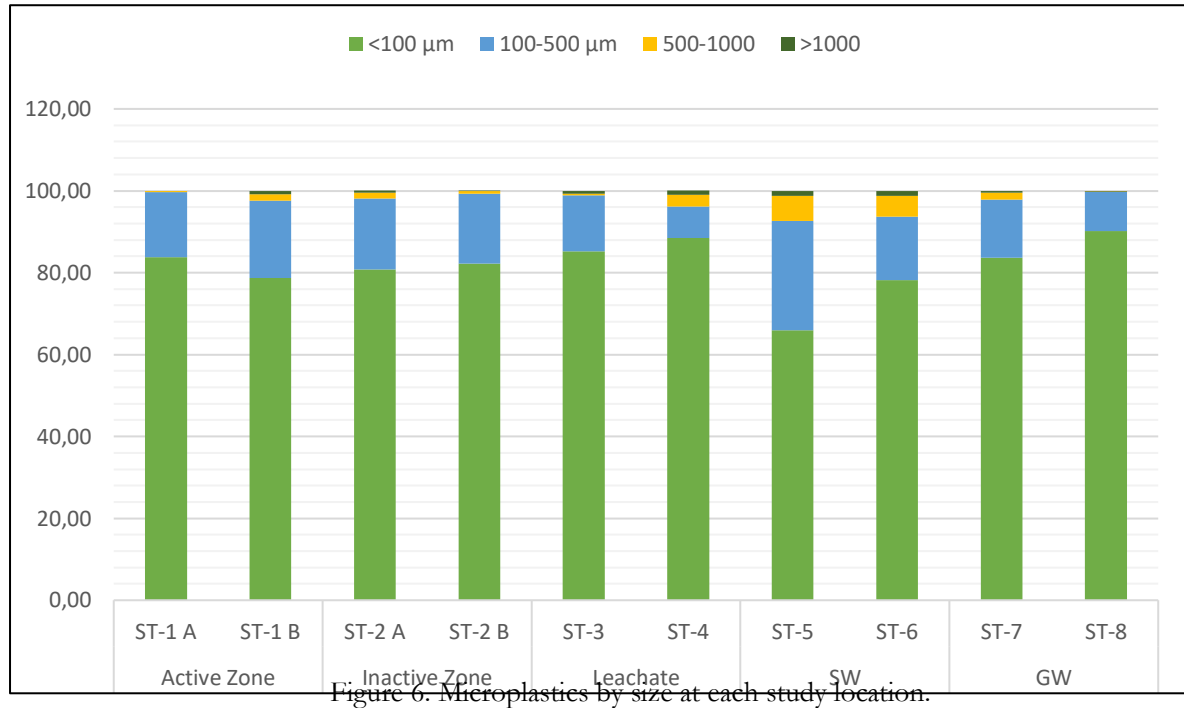


Figure 5. Distribution of microplastic shapes based on sample type (a) (b) (c) (d) (e)

Size

Microplastics are plastic particles measuring <5 mm. Microplastics found in the Gampong Jawa landfill and the environment around the landfill are generally small in size. Physical forces, photodegradation, and biological processes are some of the meteorological conditions that primarily separate small microplastics from bigger plastic waste. (Gela & Aragaw, 2022). We classified the microplastics found into four categories based on their size, namely < 100 μm , 100 -500 μm , 500 – 1000 μm and > 1000 μm .



Color

Microplastics were found at each research location based on color, as shown in the following graph.

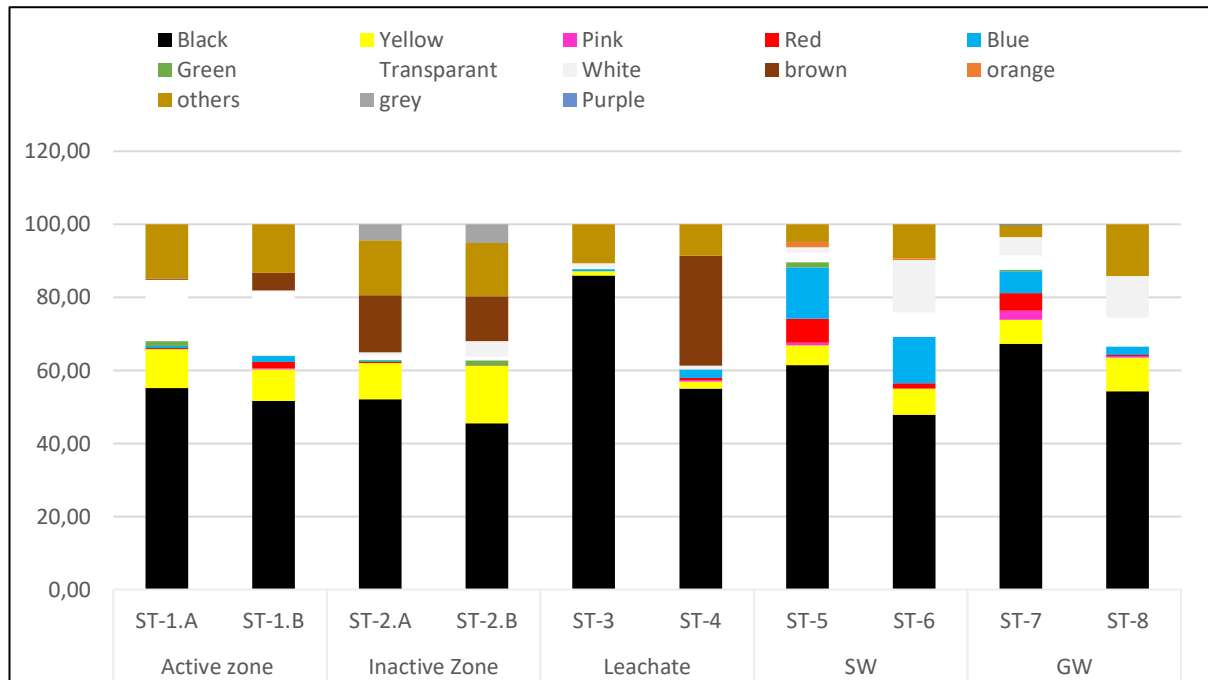


Figure 8. Distribution of microplastics based on color at each study location.

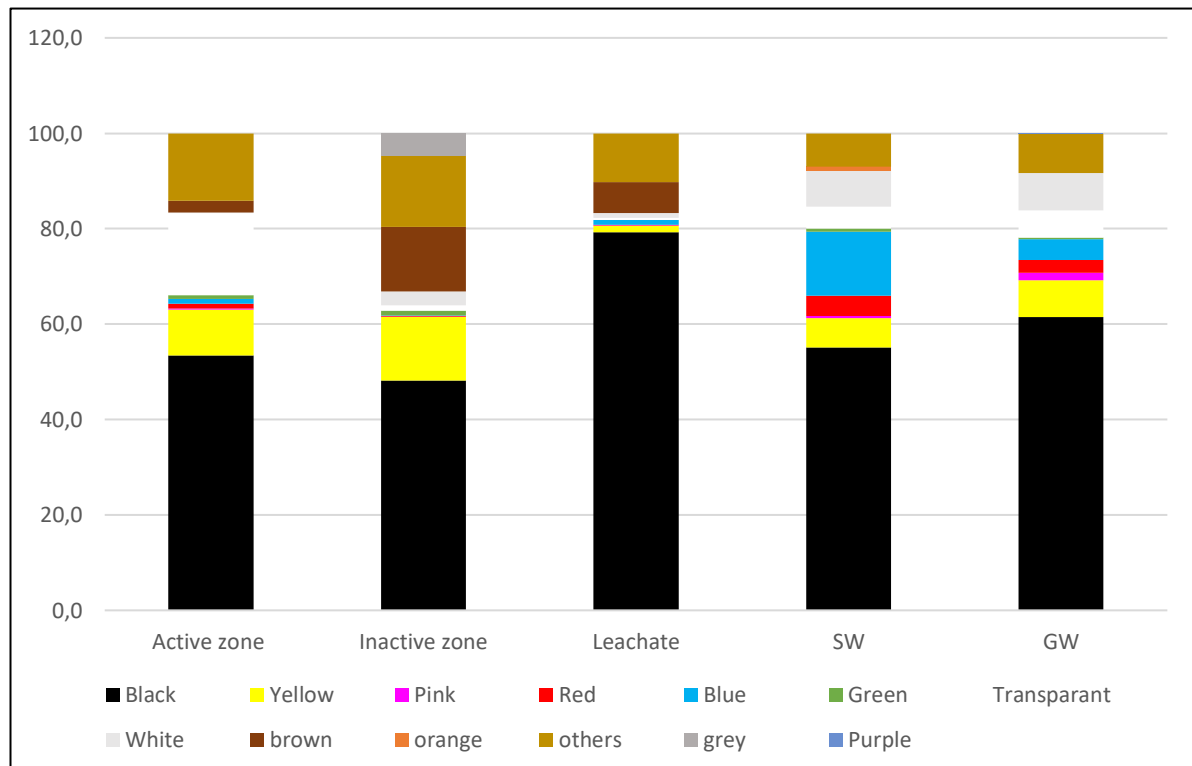


Figure 9. Distribution of microplastic color based on sample type.

Polymer Composition

This research found 8503 microplastic particles spread in the active and inactive zone landfills, leachate, surface water, and groundwater. Several particles in the form of fragments, fibers, and films found in the landfill and TPA leachate were analyzed using a Fourier Transform Infra-Red tool to detect the type of polymer.

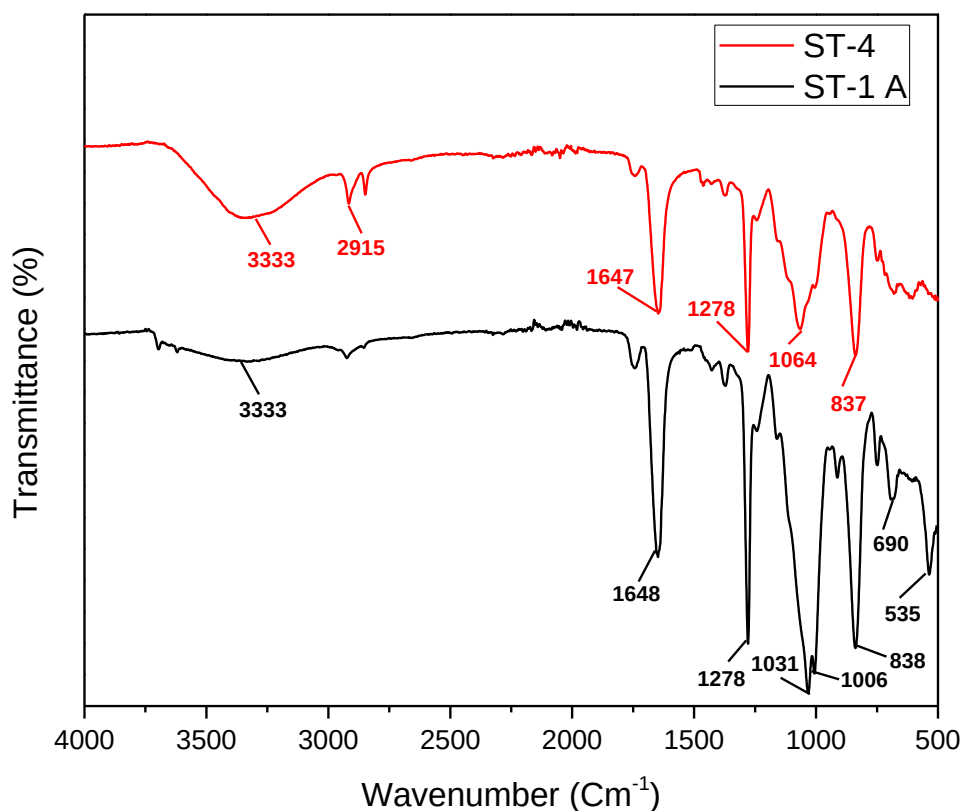


Figure 10. FTIR reading results of MP representatives on ST-1 and ST-4

Discussion

Distribution of microplastics in landfill soil

Figure 2 shows that landfill soil in the active zone (ST-1 A and ST-1 B) has an abundance of 23380 items/Kg higher than landfill soil samples from the inactive zone (ST-2 A and ST-2 B) which is 20630 items/Kg. This condition is in line with a study in Shanghai, China, which found that the abundance of microplastics in young landfills was 83 ± 10 items/g and in old landfills was 36 ± 14 items/g (Su et al., 2019). However, this finding differs from the results obtained in Hamadan, Iran, which found more microplastics in old landfills than in active landfills, namely 39813 items/Kg and 16940 items/Kg, respectively (Rahmani et al., 2023). The differences in microplastic abundance findings in the landfills of Iran, China, and Indonesia reflect variations in environmental conditions and waste management practices in each location. The higher abundance of microplastics in the active zone compared to the inactive zone in the Gampong Jawa landfill indicates the strong influence of landfill operational activities, such as waste compaction and continuous influx of new waste, combined with the humid tropical climate. This is different from the conditions in Hamadan, Iran, with its semi-arid climate, or Shanghai, China, with a more advanced waste management system in the context of a metropolitan city. This difference is also influenced by socio-economic factors such as people's consumption patterns and waste management systems. Meanwhile, in the lower soil of the active zone and inactive zone, the abundance is higher than the upper part (Figure 2a). This is because the plastic at the bottom has degraded into microplastic particles while at the top it is still macro-sized plastic. Research at the landfill around the Gulf of Thailand found a concentration of

microplastics from soil samples of 1457.99 ± 489.71 items/Kg and proves that microplastics can occur in young landfills (Puthcharoen and Leungprasert, 2019).

Distribution of microplastics in leachate

Findings The concentration of microplastics in leachate was 757 items/L and 209 items/L. The highest abundance was found in unprocessed leachate (ST-3) which was 757 items/L. Gampong Jawa TPA has 3 leachate ponds, namely pond 1 which is a pond that accommodates all unprocessed leachate, pond 2 where the aeration process takes place, pond 3 is the final storage before being discharged into the environment. After going through the processing process in pond 2, a decreasing concentration of microplastics was obtained in samples from pond 3 (treated leachate) which was 209 items/L. This result is comparable to the results of research at the Amin Bazar TPA, Dhaka on treated leachate which was 200 ± 12 MP/L lower than untreated leachate 370 ± 16 MP/L (Rahman et al., 2024). Meanwhile, compared to several other studies, the results of this study are quite high. In the Hyderabad landfill, India, the abundance of microplastics in leachate was found to range from 9 to 21 items/L (Sekar and Sundaram, 2023), Similarly, it was discovered that the leachate at the Galuga landfill in Indonesia had 77 MP (Nurhasanah et al., 2021) and that the leachate in Shanghai, China, contained 8 ± 3 items/L of microplastics. (Su et al., 2019) so also at the Municipal Waste Disposal Site (MSW) found between 0.42 to 24.58 items/L (He et al., 2019). The abundance of microplastics can be influenced by the characteristics of the leachate formed. The characteristics of the leachate formed will vary depending on the type and composition of waste in the landfill, the age of the landfill, climate conditions (rainfall, temperature) and how the landfill is managed. Microplastics in leachate can enter the environment if there is a leak or when the leachate collection and processing system is not functioning properly. Although the manufacturing and processing processes have been strictly monitored, geomembranes (protective layers of the landfill) can be damaged when installed. This can make it a path for microplastics to spread and pollute the surrounding environment (He et al., 2019).

Distribution of microplastics in surface water

According to the study's findings, surface water near the landfill had a high concentration of microplastics.. The results of the study on surface water samples in the upstream part of the landfill (ST-5) obtained an abundance of microplastics of 7 items/L and in the downstream part (ST-6) 6 items/L. The abundance in ST-5 was slightly higher than ST-6, this could be influenced by the activities of fishermen in the upstream part of the river such as repairing fishing boats, places where boats were moored, community washing activities, and domestic waste from households. The intensity of boat traffic along the river also affects the abundance of microplastics. Surface water close to the landfill location can also receive the release of microplastics from the landfill through wind and rain. The microplastic concentration from this study is much lower than the microplastic concentration in the surface water adjacent to the Amin Bazar landfill, which is 2090 ± 100 items/L. The proximity of the sample locations to numerous MP sources, including open landfills, highways (atmospheric deposition), and landfill sites, maybe the reason. (Rahman et al., 2024). In addition, microplastic concentrations in the rivers Mahanadi, India (15.1 ± 5.4 items/L) (Patidar et al., 2023) and Thames, UK (12.27 items/L) (Devereux et al., 2023), and Basin River, Surakarta (25.5 ± 0.5 to 52.2 ± 1.1 items/L) (Ismanto et al., 2023) contain relatively high microplastic concentrations compared to this study. This difference may be due to higher human activities around these rivers, river flow patterns, and hydrological characteristics that may affect the accumulation and distribution of microplastics.

Distribution of microplastics in groundwater

A fairly high abundance compared to previous research was also obtained at research locations ST-7 and ST-8, which are groundwater samples originating from community wells at a distance of ± 300 meters and ± 600 meters from the landfill. The abundance of microplastics in ST-7 which is 300 meters from the landfill is 979 items/L while in ST-8 which is 300 meters from the landfill is 979 items/L, while in ST-8 which is ± 600 meters from the landfill, an abundance of 808 items/L was obtained. This result is much higher than similar research conducted on groundwater around the Tamangapa Makasar landfill, which was 0.25 items/L to 0.95 items/L (Fajaruddin Natsir et al., 2021), a study on groundwater in a South Indian landfill found microplastic contamination ranging from 2 to 8 items/L (K et al., 2021). Meanwhile, the results of the study on groundwater at the Amin Bazar landfill ranged from 1170 items/L to 320 items/L. This proves that the landfill can release microplastic particles into the surrounding environment, and has been identified as the main source of microplastics in groundwater (Singh, S., Bhagwat, 2022). Microplastic

particles from waste disposal in landfills may migrate into the soil layer, contaminate groundwater, and then be re-dispersed into aquatic systems by wind or surface water runoff. (Upadhyay and Bajpai, 2021). Plastic debris that has been buried degrades into microplastics, particles smaller than 5 mm.. These microplastics then move following the flow of groundwater because of their very small size through the pores of the soil, polluting the aquifer that is the source of community well water.

Characterization of Microplastics

Shape

The fragment form was identified at each research location with the largest number compared to other forms as shown in Figure 4. The results of this study are in line with previous studies which found that fragment form microplastics were the dominant form found in leachate, surface water and groundwater (Rahman et al., 2024). Microplastic findings fragment form based on sample type are active zone landfill 46%, inactive zone landfill 64%, leachate 80%, surface water 54% and groundwater 62% (figure 5). The wide distribution of fragment forms in all research locations comes from the degradation and fragmentation of large plastic products that are widely used daily such as plastic bags, beverage bottles, storage containers, food and toy wrappers (Gela and Aragaw, 2022). In addition to the fragments, fiber is also the dominant form of microplastic found in all research locations (figure 4). Fiber microplastics were found 13% of active zone landfill, 11% of inactive zone landfill, 9% of leachate, 28% of surface water and 18% of groundwater. It was also reported by previous researchers that fragments and fibers are the dominant forms of microplastic found in landfills, surface water and groundwater (Su et al., 2019).

Microplastics identified in the active zone landfill (Figure 5 a) are 46% fragments, 18% fiber, 13% film, 9% pellets, 8% rods and 6% foam. In the inactive zone (Figure 5 b) fragments were found at 64%, 11% fiber, 11% rods, 10% pellets, 3% foam and 1% film. A recent study at the landfill showed that the microplastics detected consisted of 71% in the form of fibers, 16% in the form of fragments, 12% in the form of films, and 1% in the form of pellets (Rahmani et al., 2023). Another study found that refused samples contained 59.82% fragments, 13.39% fibers, 7.86% films, 18.57% granules, and 0.36% rods (Su et al., 2019). The percentage of fragments found in the inactive zone was higher than in the active zone. Meanwhile, the film form was found more in the active zone, namely 13% while in the inactive zone only 1%. This shows the increasing use of plastic packaging which then ends up in the landfill. This plastic waste is then degraded into microplastics in the form of films and seeps into deeper soil layers. This shows the occurrence of vertical transfer of microplastics in the soil.

Microplastics from ST-3 (unprocessed leachate) and ST-4 (processed leachate) had the most fragment forms, namely 81.24% and 74.16%. Other forms found are fiber 9%, rod 5%, pellet 3%, foam 2% and film 1%. Compared to the fiber form, fragments are the most common microplastics found in unprocessed leachate (Sun et al., 2021). This statement is in line with the results obtained in this study and the previous study in Suzhou, China, which found 52% of microplastics in the form of fragments, 20% in the form of films, 20% in the form of fibers, and 6% in the form of pellets (Sun et al., 2021). In addition to the fragment form which reached 54% in surface water (Figure 5 c). The fiber form is most commonly found in surface water locations compared to other study sites, namely with a percentage of 28% (Figure 5). Research in the Wei River, China, found microplastics in the form of fibers and films as the dominant form (Ding et al., 2019). Another study in the Sago River, Riau, Indonesia, found microplastics in the form of fibers, films, and fragments (Priyambada et al., 2023). Films may originate from the weathering of larger plastic debris, moreover, fibers can result from household waste from nearby creeks, air deposition, or crushed fishing nets (Bashir and Hashmi, 2022). In the surface water study sites (ST-5 and ST-6), in addition to being close to the landfill, this study location is also a place for fishermen to moor their boats, repair their boats and a route for fishing boats to the sea. Fishing and washing clothes activities also affect the abundance of fiber forms in this study location.

In the inactive landfill zone, many microplastics in the form of pellets and rods were found. Pellet forms were found as much as 14.54% in the upper soil (0-5 cm) and 7.07% in the lower soil (5-20 cm). Rod-shaped microplastics were found as much as 9.89% in the upper soil (0-5 cm) and 11.74% in the lower soil (5-20 cm). Microplastics in the form of pellets can come from primary microplastics such as microbeads in scrub products, granules in toothpaste, cleaning products (granules in detergent) and plastic pellets (Turner, 2018). Rod-shaped microplastics usually come from toothbrush fibers, cleaning brush fibers, synthetic fibers from clothing, synthetic ropes and threads, rope fibers, net fibers, and from household appliances. For pellet-shaped microplastics, there is a significant difference in concentration between the top and bottom soil. This discrepancy suggests that pellet-shaped microplastics are more likely to gather at the top

soil layer and are difficult to transfer into deeper layers.. Meanwhile, rod-shaped microplastics show a different pattern. The difference in microplastic concentration in the lower soil layer which is higher than the top soil layer indicates that rod-shaped microplastics have a better ability to move to deeper soil layers. This difference in distribution can be influenced by the physical characteristics of each form of microplastic, the process of water movement in the soil, biological activity in the soil, accumulation time in the inactive zone and the nature of the soil at that location.

Meanwhile, foam-shaped microplastics are the microplastics with the least amount found. The active zone landfill location (ST-1) is the location with the highest concentration of foam-shaped microplastics, namely 17.99% in the upper soil (0-5 cm) and 17.93% found in the lower soil (5-30 cm). This can be caused because in the active zone landfill there is still an ongoing activity of accumulating waste containing foam materials such as styrofoam which is now widely used as food containers. This waste is then degraded and fragmented into smaller particles (microplastics). Waste compaction activities can also accelerate the fragmentation process of foam materials.

Table 1. Results of this study compared to those of earlier, comparable studies

Type of Sampel	Abundance	Color of Mp	Form of Mp	Scale of Mp	Types of Polymers	Ref
Leachate	270±13 MP/L	Blue, red, white, transparent, green, black, purple	Fragment (44.3%), Fiber (41.8%), pellets (5.1%), film (5.1%), foam (3.8%)	0.1 – 0.5 mm (36.7%)	LDPE, HDPE, PET, nitrile, PP, nylon	(Rahman et al., 2024)
Surface water	2090 ± 100 MP/L	Transparent, Blue, Red, White, Yellow, Green, Black, Purple	Fragment (60.3%), fiber (15.5%), foam (9.1%), pellet *8%), film (7.1%)	0.1 – 0.5 mm (58.4%)	LDPE, HDPE, PET, nitrile, PP, nylon	(Rahman et al., 2024)
Ground water	647 ± 22 MP/L,	Transparent, Blue, Red, White, Yellow, Green, Black, Purple	Fragment (56.8%), fiber (21.2%), pellets (8.7%), film (8.1%), foam (5.2%)	0.1 – 0.5 mm (56.6%)	LDPE, HDPE, PET, nitrile, PP, nylon	(Rahman et al., 2024)
Leachate	9-21 items/L	yellow (35%), transparent (16%), purple (15%), blue (11%), pink (8%), white (6%), black (3%), green (2%), and orange (1%).	fibers (83%), followed by fragments (11%), films (3%), and foam (2%)	-	Low Density Polyethylene, Polypropylene, Polyethylene Terephthalate, Nitrile, Cellulose acetate	(Sekar and Sundaram, 2023)
Rubbish	62±23 items/Kg		Fragments (59.82%), Fiber (13.39%), Film (7.86%), Granules (18.57%), Rods (0.36%)		PE, PEUR, PS, PET	(Su et al., 2019)
Ground water	2-80 items/L	Yellow (2%), blue (6%), red (18%),	Polyethylene (1%), fiber/PVC		PP,PS	(K et al., 2021)

		green (8%), black (27%), white (38%)	(2%), fragments (3%), foam (6%), pellets (18%), nylon (70%)			
Surface water	3.67-10.7 items/L		Pellets, foam, fragment, fiber, film	<0.5 mm (68.1 %), >5 mm, 4-5 mm, 3-4 mm, 2-3 mm, 1-2 mm, 0.5- 1 mm	PE, PVC, PS	(K et al., 2021)
Landfill land	-	-	Film, fragment	1- 2000µm	LDPE, HDPE, Cellulose acetate (CA), HDPE	(Afrin et al., 2020)
Different zones of waste landfill site	3160-76513 items/kg	Black (49%), white (6%), red (4%), green (1%), others (11%)	Fragment (16%), Film (12%), pellets (1%)	25µm - 5 mm (40.68%)	PP (33%), PES (11%), PET (7 %)	(Rahmani et al., 2023)
Active zone	23340 – 23420 items/ Kg	Black, yellow, pink, red, blue, green, transparent, white, brown, Black, yellow, pink, red, blue, green, transparent, white, brown, gray	Fiber fragment, film, pellets, foam, rod	<100 µm, 100- 500µm, 500- 1000µm, >1000µm	PS	Current studies
Inactive zone	16380-24880 item/Kg	Black, yellow, pink, red, blue, green, transparent, white, brown, gray	Fragment, film, fiber, foam, pellet, rod			Current studies
Leachate	209-757 items/L	Black, yellow, pink, red, blue, transparent, white, brown Black, yellow, pink, red, blue, green, transparent, white, orange	Fragment, fiber, film, pellet, foam, rod		PET	Current studies
Surface water right	6-7 items/L	Black, yellow, pink, red, blue, green, transparent, white, orange, purple	Fragment, fiber, film, pellet, foam, rod			Current studies
Ground water	808-979 items/L		Fragments, fiber, film, pellets, foam, rod			Current studies

Microplastic Size

In general, the findings of microplastics based on size in this study ranged from 1,897– 1,640 µm (0.001897 – 1.64 mm). The distribution of microplastic sizes found in each location was grouped into 4 (four) categories <100 µm, 100-500 µm, 500-1000 µm and > 1000 µm is shown in figure 6. Microplastics measuring < 100 µm dominates all study sites Microplastics measuring <100 µm found in active zone landfills 81.3%, inactive zone landfills 82%, leachate 86%, surface water 71.2% and groundwater 87%

(figure 7). The findings of this investigation are comparable to those of prior investigations.. The most prevalent particle size range in water and sediment samples is microplastics with a 0.00417 - 0.5 mm dimension (Gela and Aragaw, 2022). The Tamangapa Makasar landfill's groundwater contained microplastics with sizes ranging from 0.069 mm to 4.459 mm, with the greatest number of microplastics being less than 2 mm (86%) (Fajaruddin Natsir et al., 2021). In the MSW landfill, 77.48% of microplastics measuring 100 – 1000 μm were also found. The discharge of microplastics in landfills is a long-term process (He et al., 2019). These tiny microplastic particles are more likely to proliferate in the aquatic environment and enter aquatic creatures' food chains. Because of their greater surface area to absorb associated toxins, they can be a more significant threat to aquatic life than big microplastics (Devriese et al., 2017).

Microplastic Colors

Transparent fibers typically originate from the fragmentation of fishing gear or nets, while colored particles result from fragments from commonplace plastic products like textiles and packaging. The color of microplastics varies depending on the parent plastic's color and how long it has been used (Wang et al., 2020). From Figure 8, it can be seen that the colors of microplastics identified in all research locations consist of black, yellow, pink, red, blue, green, transparent, brown, gray, orange, purple, and white. According to other studies conducted at the Amin Bazar TPA, microplastic colors include red, blue, green, yellow, brown, translucent, purple, and black. This conclusion is consistent with those findings. (Rahman et al., 2024). The results of the study in leachate at the Hyderabad India landfill also identified microplastic colors such as yellow, transparent, purple, blue, pink, white, black, green and orange (Sekar and Sundaram, 2023). The color variations indicate the diversity of microplastic sources and the different types of human actions that cause pollution. The base plastic product's color determines the color of microplastics, although weathering processes can readily alter the color (Mohammadi et al., 2022) Particularly when biological, chemical, and physical processes take place in landfills (Trihadiningrum et al., 2023).

In all study sites, black dominated the microplastic findings (figure 8). Similar results were also found in Hamadan, Iran (Rahmani et al., 2023). The dominance of black may be related to the widespread use of this color in consumer and industrial plastics (Efendy et al., 2024), as well as household products such as food packaging and plastics for agriculture (Deng, H et al. 2023). Plastic fragmentation into smaller particles, known as microplastics, results from landfill operations such as garbage compaction with heavy machinery and the stockpiling process.. The dominance of black color throughout the study location indicates the resistance of black microplastics to degradation. The hydrophobic nature and density allow these black particles to survive during the transport process. Anaerobic conditions in landfills, chemical reactions with leachate, UV exposure and microorganism activity can also affect the character of microplastics where some types of plastics can darken over time due to the weathering process.

In Figure 9, the concentration of yellow color is higher in the inactive landfill zone compared to other locations, namely 13.4%. In contrast to other research locations, the active zone exhibits higher transparency. Transparent and yellowish particles are abundant. Indicates that most of the microplastics are old and have been in the landfill for a long time (Sun et al., 2021). The most dominant black color in leachate reaches 79.3% can come from waste sources that are mostly black, the weathering process can also make the color of the plastic dark over time. This result aligns with previous research that found black (24.7%) and red (24.7%) as the dominant colors (Rahman et al., 2024). Black color was found most in all study sites, including SW and GW, while white was found most in surface water and groundwater, followed by other colors such as yellow, pink, red, blue, green, transparent, orange, and purple. Similar results were also found in the River Thames, UK, which found black as the dominant color followed by other colors such as blue, red, white, orange, yellow, transparent, brown, pink, green, purple, and gold (Devereux et al., 2023). The potential danger of microplastics to biota can be influenced by their color, because it is suspected that the microplastics are their food. The white color of microplastics makes this material easier to swallow by various marine organisms ranging from plankton to fish, so it has the potential to pollute the food chain and cause physiological disorders due to accidental consumption (Qiu et al., 2020).

Polymer Composition

Based on the FTIR spectra (Figure 10), peaks that show the characteristics of polyethylene terephthalate are known. The FTIR reading results on ST-1 A show a wavelength 3333.62 cm^{-1} , indicating the presence of O-H bonds, which is characteristic of hydroxyl functional group. Additionally, the peak at 1648.11 cm^{-1} suggests the existence of C=O bonds, commonly found in esters or amides, while the peak at 1278.75 cm^{-1} (69.65% transmittance) is indicative of C-O bonds, further supporting the presence of ester functionalities. These spectral features align closely with those observed in the standard spectrum for

polyethylene terephthalate (PET), suggesting that the analyzed polymer may indeed be a type of polyester, particularly PET, based on its characteristic spectral signatures.

The FTIR reading results on ST-4 (figure 10) show a wavelength of 3332.26 cm⁻¹ indicating wide OH stretching and indicating the presence of hydroxyl groups (-OH), then the wave peak is at 2915.87 cm⁻¹ indicating CH stretching (CH₂) which is characteristic of the carbon chain. The number 1647.25 cm⁻¹ indicates C=O stretching (carbonyl) which can indicate oxidative degradation of plastic. 1278.64 cm⁻¹ indicates CH bending and CO stretching, 1064.44 cm⁻¹ indicates COC stretching (ether), 837.97 cm⁻¹ indicates CH deformation., 414.41 indicates molecular framework vibration. The presence of a wide OH peak at 3332 cm⁻¹ also indicates that this plastic has undergone degradation in the landfill environment which generally occurs due to exposure to moisture, microorganisms and other environmental factors.

Based on the spectrum pattern and identified peaks, the samples at ST-1 A and ST-4 contain Polyethylene Terephthalate (PET) type polymers. PET is one of the most common types of plastic found in landfills. PET is the most widely used plastic in the packaging industry because it has excellent mechanical, thermal and chemical resistance and very low gas permeability compared to Polyethylene, Polystyrene and Polypropylene (Khairul Anuar et al., 2022). Similar results were also shown in a previous study, landfills in Thailand found polymers Polyethylene (PE), Polypropylene (PP) and Polyethylene Terephthalate (PET) in soil and leachate (Puthcharoen and Leungprasert 2019). Likewise, in Laogang landfill, Shanghai, China, plastics, polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), poly amide (PA), polystyrene (PS), and ethylene-propylene copolymer (EPM) were found (Su et al., 2019).

The finding of high abundance of microplastics at the Gampong Jawa landfill site indicates that the process of changing status to a transfer station does not immediately eliminate the potential for microplastic pollution that previously occurred when it was still functioning as a final disposal site (landfill). The accumulation of microplastics in the soil and leachate appears to remain a potential source of pollution that can continue to spread to the surrounding environment, including the water system, even after operating as a transfer station for 6 years. Waste transfer and handling activities at the transfer station also have the potential to release new microplastics into the environment. This is a serious concern that needs to be addressed comprehensively to prevent the further spread of the negative impacts of microplastics in the future. The results of this study emphasize the need to implement better waste management strategies, including environmentally friendly processing technologies and strict monitoring systems, even at landfills that function as transfer stations. Comprehensive mitigation efforts are needed to overcome this microplastic problem.

Microplastic contamination can be reduced by reducing plastic waste, improving waste management, and developing microplastic removal and remediation technologies. Integration of biological treatment systems such as phytoremediation and bioremediation can also increase the efficiency of microplastic removal (Liu et al., 2024). The application of the circular economy concept in plastic waste management such as integrated recycling systems and environmentally friendly processing technologies can be a solution to reduce the burden of microplastics in the environment. The use of membrane bioreactors-nanofiltration - reverse osmosis on leachate has been proven to be effective in reducing the particle load and mass of microplastics, although there are indications that very small microplastics can form and be released from the membrane system (Sun et al., 2021). The development of biodegradable materials as an alternative to conventional plastics needs to be encouraged to prevent the accumulation of microplastics in the future. Innovation in the field of bioplastics and environmentally friendly materials can support the transition to a sustainable economy in accordance with the principles of sustainable development. This green technology approach not only contributes to the reduction of microplastic pollution but also supports the achievement of several SDGs targets, especially those related to clean water and sanitation (SDG 6), sustainable consumption and production (SDG 12), and ecosystem protection (SDG 14).

Conclusion

This study revealed that microplastic contamination has spread to the soil, leachate, river water and well water around the landfill. An alarming finding was the high concentration of microplastics in groundwater samples that reached 808 to 979 items/L, as well as leachate with a concentration of 209 to 757 items/L. Meanwhile, surface water contains 6.29 to 7.2 items/L of microplastics and landfill soil samples show the presence of 23340 to 23420 items/Kg of microplastics. Physical characterization reveals the diversity of microplastic forms found including fragments, fibers, films, pellets, foams and rods with sizes varying from 1,897 to 1642.79 µm. Microplastics found in all study sites were predominantly <100 in size µm.

Polyethylene Terephthalate is polymer detected in soil samples and landfill leachate. The high concentration of microplastics found especially in groundwater raises serious concerns about the potential for groundwater contamination from landfill activities that have a direct impact on the health of the surrounding community. This study is an initial step in understanding the role of landfills as a source of microplastic release into the environment. These results also highlight how crucial it is to create efficient mitigation plans to lessen the effects of landfill microplastic pollution. Furthermore, this study paves the way for subsequent studies to develop comprehensive solutions to address the problem of microplastics in landfills. Given the large implications of these findings for environmental and public health, further, more in-depth research is needed to understand the mechanisms of microplastic transfer, its long-term impacts and the development of more effective landfill management methods in preventing microplastics from being released into the environment, including for landfills that already function as transfer stations.

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