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Distribution and ecological risk of microplastics in soil at the Jatibarang landfill in Semarang, Indonesia

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ABSTRACT

Inadequate waste management contributes significantly to the accumulation of plastic waste, as landfills accept unsorted waste. Various natural processes in landfills play a crucial role in microplastic pollution of both soil and aquatic systems. This study examined samples from Jatibarang Landfill, Indonesia, the largest waste disposal site in Central Java. Soil samples were collected from a depth of 0 to 20 cm in three zones – active, passive, and areas near settlements – and analyzed for microplastic abundance, size, shape, color, and polymer type. The study aimed to evaluate the distribution, ecological risks, and impacts of microplastics on the physical and chemical properties of soil at Jatibarang Landfill. Results indicated a high microplastic abundance, with counts reaching 2340 particles per kilogram of soil, particularly in areas close to settlements. The primary types of microplastics identified were polypropylene (PP), polystyrene (PS), and low-density polyethylene (LDPE). The polymer hazard index (PHI) and coefficient of microplastic impact (CMPI) were employed to assess the potential risks of microplastic pollution. Polypropylene was identified as the most significant pollutant due to its widespread use and persistent nature. Improved landfill management strategies are essential to mitigate microplastic pollution and its adverse environmental effects.

Keywords: microplastic, soil, distribution, ecological risk, landfill.

INTRODUCTION

Plastic pollution has become a global environmental issue. The production of plastic has surged to 300 million tons annually (Yu et al., 2020), with Indonesia ranking as the second-largest waste-producing country after China. Large quantities of plastic waste are deposited in landfills, where it fragments into secondary microplastics. This process introduces microplastics into the soil environment (Wang et al., 2022) and eventually into landfill leachate (Kabir et al., 2023). The volume of plastic waste, leachate management practices, and landfill age all contribute to the prevalence of microplastics (Upadhyay and Bajpai, 2021). Fragmentation of plastic waste in landfills leads to the formation of microplastics, with 99.36% originating from landfill sources. Among these, 77.48% of microplastics measure between 100 and 1000 µm. The generation, accumulation, and release of microplastics in landfills is a prolonged process. Research provides compelling evidence that landfills not only store plastic waste but also act as sources of microplastic pollution (He et al., 2019). Microplastics on the soil surface, along with leachate, migrate into the soil and pose a risk of contaminating groundwater (Monkul and Özhan, 2021). The abundance, distribution, and migration of microplastics from landfills to soil and groundwater are also influenced by meteorological factors (Upadhyay and Bajpai, 2021). Understanding the mechanisms behind microplastic transport in soil is therefore essential.

Microplastic migration in soil is influenced by the physical and chemical properties of landfill soil. Soil pore size determines microplastic movement: smaller microplastics can migrate through pores, while larger ones become trapped, degrading over time and potentially reaching groundwater. Additionally, soil porosity and permeability play significant roles. Finer soils retain smaller microplastics, whereas coarser soils allow easier migration (Upadhyay and Bajpai, 2021). Chemical factors such as the pH, salinity, and organic matter content of leachate also affect microplastic mobility and fate in soil. Meteorological conditions, including rainfall and wind, further influence microplastic migration. Heavy rainfall increases leachate volume and surface runoff, while wind can disperse microplastics from the soil surface.

The physical and chemical characteristics of landfill soil play a crucial role in determining the migration and retention pathways of microplastics, ultimately influencing potential ecological and human health risks (Guo et al., 2020). Human exposure to microplastics is associated with various health issues, including metabolic disorders, neurotoxicity, and an increased risk of cancer (Rahman et al., 2021). Additionally, microplastics impact ecosystems, affecting marine life, soil, and air (Ghosh et al., 2023). They can accumulate within aquatic food chains, resulting in higher concentrations at elevated trophic levels (Blackburn and Green, 2022). These impacts become more severe in the absence of an adequate waste management system.

The Jatibarang landfill, operational since 1993, was initially designed to accommodate waste for up to eight years, until 2001. it remains in use today and, according to its management, can continue to operate for another 5–10 years if the utilized area expands to 25 hectares and the waste processing system transitions from a controlled landfill to a sanitary landfill (Semarang City Environmental Service, 2018). Over its 30 years of operation, leachate runoff has significantly polluted soil and groundwater. Jatibarang landfill soil is crucial for understanding their impact on soil and groundwater environments.

Recent studies on landfill soil microplastics highlight concerning findings. In Depok City, microplastic concentrations in waste embankment soil reached 60,111.67 particles per kilogram, with fragments accounting for 63% (Pratiwi et al., 2024). Microplastic contamination in well water has also been documented. Around the Tamangapa landfill in Makassar City, microplastic concentrations ranged from 0.25 to 0.95 particles per liter, consisting of 72% fibers and 28% fragments, with sizes between 0.069 mm and 4.459 mm (Fajaruddin Natsir et al., 2021). The proximity of wells to landfill contamination sources significantly influences microplastic abundance. For instance, research by Utami and Liani (2021) at the Piyungan landfill in Yogyakarta revealed the highest microplastic content (146 ±109 particles per liter) in well water within 0–1 km from the landfill. This decreased to 116 ±31 particles per liter at 1–2 km and 77 ±23 particles per liter at 2–3 km.

Most research investigates the distribution and properties of microplastics, but little focuses on their impact in different zones of landfills. Rahmani et al. (2023) reported that microplastic abundance is significantly higher in leachate lagoon zones and old waste disposal sites compared to active zones. Microplastics in the soil surrounding landfills are influenced by the composition of landfill waste. For example, a study in the Republic of Korea found average microplastic concentrations of 73.4 MPs/kg and 97.8 MPs/kg near landfills, with fragments, fibers, and films being the predominant forms, and polypropylene (PP) and polyethylene (PE) as the main polymer types (Kim et al., 2023). In Indonesia, no studies have specifically examined the distribution or transport processes of microplastics within various landfill zones or their impact on ecological risks and the physical and chemical properties of soil. This study seeks to analyze the distribution, ecological risks, and effects of microplastics on the physical and chemical characteristics of soil in the Jatibarang landfill. The findings aim to inform policymakers about mitigating microplastic pollution through sustainable landfill management to reduce risks to public health and the environment.

METHOD

Research location

This study was conducted in January 2024 at the Jatibarang Landfill, located in Kedungpane Village, Mijen District, Semarang City, Indonesia. The landfill spans an area of 460,183 m², with the waste area covering approximately 276,469.8 m² and infrastructure occupying 184,073.2 m². Waste collection activities at the landfill have been carried out in three zones. The first zone, referred to as the Old Zone, is located in the northern part of the landfill, covering 5.1 hectares, and is no longer in use, marking it as a passive zone. The second zone, Zone I, is an active area covering 4.6 hectares. The third zone, zone II, is another active area spanning 5.8 hectares that overlaps with Zone I. Soil samples were collected at a depth of 0–20 cm, which serves as a critical indicator for analyzing the transfer of microplastics to adjacent ecosystems and assessing immediate risks to soil and public health (Pratiwi et al., 2024).

Soil samples were collected from three locations, as shown in Figure 1. The samples were obtained using a soil drill, followed by a sample mixing process. Subsequently, 2 kilograms of soil, cleaned of large materials, were stored for laboratory analysis. GPS was used to record the exact sampling locations.

Sample preparation and microplastics identification

The separation of microplastics from soil is a critical step in identifying microplastics within soil systems. Zhang et al. (2018) demonstrated an effective approach using a modified flotation method. For this study, approximately 100 grams of soil was dried at 90 °C in an oven, and the dried soil was sieved using a 16-mesh sieve. The sieved soil, measuring about 100 grams, was further filtered through a 1.18 mm pore sieve. A 20 ml volume of saturated NaCl solution was added to the soil and left for 24 hours to facilitate the separation of the soil matrix from microplastics.

The top 100 ml of the solution was carefully extracted, and 10 ml of 30% H_2O_2 was added. The mixture was stirred using a magnetic stirrer at 75 °C for 24 hours to remove organic matter and impurities. The resulting sample was filtered using fiber filter paper, and the microplastics were examined under an Olympus binocular microscope with a 200× magnification. Morphological identification of microplastics included analyzing their size, shape, and color, while polymer type verification was performed using a PerkinElmer Frontier fourier transform infrared (FT-IR) spectrometer.

Risk evaluation of microplastic pollution was calculated using the polymer hazard index (PHI) and the coefficient of microplastic impact (CMPI). The PHI quantifies the toxicity of chemical compounds in polymers (Xu et al., 2018) and is determined using the formula:

$$PHI = \sum S_n \times P_n \tag{1}$$

where: Sn represents the hazard value of a polymer, and Pn denotes the proportion of each polymer type. PHI values are classified into five hazard levels (Lithner et al., 2011): 0–1 (I), 1–10 (II), 10–100 (III), 100–1000 (IV), and >1000 (V) (Ranjani et al., 2021).

The CMPI evaluates the impact of various microplastics and is calculated as:

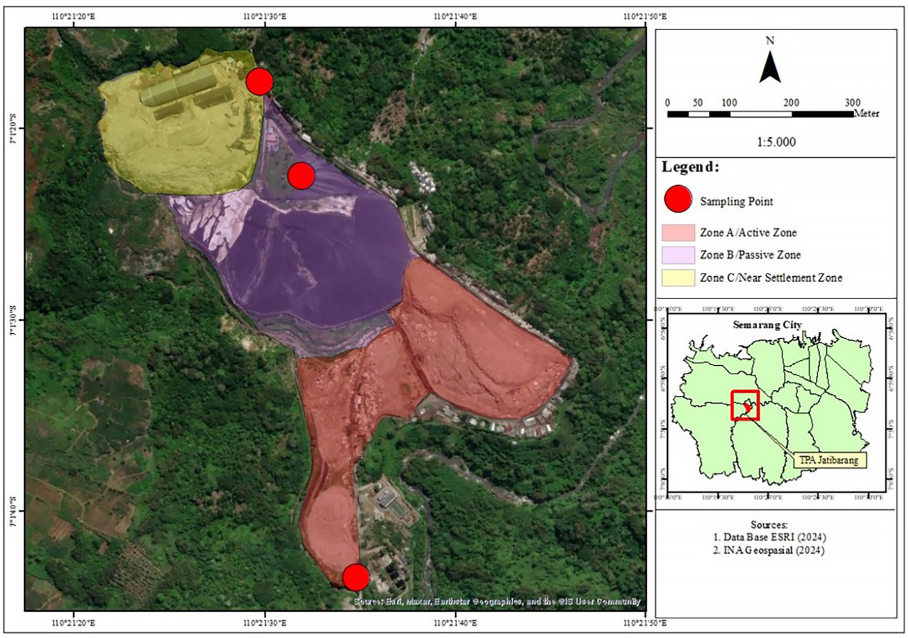

Figure 1 Sampling points at Jatibarang landfill, Semarang

$$CMPI = \frac{Specific\ MP}{Shape\ Total\ MPs} \quad (2)$$

where: *CMPI* values are categorized into four levels: 0.0001–0.1 (minimum), 0.11–0.5 (average), 0.51–0.8 (maximum), and 0.81–1 (extreme) (Rangel-Buitrago et al., 2021; Unnikrishnan et al., 2023).

Determination of soil physicochemical properties

The determination of soil physicochemical properties in the Jatibarang landfill was conducted to analyze the effect of microplastics on soil characteristics. The measured physicochemical parameters included water content, specific gravity, soil bulk density (SBD), soil total porosity (STP), permeability, soil pH, soil organic matter (SOM), and total organic carbon (TOC). Water content was determined using the gravimetric method, specific gravity was measured with the pycnometer method, SBD and STP were assessed using the ring method, permeability was evaluated by the constant head method, pH was measured using a pH meter, and SOM and TOC were determined using the Walkley-Black method.

RESULTS AND DISCUSSION

Distribution of microplastics in each sampling zone in Jatibarang landfill

Microplastics were identified in soil samples collected from all three zones of the Jatibarang landfill region. As shown in Figure 1, the residential zone exhibited the highest concentration of microplastics, with 2340 particles per kilogram of dry soil. The highest abundance was observed in the landfill area adjacent to the residential zone, likely due to its proximity to settlements. Microplastics are transported into the soil through rainfall runoff and wind (Qiu et al., 2020). indicate that residential environments contain significant amounts of microplastics, predominantly composed of polyethylene and polypropylene polymers (Yoon et al., 2024).

The concentration of microplastics in the active zone exceeds that in the passive zone, reaching 1,350 particles per kilogram of dry soil (Figure 2). The higher concentration of microplastics in the active zone compared to the passive zone can be attributed to several factors. First, the continuous accumulation of waste, particularly plastic waste undergoing degradation, in the active area of the Jatibarang landfill leads to increased microplastic formation. Recent studies indicate that microplastics in active zones are significantly influenced by environmental physical, chemical, and biological activities. Microplastics are more abundant in active landfill areas and protected regions, with concentrations as high as 76,513 particles per kilogram in leachate pond locations (Chamanee et al., 2023; Rahmani et al., 2023). In contrast, no new waste is introduced into the passive zone; thus, microplastics result solely from the breakdown of pre-existing waste.

Second, plastic decomposition occurs more frequently in the open environment of active zones, where plastic waste is directly exposed to

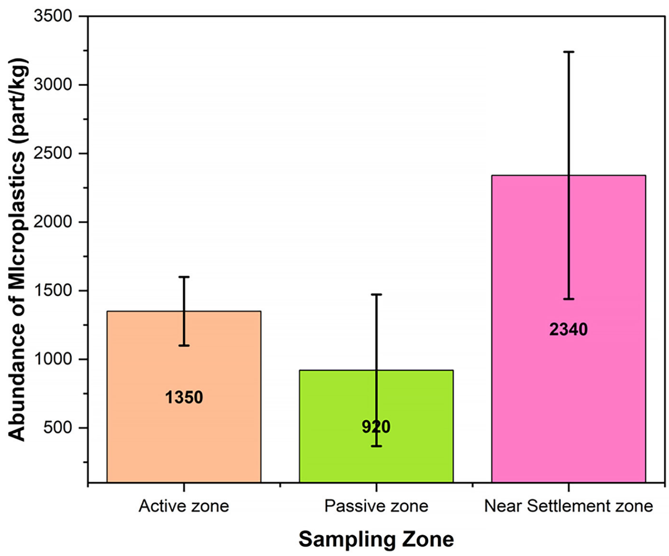

Figure 2. Microplastics abundance based on soil sample zone

sunlight, wind, and precipitation. Ultraviolet radiation accelerates the photodegradation of plastics, while wind and precipitation contribute to plastic fragmentation into microplastics (Wojnowska-Baryła et al., 2022). In the passive zone, however, the trash mounds are more stable, and the area is covered, reducing microplastic generation (Sholokhova et al., 2023).

Third, trash management activities at operational landfills, such as compaction, processing, and grinding, increase microplastic production from plastic waste. Conversely, these processes cease in inactive landfills, resulting in a reduced generation of new microplastics.

The passive zone of the Jatibarang landfill was operational from 1993 until its closure in 2017. This extended operational period (24 years) facilitated a stable decomposition process, leaving fewer uncompressed materials. Consequently, the passive zone contains fewer microplastics (920 particles per kilogram) compared to the active zone, which has been operational for only seven years. The age of a landfill significantly affects microplastic production and accumulation. A study by Sholokhova et al. (2023) reveals that younger landfill areas exhibit higher microplastic concentrations, reaching up to 55 particles per gram, whereas older areas show reduced microplastic abundance.

The aging processes significantly influence the shape, size, color, structure, and distribution of microplastics in landfill areas, particularly in the active and passive zones with distinct environmental characteristics. Changes in mechanical and thermal properties may affect microplastics over the long term (Shi et al., 2024). In the active zone, microplastics are frequently exposed to UV light, which induces photo-oxidative degradation. Plastics undergoing photo-oxidative degradation experience surface fragmentation (Burrows et al., 2024), leading to smaller particle sizes and altered shapes.

In contrast, in the passive zone, although plastic waste is compressed and shielded from UV light, it may still undergo chemical aging processes due to interactions with leachate fluids. These interactions can cause microplastic surfaces to become rough and perforated. Such rough surfaces increase the likelihood of microplastics interacting with other environmental pollutants (He et al., 2023).

Shape and color distribution of microplastics in landfill soil

The main types of microplastics identified are films (45%), fragments (30%), fibers (24%), and pellets (1%) (Figure 3). This finding aligns with data from the Lapes landfill in Kaunas County, Lithuania, where films were the predominant type of microplastic at all depths, followed by fragments (Sholokhova et al., 2023). The prevalence of microplastics in film form originates primarily from domestic plastic packaging, which is a significant contributor to landfill plastic waste (Su et al., 2019). Additionally, studies conducted elsewhere reveal that fibers are the most common form of microplastics, as observed in the Hamadan landfill in Iran (71%) (Rahmani et al., 2023a) and landfills in the Republic of Korea (26.4–45.0%) (Kim et al., 2023). The types of microplastics present in landfill soil are influenced by the composition of waste and the landfill's age. Since most microplastics result from the fragmentation of larger plastics, the volume of

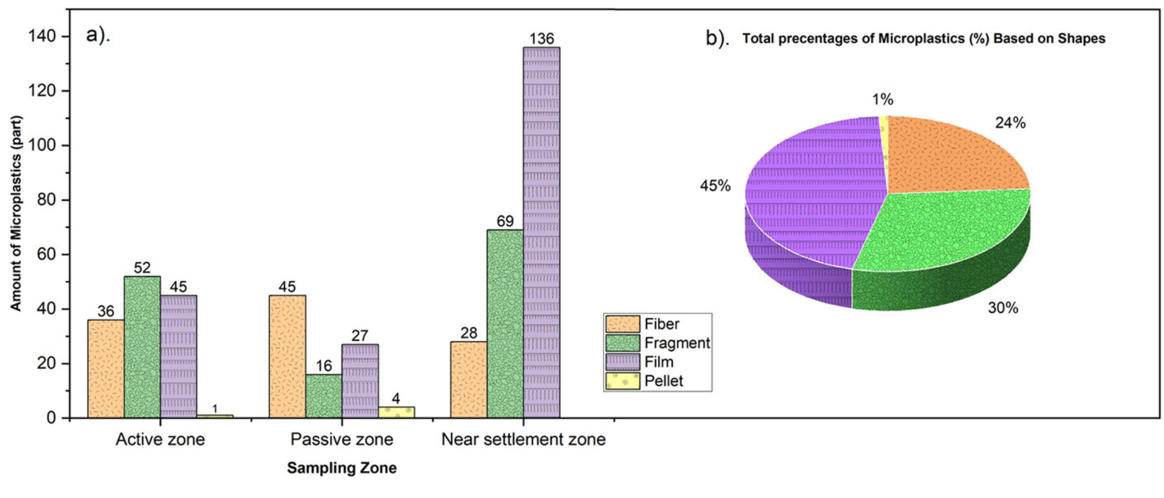

Figure 3. Shape distribution of microplastics in soil systems

plastic waste significantly affects their prevalence. Consequently, microplastics are a major pollutant in landfills and vary in distribution depending on the landfill's stage of degradation (Su et al., 2019).

The most common color of microplastics is transparent, followed by black, green, blue, red, and purple (Figure 4b). Research by Feng et al. (2021) and Yang et al. (2022) similarly found that transparent microplastics represent the highest proportion in soil. The abundance of black microplastics is attributed to the widespread use of black plastics in consumer products and food packaging, particularly trash bags, a finding confirmed by previous studies (Rahmani et al., 2023).

Polymer types distribution of microplastics in landfill soil

The frontier Fourier transform infrared (FTIR) analysis is a reliable method for identifying and distinguishing various plastic polymers, revealing the distinct chemical properties inherent to each material. This approach is essential for understanding the predominant polymers present in landfill soil. Identifying these polymers aids in determining the distribution and fate of microplastics in the environment, particularly in landfill soil (Jung et al., 2018). FTIR analysis was conducted to investigate the distribution of polymer types in landfill soil across the following zones: active zone (Figure 5), passive zone (Figure 6), and the zone close to the settlement (Figure 7).

By identifying the polymers through FTIR analysis, strategies for waste management can be developed. The graphical FTIR results illustrate the polymer distribution in each zone. Figure 5 highlights the microplastic polymers found in the active zone, Figure 6 depicts the polymers present in the passive zone, and Figure 7 shows the microplastic polymers near the settlement zone, morphologically characterized as films, pellets, fibers, and fragments.

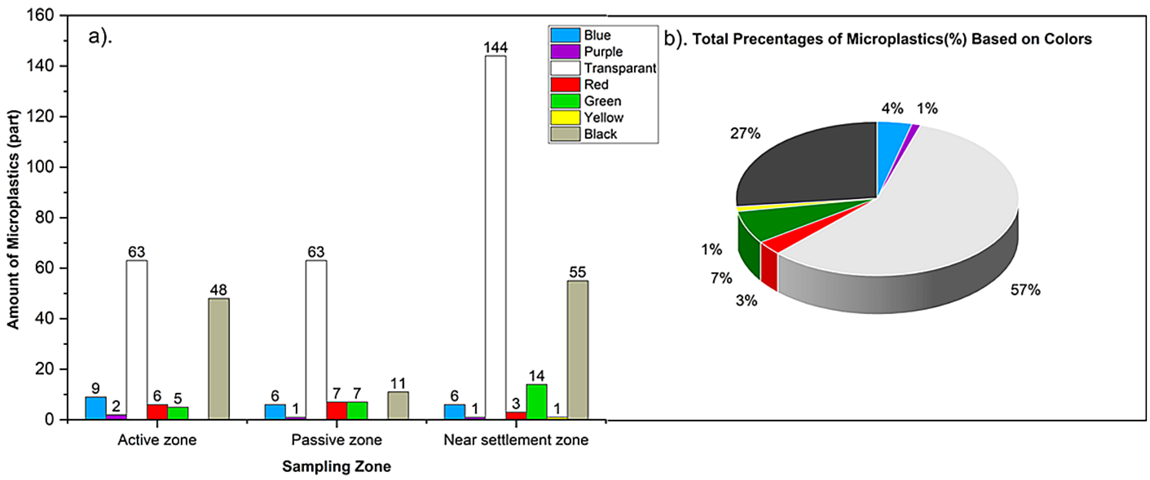

Figure 4. Color distribution of microplastics in soil systems

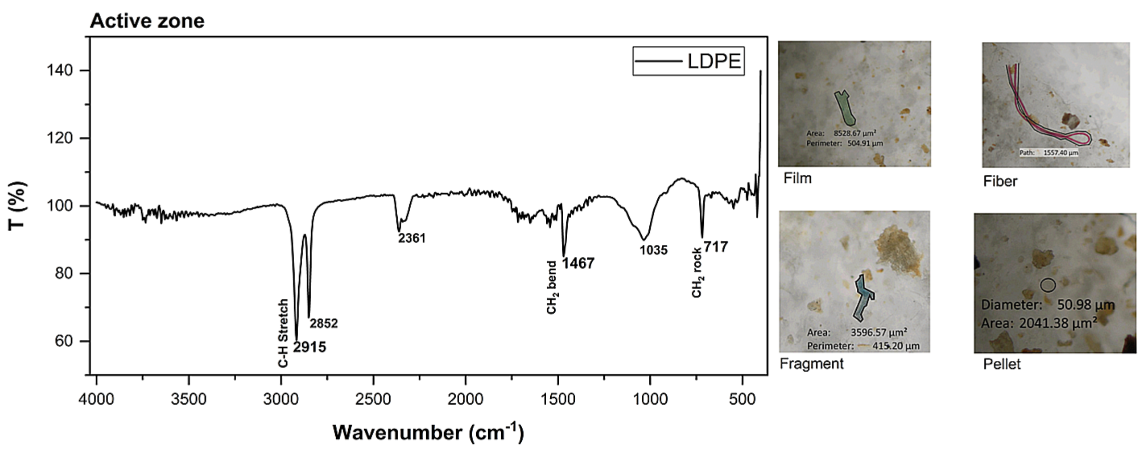

Figure 5. FTIR analysis and shape of microplastics in the active zone

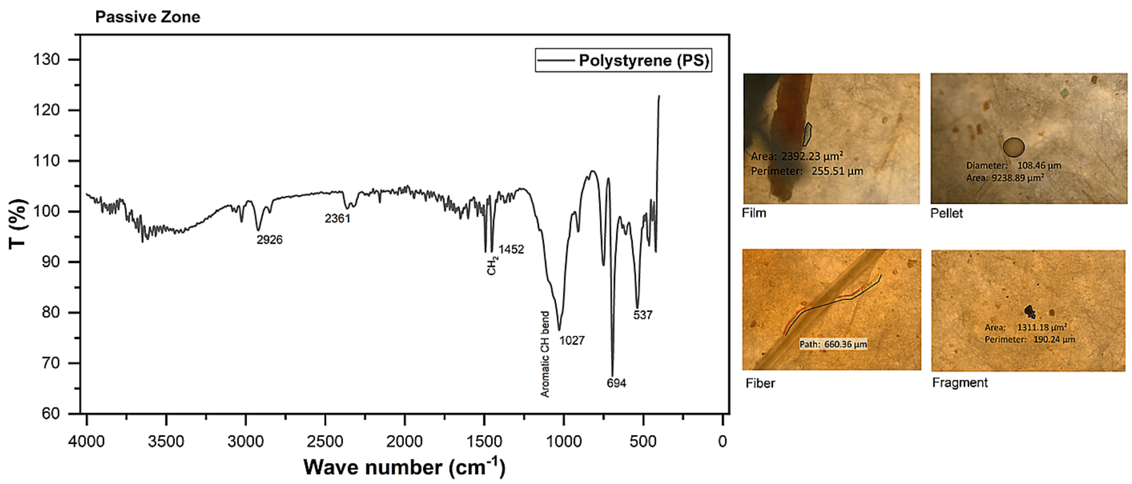

Figure 6. FTIR analysis & shape of microplastics in the passive zone

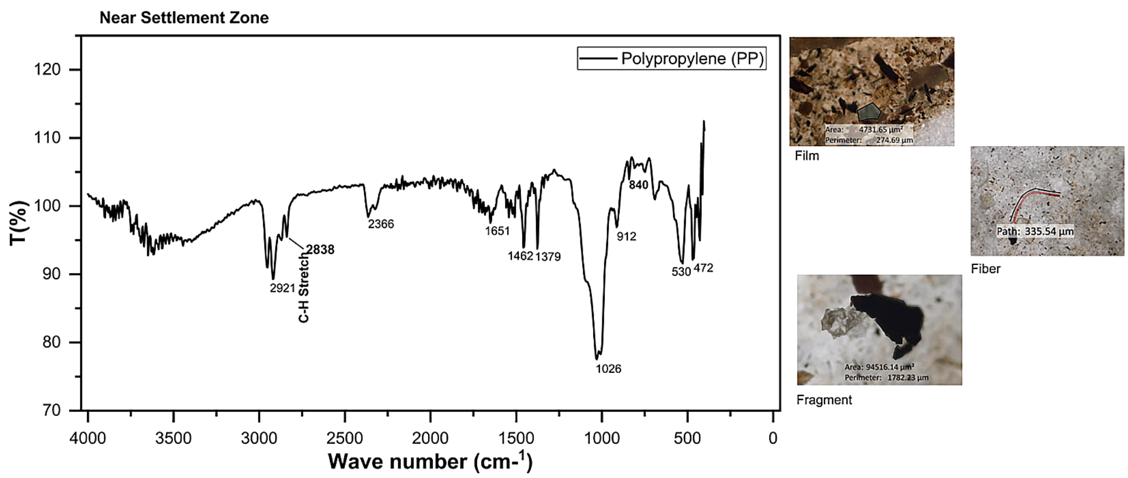

Figure 7. FTIR analysis & shape of microplastics in the near settlement zone

The FTIR graphic from the active zone (Figure 5) confirmed the presence of low-density polyethylene (LDPE), as indicated by transmittance peaks at specific absorption band values: 2915 cm^{-1} (C-H stretch), 1467 cm^{-1} (CH_2 bend), and 707 cm^{-1} (CH_2 rock). Microscopic identification (Figure 5) further revealed that LDPE appeared in various shapes, including fibers, fragments, films, and pellets. In the passive zone, the FTIR analysis (Figure 6) identified the polymer as polystyrene (PS), with absorption band peaks at 1452 cm^{-1} (CH_2 bend), 1027 cm^{-1}, 694 cm^{-1}, and 537 cm^{-1} (aromatic CH bend). Microscopic identification confirmed that microplastics in the passive zone had similar shapes to those in the active zone, including fibers, fragments, films, and pellets.

The FTIR analysis conducted in the near settlement zone (Figure 7) identified the polymer as polypropylene, with absorption band peaks at 2838 cm^{-1} and 840 cm^{-1}. Unlike the active and passive zones, the morphologies of microplastics in the near settlement zone did not include pellets but were observed as films, fibers, and fragments. Based on the FTIR analysis, polypropylene is the dominant polymer type in the Jatibarang landfill soil. Polypropylene primarily originates from various plastic items, such as packaging materials and disposables. Its extensive use and resistance to degradation contribute significantly to environmental contamination.

Ecological risk index of microplastics in landfill

The ecological risk index is determined using the polymer hazard index (PHI) (Table 1) and the coefficient of microplastic impact (CMPI). This study assesses the potential microplastic

Table 1. Polymer hazard index (PHI)

Sampling point	Polymer	Hazard level	Risk categories level
Active zone	Polypropylene (PP) Low-density polyethylene (LDPE)	I II	Minor Medium
Passive zone	Polypropylene (PP) Polystyrene (PS)	I II	Minor Medium
Near settlement zone	Polypropylene (PP)	II	Medium

pollution at the TPA Jatibarang landfill in Semarang. The PHI serves as an effective tool for evaluating the potential environmental hazards posed by microplastics.

In the active zone of Jatibarang Landfill, polypropylene (PP) is classified as hazard level I, placing it in the minor risk category. Low-density polyethylene (LDPE), categorized as hazard level II, falls into the medium-risk category due to its higher propensity to generate microplastics. Polymers such as PP and LDPE exhibit slow degradation rates, contributing to their environmental persistence.

In the passive zone, polypropylene is categorized as hazard level I (minor risk), while polystyrene is classified as hazard level II (medium risk. In the near settlement zone, polypropylene is the sole polymer identified, classified as hazard level II and medium risk. The significant presence of polypropylene in this zone is attributed to its widespread use in everyday domestic products such as plastic bags, bottles, and packaging materials. Polypropylene's low cost, high stability, and chemical resistance make it one of the most widely used plastics globally (Pires et al., 2019). The presence of polypropylene in the active and near settlement zones indicates that household waste is a major source of plastic contaminants.

Research from a landfill in Tehran reports PHI values for microplastics within hazard levels III–IV, indicating substantial ecological risk. Mesoplastic (MEP) exhibit lower ecological risks, ranging from levels II to IV (Ghorbaninejad Fard Shirazi et al., 2023). The durability of polymers poses a long-term threat to ecosystems, particularly aquatic environments, where they contribute to bioaccumulation within the food chain. Mitigation measures are critical for waste management systems, especially in areas near residential zones and water resources.

The results derived from the coefficient of microplastic impact shown in Table 2 classify microplastics into several forms: fiber, fragment, film, and pellet. The findings indicate that microplastics in film form dominate in various zones, particularly near settlement areas, with a CMPI value of 0.58, categorized as the maximum level. This suggests a higher potential for the accumulation of microplastics in film form near population centers, likely due to increased human activities, such as the widespread use of single-use plastics.

In landfill soil zones, the CMPI distribution generally aligns with average categories for most microplastic forms, except for pellets, which exhibit the lowest CMPI values. This highlights that landfill sites not only act as significant waste accumulation zones but also facilitate the buildup of microplastics in various forms. In both the active and passive zones, the CMPI values are lower than those in the settlement zone but remain within the average category. This may correlate with reduced environmental interaction and human activity in these areas.

The impact of microplastic distribution on the physical and chemical properties of soil in Jatibarang landfill

The water content in landfill soil varies significantly among the active, passive, and near-residential zones. Microplastic pollution in landfill

Table 2. Coefficient of microplastic impact (CMPI)

Sampling point	Fiber		Fragment		Film		Pallet	
	CMPI	Categories	CMPI	Categories	CMPI	Categories	CMPI	Categories
Active zone	0.27	Average	0.39	Average	0.34	Average	0.01	Minimum
Passive zone	0.49	Average	0.17	Average	0.29	Average	0.04	Minimum
Near settlement zone	0.12	Average	0.30	Average	0.58	Maximum	0.00	Minimum

soil influences soil water content by clogging soil pores, which reduces the soil's ability to absorb and retain water. Wang et al. (2020) found that plastic residues measuring 4 cm² can increase the macropore ratio of soil, thereby reducing its water-holding capacity. This finding aligns with the observation that the active zone has the lowest soil water content (20.73%) compared to the passive zone and the near-residential zone. This condition is attributed to the active zone having the highest abundance of microplastics (1,347 particles/kg) among the three zones. Additionally, smaller MPs (150 µm) at higher concentrations (2%) can increase the water-holding capacity of clay soils by enhancing soil porosity and surface area (Wang et al., 2023).

The passive zone at the Jatibarang landfill exhibits a water content of 26.78%, higher than that of the active zone (Figure 8). This zone serves as the final cover soil and plays a crucial role in the methane oxidation process. Covered by a geomembrane layer, the passive zone functions as a Danida gas landfill area for methane gas storage and is no longer subject to waste disposal activities. Methane (CH_4) is oxidized by methanotrophic bacteria into carbon dioxide (CO_2) and water (H_2O), with peak activity occurring approximately 10 years after landfill closure. Gas production then diminishes, entering a lean gas phase after around 40 years (Sindern et al., 2014). Reduced bacterial activity in the passive zone results in water evaporation exceeding water production.

The zone near settlements exhibits the highest water content (28.70%). This condition is primarily due to human activities, particularly those involving plants and poultry. Plant roots enhance soil structure, making it looser and increasing soil permeability, which facilitates greater infiltration.

Bulk density is the ratio of the mass of soil particles to the total volume of soil and is closely correlated with soil porosity (Salam, 2020). When soil experiences compaction, such as from the use of tractors on landfill sites, the pore space decreases, resulting in an increase in the soil's weight per unit volume. Conversely, when soil pore space increases, for instance, through soil processing, the bulk density decreases.

According to Wang et al. (2022), bulk density is a critical indicator of soil fertility. More porous soils have lower bulk density, while denser soils exhibit higher bulk density. Based on bulk density standards, soils are classified as loose (<1.00 g/cm³), suitable (1.00–1.25 g/cm³), dense/tight (1.25–1.35 g/cm³), and compact (>1.35 g/cm³) (Zhang et al., 2024). The average bulk density of landfill soil in the active zone is the highest, at 1.30 g/cm³ (dense/tight soil), followed by the zone near settlements at 1.17 g/cm³ (suitable soil), and the passive zone at 1.14 g/cm³ (suitable soil) (Figure 8).

In the passive zone of the Jatibarang landfill, the bulk density is the lowest (1.14 g/cm³) due to the completion of the decomposition process and soil stabilization. In contrast, the active zone exhibits the highest bulk density (1.30 g/cm³) as a result of ongoing compaction activities. Soil bulk density decreases with an increase in organic matter (Ruehlmann and Körschens, 2009). In the zone near settlements, the presence of vegetation reduces soil aggregation, making the soil more fertile and looser. Consequently, the bulk density

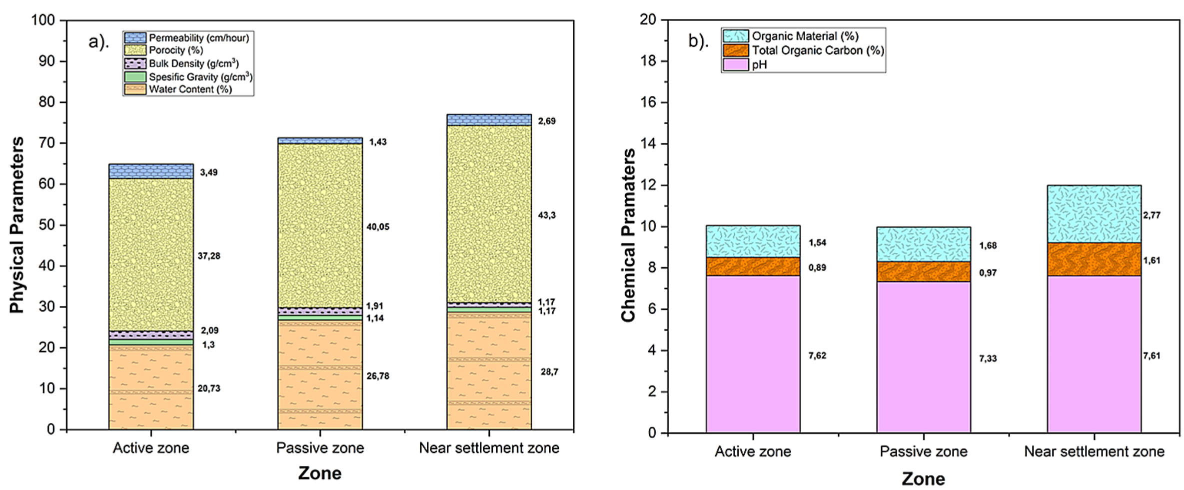

Figure 8. Characteristics of Jatibarang landfill soil: a) physical parameters; b) chemical parameters

in this area (1.17 g/cm³) is lower than in the active zone but higher than in the passive zone.

A higher bulk density reduces the vertical migration of microplastics, confining them to surface layers where they are more likely to migrate horizontally under the influence of rain and wind. This horizontal movement decreases the accumulation of microplastics in deeper soil layers (Zhang et al., 2024). In this study, the highest concentration of microplastics (2,340 particles/kg of soil sample) was found in the zone near residential areas. This result contrasts with findings by Zhou et al. (2023), who reported that soil with higher bulk density tends to contain more microplastics. Here, the active zone, with the highest bulk density (1.3 g/cm³), contained 1,350 microplastic particles/kg, fewer than the zone near residential areas.

Based on microplastic shapes (Figure 3), the zone near residential areas exhibited the largest proportion of film forms (136 particles) compared to the active zone (45 particles) and the passive zone (27 particles). This result contrasts with Zhang, Yang, and Zhang (2024). However, the active zone showed a larger proportion of film forms (45 particles) than the passive zone (27 particles), aligning with Zhang, Yang, and Zhang (2024), who found that higher bulk density correlates with a greater proportion of film-form microplastics and a lower proportion of pellet microplastics. Increased bulk density causes soil pores to shrink, leading to the accumulation of film forms and larger microplastics in the upper soil layers. Conversely, smaller microplastics, such as pellets, are more likely to migrate vertically through the soil compared to larger microplastics and other forms (Li et al., 2023; Yang et al., 2022; Zhou et al., 2023).

Specific gravity refers to the ratio between the density of soil grains and the density of water. Bulk density, on the other hand, is the ratio of the weight of soil grains to their volume. According to Figure 8, the specific gravity of landfill soil varies across zones. The passive zone exhibits the lowest specific gravity at 1.91 g/cm³, while the active zone and the near-residential zone have specific gravities of 2.09 g/cm³ and 2.098 g/cm³, respectively.

The total volume of soil pores, referred to as soil porosity, plays a crucial role in soil structure. At the Jatibarang landfill, soil porosity ranges from 37.28% to 43.30% (Figure 8). Soil water content tends to increase with higher total soil porosity due to the presence of more pores that can retain groundwater. Conversely, if macropores dominate, soil water content decreases as soil porosity increases. Soil porosity is vital for supplying water and air to soil microorganisms and plant roots. Therefore, maintaining proper soil porosity is essential for supporting soil biological activity and healthy plant root development.

Soil permeability reflects the soil's ability to transmit water through its pores (Alista and Soemarno, 2021). Permeability affects how much rainwater can infiltrate the soil and how much becomes surface runoff, which in turn influences the depth at which microplastics penetrate landfill soil. The active zone of the Jatibarang landfill has the highest permeability value at 3.49%, indicating greater water movement through the soil.

Microplastics significantly affect the physicochemical properties of soil, including soil pH and the composition of organic matter. Soil pH is a critical characteristic in terrestrial ecosystems, influencing nutrient availability. In landfills, soil pH typically varies from acidic to neutral. The active zone exhibits the lowest pH level at 7.33, likely due to the production of acidic substances during waste decomposition (Reddy et al., 2020). In contrast, the decomposition processes in the passive zone have slowed or ceased, resulting in a more neutral pH of 7.62, similar to the near-settlement zone with a pH of 7.61 (Figure 8).

The soil pH at the Jatibarang landfill is influenced by the type and shape of various microplastic polymers. A recent study on coastal regions found that microplastics in fragments and foam can significantly increase pH levels, while microplastics in film form have a lesser impact on pH changes (Zhao et al., 2021). The shape and size of microplastics are critical factors affecting soil properties and the mobility of metals within the soil (Medyńska-Juraszek and Jadhav, 2022). When microplastics enter the soil, their chemical components are released during decomposition and degradation processes, which directly influence soil pH. Additionally, microplastics can indirectly affect soil pH by altering microbial community structures, leading to modified microbial secretions. The extent of pH variation depends on the surrounding soil environment (Zhang et al., 2023).

Microplastics may also act as hidden carbon stocks in soil, disrupting carbon sources through the contribution of carbon from plastic polymers, thereby impacting the soil organic matter (SOM) cycle (Chen et al., 2024). Soil solids consist of two primary components: inorganic elements such as soil minerals, and organic compounds derived from various human, animal, and plant materials (Salam, 2020). The active zone of landfill soil contains the lowest organic material content at 1.54%, followed by the passive zone at 1.68%, and the zone near residential areas at 2.77% (Figure 8). The variation in organic material content across zones in the Jatibarang landfill is often associated with the environment and human activities specific to each area.

The active zone of the landfill exhibits the lowest soil organic matter concentration due to continuous waste dumping and processing. The recently delivered waste lacks sufficient time to decompose into stable organic material. Organic matter decomposition in this zone is limited because microorganisms cannot function at their full potential, and composting processes have not reached their optimal phase. Additionally, heavy machinery and refuse vehicles frequently compact the soil in the active zone, reducing soil aeration and impeding organic matter decomposition. Compaction diminishes oxygen availability, restricting the activity of bacteria responsible for breaking down organic material.

In contrast, the passive zone contains a higher SOM concentration than the active zone, as the decomposition process has likely reached a stable equilibrium. This suggests that less new organic matter is introduced while pre-existing organic matter remains partially degraded or becomes integrated into the soil. Near residential areas, supplementary organic matter from human activities increases SOM concentration, with levels reaching 2.77%.

The SOM content in Jatibarang landfill soil ranges from 0.89% to 1.61%. Total organic carbon (TOC) significantly influences various physical and chemical soil properties, including nutrient retention (cation and anion exchange capacity), soil stability, soil color, and nutrient cycling. Soils with higher clay content may exhibit enhanced cation exchange capacity. The high cation exchange capacity of organic matter plays a key role in improving soil stability. However, microplastics can alter these characteristics by absorbing hazardous substances in soil solutions and modifying physical properties such as increased porosity, changes in aggregate structure, or fusion into soil aggregates. These modifications also impact microbial activity.

CONCLUSIONS

This study detected considerable quantities of microplastics in the soil of the Jatibarang landfill in Semarang. The residential zone exhibited the highest concentration of microplastics (2,340 particles/kg of soil sample), followed by the passive and active zones. Polypropylene, polystyrene, and low-density polyethylene were identified as the most prevalent forms of microplastics. The ecological risk analysis revealed that polypropylene, widely used in household plastic products, is the primary contributor to the minor to medium risk categories of microplastic pollution at the Jatibarang landfill.

Microplastics in landfill soil tend to migrate horizontally and accumulate in the upper soil layers due to human activities, presenting a higher risk of pollution in areas near residential zones. The physical and chemical properties of the soil, including bulk density, pH, and porosity, significantly influence the distribution and mobility of microplastics. These findings emphasize the urgent need for enhanced waste management strategies at the Jatibarang landfill and its surrounding areas to mitigate the potential environmental and health risks posed by microplastics. Effective mitigation measures and regulations, particularly in zones adjacent to residential areas, are critically necessary to prevent further microplastic migration into the surrounding ecosystem and groundwater.

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