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High Microplastics Contamination Around the Pakusari Landfill, Jember, Indonesia: A Profiling and Pollutant Load Index Analysis

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ABSTRACT

Introduction: Microplastics in landfills pose significant environmental and public health risks owing to their persistence, role as disease vectors, and potential for bioaccumulation. This study aimed to characterize the abundance, distribution, and pollution levels of microplastics in Pakusari landfill, Jember, Indonesia, across leachate, soil, groundwater monitoring well, and manually dug well samples.

Material and Methods: Samples, collected with contamination controls, underwent digestion with hydrogen peroxide (H_2O_2), followed by microplastic analysis (Leica) for quantification (count, size, color, and type) and polymer identification via Fourier transform infrared spectroscopy.

Results: This study found an average abundance of 358 particles, with dominating by fiber. Polyethylenimine (PEI) was consistently detected, and the prevalent size range was 0.12 ± 4.22 mm. The calculated Pollutant Load Index (PLI) averaged 3.67 across all samples, indicating Class IV (high) pollution levels.

Conclusion: These findings demonstrate severe microplastic contamination at the site, necessitating urgent mitigation strategies and improved waste management practices to prevent further environmental degradation and transform waste.

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Introduction

The reliance on plastic products is increasing owing to the growing population and higher consumption levels across various sectors, including industry, textiles, agriculture, and domestic applications[1, 2]. However, the growing reliance on plastic poses environmental challenges, as not all plastic waste can be reused, recycled, or repurposed effectively. The conversion of plastic waste into smaller particles, known as

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microplastics, has emerged as a critical global issue [3], including in Indonesia[4, 5]. Microplastics are pollutants resulting from the degradation of plastic materials into particles smaller than 5 mm in diameter [6]. Microplastics originating from land waste can infiltrate drainage systems and make their way to the ocean. Over time, they become deposited and bioaccumulated within various biotic components of the ecosystem. Recent studies have demonstrated that microplastics contaminate food products such as horticultural crops, fish, and rice [7-9].

Public and environmental health are both at risk owing to the widespread contamination caused by microplastics. The buildup of these persistent particles compromises the integrity of ecosystems from an environmental perspective. They can easily enter the food web, contaminate freshwater and marine systems, and change the physical characteristics of soil. In both aquatic and terrestrial organisms, bioaccumulation can have detrimental physiological effects that jeopardize ecological function stability and biodiversity. Research conducted previously has demonstrated that biota samples have been consumed by local community who have been contaminated by microplastic, with average daily intake has been calculated to be >50g/day [10]. Human exposure, which mostly occurs through the consumption of tainted food and water, inhalation of airborne particles, and even skin contact, is a serious public health concern [11]. Once within the body, these particles can lead to oxidative stress, chronic inflammation, and physical harm. Therefore, investigating microplastic pollution in sources that can directly impact human resources, such as landfills, is crucial for assessing risk and formulating protective public health strategies.

Waste management at final disposal sites, such as landfills, can be a significant source of microplastic contamination in the surrounding environment. Inefficient waste processing often results in the accumulation of debris and incomplete degradation of waste materials. Plastic waste is the primary contributor to microplastic pollution, with residues from terrestrial ecosystems being transported into marine environments through infiltration [12, 13]. Landfills not only contribute to microplastic contamination but also produce leachate containing pathogenic microbes and heavy metals [14, 15]. A study encompassing 15 nations has demonstrated that the concentration of microparticles in both raw and treated landfills varies significantly, ranging from undetectable levels (0-382 particles/L) to a maximum of 2.7 particles/L [16]. Furthermore, an established correlation was identified between the presence of microplastics and elevated levels of leachate. In addition to these findings, microplastics were detected in landfill sites, with an average abundance of 124.25 particles per kilogram [5, 17, 18]. Microplastics degrade environmental quality and pose serious health risks [19].

Additionally, research has shown that microplastics are not only physical contaminants but can also serve as carriers for disease and other hazardous substances. For example, microplastics found in ballast water can transport pathogenic bacteria, which may pose a health risk [20, 21]. Microplastics made of polyethylene (PE) can adsorb pesticide residues, such as terbuthylazine [22]. Other toxic compounds, such as perfluoroalkyl substances (PFASs), polycyclic aromatic hydrocarbons (PAHs), and hexachlorocyclohexane (HCH), have likewise been detected on microplastic surfaces [23]. The global presence of microplastics has reached an alarming level, prompting various adaptive strategies to reduce plastic use by substituting with biodegradable materials [24].

A substantial body of research has been dedicated to the study of microplastic contamination in seafood, surface water and well water in coastal or near river basin areas [24–26]. However, there remains a paucity of research assessing the water or soil in the vicinity of landfill sites, particularly in Jember City. The present study aimed to profile the presence and distribution of microplastics at the Pakusari landfill in East Java, Indonesia, which serves as a crucial disposal site in the eastern part of East Java. In this study, the Pollutant Load Index (PLI) was utilised to evaluate the contamination level associated with

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microplastic abundance. PLI is usually used to evaluate the level of heavy metal pollution within the ecosystems yet here [11], we used the PLI formula for heavy metal calculation to assess microplastic concentration. Recognizing that local communities rely on groundwater wells for their clean water needs, this initial investigation will provide valuable insight and serve as a solid scientific basis for developing effective, sustainable wastewater governance and management practices.

Materials and Methods

Study area

The Jember Regency is located at the easternmost point of Java. The Indonesian Central Statistics Department has determined that Jember Regency experiences relatively high annual rainfall, with an average of 157.1083 millimetres per year. The region also has an average temperature of 27.12°C and an average humidity level of 73.20%, as reported in the aforementioned statistical publication. The Jember Regency has a fairly large final waste management facility; indeed, the largest waste management center in the eastern part of East Java Province is located in Pakusari, Jember Regency. The location of the landfill site is specified by the following geographical coordinates: 8.1698° S, 113.7613° E. The site receives a variety of waste materials, including urban waste, plastics, agricultural waste, market waste, and household garbage. The location of the landfill site was determined to be 8.5 km from Jember City. As demonstrated in Figure 1, the landfill site is situated in the center of an agricultural area and in close proximity to residential settlements.

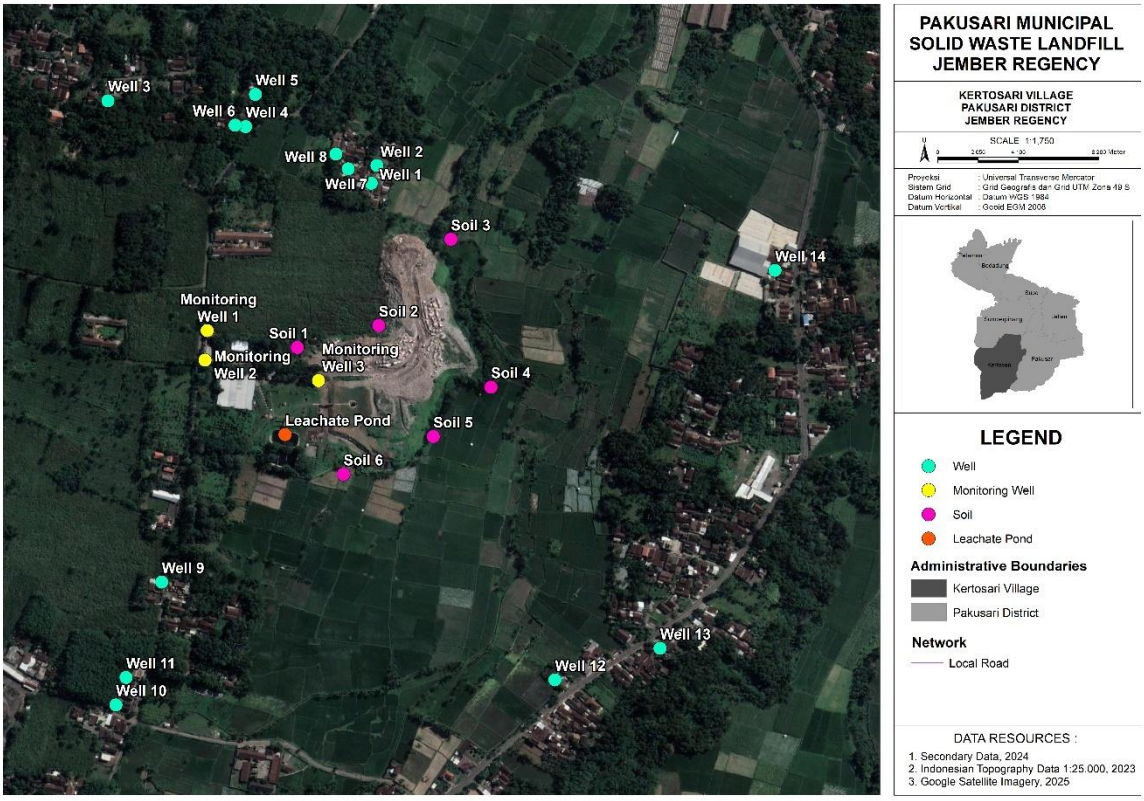

Figure 1: The location of study.

Pakusari landfill was designed as a control landfill, yet in this operation, the majority of the waste was simply dumped in an open manner. This approach did not include the implementation of a protective layer or geomembrane to prevent leachate infiltration into groundwater. Furthermore, there was an absence of a leachate collection and treatment plant within the landfill itself. Therefore,

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it is vital to consider the potential for contamination of the groundwater and soil in the vicinity of the landfill site, as a result of its impact on the surrounding area.

Sample collection and preparation

The samples analyzed in this study included leachate water, soil, monitoring well water (wellmon), and household well water. Leachate samples were collected as composites from the outlet point towards the residential area. The samples of leachate were collected from the designated collection point or pool, with the understanding that they were also contaminated by rainwater present within the collection pool. Soil samples were collected as composites from five designated coordinate points. Monitoring well water was collected from within the landfill area, while the household well water samples were gathered from locations 10 – 20 meters away from the landfill. All sampling points were determined using purposive sampling. In total, samples were collected from one (1) leachate point, three (3) monitoring wells, eight (8) household wells, and six (6) soil points. All samples were collected in the dry season on a single day.

Soil samples were collected from the surface at a depth of 0 – 30 cm, with each sample weighing 500 g. The samples were placed in boxes, sealed with aluminum foil, and labeled accordingly. In addition, water samples were collected from household wells and monitoring wells using a 0.4 mm plankton net to gather a 1-liter water sample. To avoid contamination from plastic materials, the water samples were stored in 1-liter glass jars. The samples were taken at a depth of approximately 2 meters below the water surface. All collected water samples were stored in cool boxes before being transported to the laboratory [23]. Leachate water was sampled according to the Indonesian Government Standard SNI 6989.59 (2008). Briefly, approximately 250 mL of leachate was collected using a dipper into glass jars, labeled, and stored in cool boxes prior to laboratory analysis.

Microplastic extraction and identification

Microplastic extraction and identification were conducted at the Soil Chemistry Laboratory, Department of Soil Science, University of Jember. To remove organic matter from the samples, the wet peroxide oxidation (WPO) method was utilized. The filter papers were preconditioned in a desiccator. Soil samples were air-dried for 24 to 48 h at 60°C and then sieved using a 0.3 mm mesh. Approximately 30 g of each soil sample was placed in a beaker and mixed with 300 mL of sodium chloride (NaCl) solution. Water and leachate samples were treated in beakers with 150 mL of 30% hydrogen peroxide (H_2O_2), which were then sealed with aluminum foil (Wang et al., 2024a), and heated at 70°C for 60 minutes. The resulting suspensions were pipetted and centrifuged at 350 rpm for 5 minutes. The suspensions were allowed to precipitate for 90 min and then filtered using a vacuum pump. The remaining samples containing microplastics were collected on Petri dishes for further analysis.

Microplastics retained on the Petri dishes were observed using a Leica microscope to assess their color, size, and morphology. Additionally, Fourier transform infrared spectroscopy (FTIR) was used to analyze the polymer compounds in each sample. The observations were categorized based on the source of the microplastics and the type of sample analyzed.

PLI (Pollutant Load Index) assessment

The microplastic identification results from our study area showed significant differences compared to those from other locations. We employed the Pollutant Load Index (PLI) to evaluate the extent of microplastic pollution based on particle abundance. Here, the PLI reflects the degree of pollution in an ecosystem based on the abundance of microplastic particles. It serves as a methodological approach for pollution risk assessment and strategic management. The formula for calculating the PLI is as follows:

$$CF - i = \frac{Ci}{Coi} \quad \text{Equation 1}$$

$$PLI_i = \sqrt{CF} - i \quad \text{Equation 2}$$

$$PLIzone = \sqrt[n]{PLIi - n} \quad \text{Equation 3}$$

where CF_{-I} is the pollutant coefficient of the i-th

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sample, Ci is the abundance of microplastic particles in the sample type, and Coi is the reference of the total in the observed sample type. PLI_{-n} is the value of each n-th sample in the n-th sample and type. Based on the PLI value, several categories are based on the level of pollution (**Error! Reference source not found.**).

Table 1: Classification of pollution level based on PLI values.

Level/Class	PLI	Category
I	0	Safe
II	1-2	Low
III	2-3	Medium
IV	3-4	High
V	>5	Very High

Data Analysis

Sampling site mapping was conducted using ArcGIS version 10.2. Data were analyzed using descriptive statistical methods. The visualizations and data processing designs were created using open-source Python version 3.11 combined with bioicons (https://bioicons.com/) and Flourish data visualization tools (https://app.flourish.studio/projects). Strip plots and regression analyses were performed to explore the relationship between microplastic abundance and potential contamination sources. These methods provided a means to evaluate the correlation between the two pollution-related variables.

Ethical Clearence

The research has received ethical clearance from the Ethics Committee of the Faculty of Dentistry at Universitas Jember, with ID number 2649/UN25.8/KEPK/DL/2024.

Results

Abundance of microplastics in the study area

The study revealed the presence of microplastics in all four locations: Well, Soil, WellMon and Leachate. The analysis also provided insights into the abundance and size distribution of these particles. The result presented in figure 2.

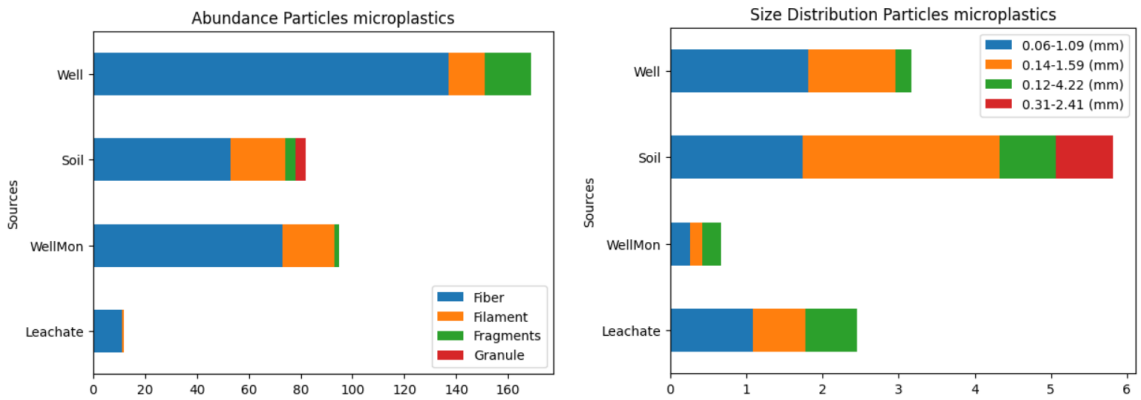

Figure 2: Abundance and size distribution of microplastics at the study site.

As shown in Figure 2, the average number of detected microplastic particles was 89.5 ± 64.4 particles. Among these, fiber-type microplastics were the most prevalent at almost all sampling points, with the highest number of particles detected in monitoring wells. The average size of microplastics found in soil samples was approximately 0.12 ± 4.22 mm, with the highest concentration located in soils near the waste processing area.

As shown in Figure 3, the size distribution of the microplastics is presented. The color of the microplastics is indicative of their size distribution coloration. This indication is derived from the sources of the samples. The size distribution of microplastics was assessed using kernel density analysis. This approach can map microplastic size distributions sourced from various contamination sites.

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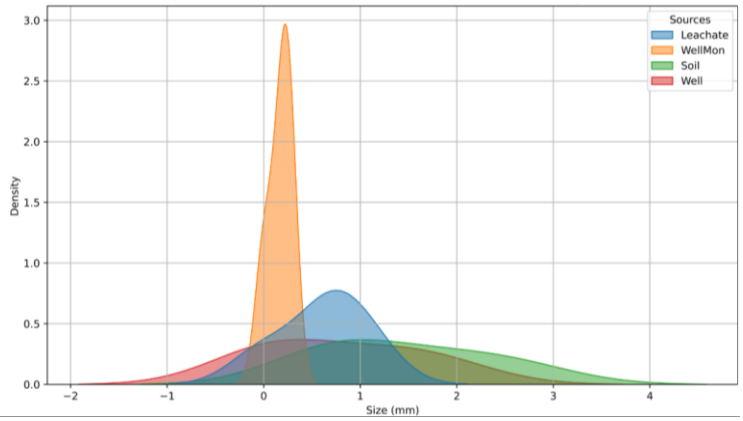

Figure 3: Size distribution of microplastics based on contamination source.

As visualized in Figure 3, the highest density along the Y-axis was recorded from monitoring well (wellmon) samples located near the landfill site. Leachate and monitoring well water samples tend to produce smaller microplastics. In addition, fibers and fragments are the most prevalent among the different types.

The relationship between microplastic size and type based on the contamination source is shown in Figure 4.

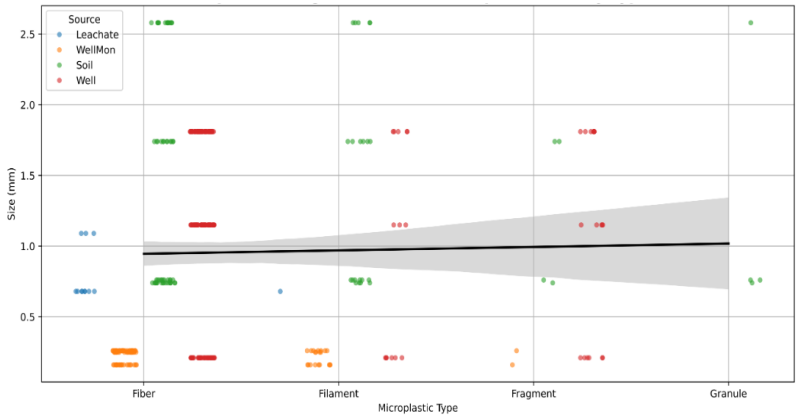

Figure 4: Relationship between microplastic size and type based on contamination source.

As shown in Figure 4, colorization provides a visual representation of the sources of microplastic contamination in terms of size and type. Based on Figure. 4, fiber and filament microplastics are predominantly below 1 mm in size. The black line, which approaches a slope of 1, indicates a linear relationship between microplastic type and size, suggesting a strong correlation. The size of the microplastics varies depending on their type. The gray bands represent confidence intervals (CI) reflecting the uncertainty of the regression model; these bands widen on the right, indicating greater variability in larger particle sizes. The orange-colored zone represents fiber and filament microplastics in soil samples, averaging approximately 0.2 ± 0.4 mm.

In order to ascertain the morphology of micropalstics, it is necessary to present the original microscopic visualisation. The visual representation and structural characteristics of microplastics are demonstrated in figure 5.

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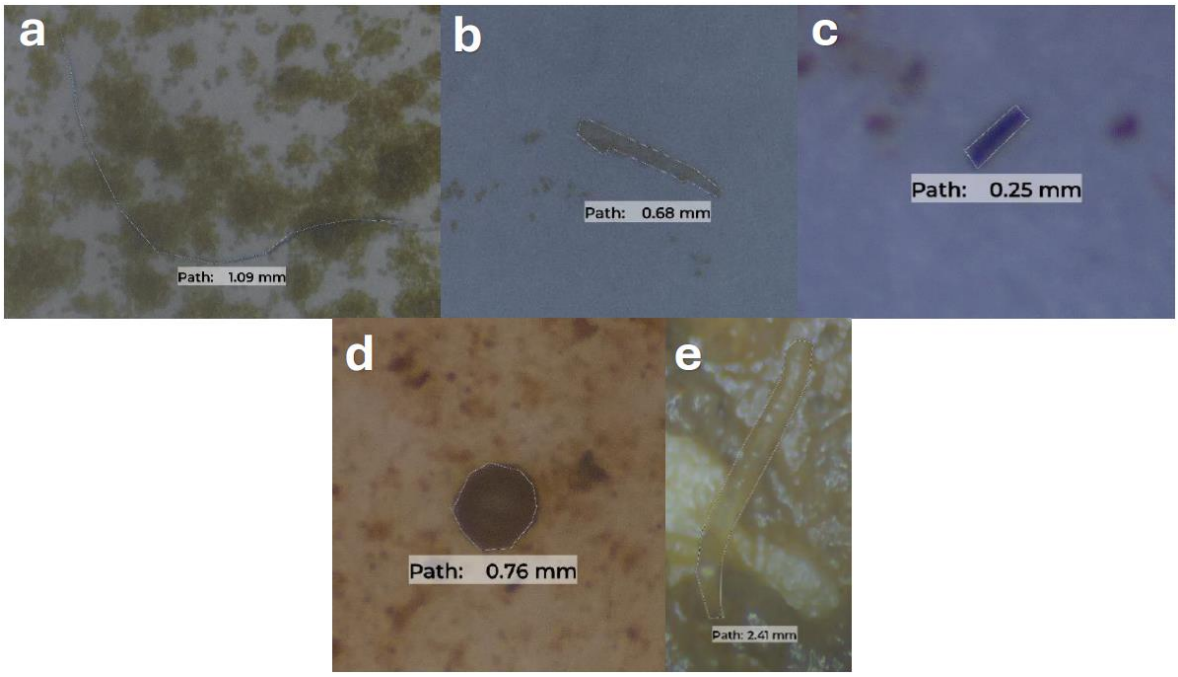

Figure 5: Microplastic morphology was collected from various sample types. Legend: a) fiber; b,e) filament; c) fragment; d) granule.

As demonstrated in Figure 5. The analysis of samples from soil, leachate, and well water revealed the presence of multiple forms of microplastics, including fibres, filaments, fragments, and granules.

The chord diagram in Figure. 6. illustrates the diversity of microplastic types based on the sources of contamination. The outer segment of the diagram depicts the types of microplastics identified from different samples. The curved connecting lines illustrate the relationship between microplastic type and color, facilitating the mapping of types and levels of dominance. The line width of each segment indicates the relative amount of microplastics based on color type.

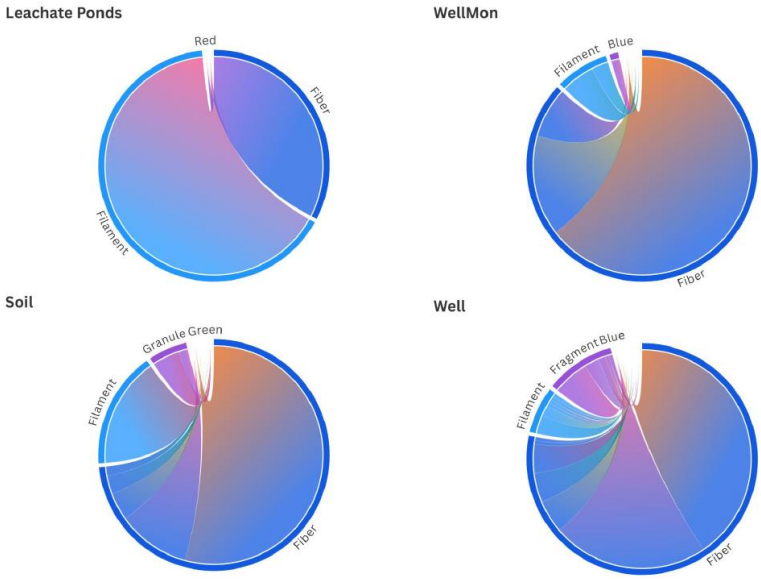

Figure 6: Microplastic polymer structures of several sample types.

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Each distinct type of microplastic is characterized by a unique polymer composition. The application of Fourier-transform infrared (FTIR) analysis to the identification of microplastic contamination revealed the presence of polypropylene (PP) in both monitoring and public well samples, and soil is polyester polymer. Nonetheless, the analysis of leachate samples has not yielded the common type of microplastic polymer that has been identified. As illustrated in Figure 7, the result of the FTIR spectrum is evident.

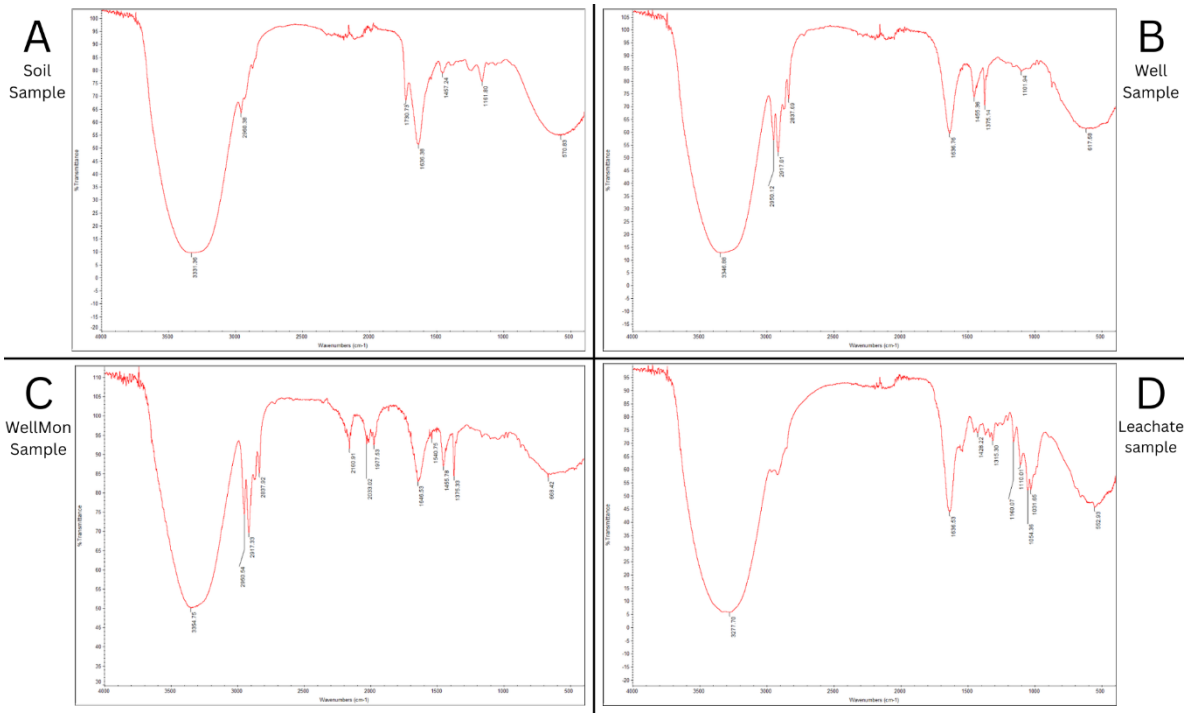

Figure 7: Polymer structure of microplastics in soil, well-dug, wellmon, and leachate samples.

As shown in Figure 7, the wave number in the landfill soil sample peaks at 1730.73 cm^{-1}, which is indicative of a carbonyl group, and there is a smaller peak at 2960.38 cm^{-1}, which is indicative of the presence of carbon chains. These findings suggest that the microplastic polymer was polyester-based. Figure 7B shows that the FTIR spectrum of the well sample exhibited signs of polypropylene microplastic contamination, evidenced by characteristic aliphatic C-H stretching peaks at 2949.64 and 2837.38 cm^{-1}, as well as distinctive bending vibrations at 1455.43 and 1375.09 cm^{-1}. Figure 7C shows that the predominant polymer type in the monitoring well was polypropylene (PP), as indicated by the presence of a distinctive methyl peak at 1375.33 cm^{-1}. Figure 7D shows the FTIR analysis of the leachate sample, providing valuable insights into its chemical composition. The spectrum displays a carbohydrate- or cellulose-based polymer peak at 1160.07 cm^{-1}, corresponding to the C-O bond. This finding suggests the presence of natural or semi-synthetic microfibers rather than the more prevalent microplastic polymer.

Microplastic risk assessment

As shown in Figure. 8, 24 samples were collected, including leachate, monitoring wells (wellmon), soil, and household wells (well). The leachate sample revealed a Pollutant Load Index (PLI) of 3.46, categorizing it within the high-risk range. Some soil samples exhibited even higher levels of contamination, with a maximum PLI value of 6.08. The highest PLI was observed in the monitoring well samples, which reached 6.78, classifying it as very high risk (PLI > 5). The average PLI value across all samples from the study site was 3.67.

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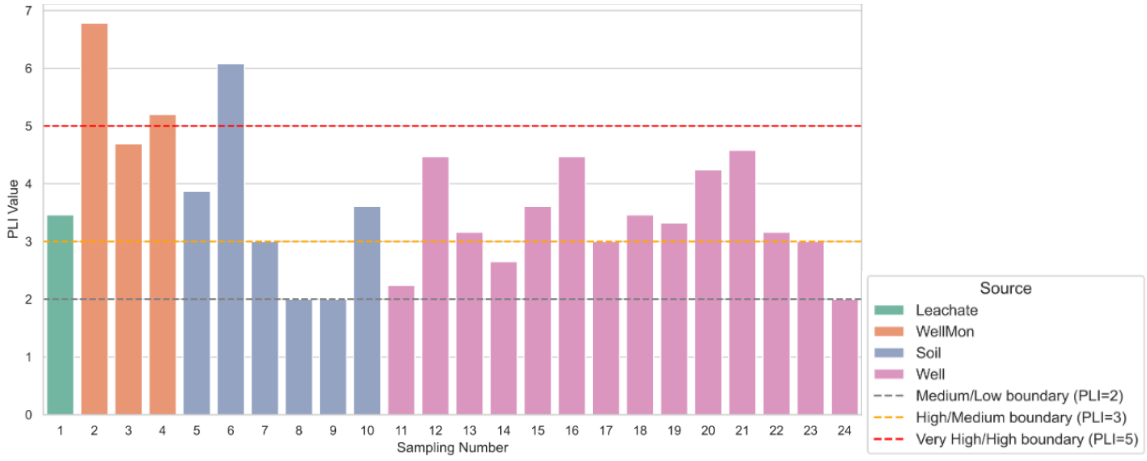

Figure 8: PLI index at the study site based on microplastic abundance.

Discussion

This study confirmed that all samples collected from the Pakusari landfill (TPA Pakusari) and surrounding areas were contaminated with microplastics, indicating that the landfill is a significant source of pollution of both soil and groundwater. This contamination is largely attributed to the accumulation of unsorted plastic waste at the site, which undergoes physical, chemical, and biological degradation. The predominance of fiber-type microplastics is a key finding, which is consistent with previous studies that identified synthetic textiles as a major contributor to environmental microplastic pollution [25-28].

The presence study also detected leachate contamination of microplastics. However, the abundance of microplastics was low, and the monitoring well exhibited a high concentration of particles. Research conducted on active and inactive landfill sites in Indonesia has demonstrated that the leachate sample was most contaminated by fibre-shaped microplastics [29]. A further study demonstrated that microplastic concentration was highest in leachate around the dumpsite, followed by fresh leachate, untreated leachate, and treated leachate [30]. It is evident that leachate can act as a primary medium for the transportation of contaminants in the monitoring well.

This study detected the dominant shape of microplastics as fragments. These fragments likely originate from the breakdown of larger plastic debris via ultraviolet (UV) degradation at the landfill surface [31]. Granules, in contrast, are generally manufactured microplastics commonly used in cosmetics, transportation materials, and industrial processes, which are characterized by their spherical or oval shapes. Monitoring wells serve as key indicators of water quality, and their contamination raises public health concerns.

Microplastic size variation is influenced by multiple factors, including physical, chemical, and biological processes, polymer composition and exposure to sunlight (UV radiation) [32]. Leachate and monitoring well samples generally contained smaller microplastics, with fibers and fragments being the most abundant.

The present study identified the polymeric composition of microplastics in soil and well water samples, revealing the presence of polypropylene (PP) and polyester (PES). Such fibers, often composed of polymers such as polyester (PES), nylon (polyamide), polyacrylonitrile, and polypropylene (PP), were detected in both soil and well water samples, suggesting vertical migration through soil layers and subsequent infiltration into groundwater [33]. A study of landfill sites revealed that polypropylene is the most prevalent type of microparticle. [34, 35]. Polymers such as polyethylene (PE), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), high-density polyethylene (HDPE), and polyether sulfone elastomer blends (PES-EL) have different levels of

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resistance to UV-induced degradation [36, 37]. Various purification and characterization methods for microplastics with polymers such as HDPE, LLDPE, PA66, PS, PET, and SBR involve the use of SDS and hydrogen peroxide to remove organic materials [38]. Polymers such as polypropylene and polyester, primarily sourced from industrial manufacturing and synthetic textiles, respectively, are predominantly identified in municipal landfills [39, 40]. This high prevalence is directly linked to the massive influx of mismanaged household waste, particularly discarded clothing and textile materials.

Microplastics tend to remain trapped in soil for extended periods because of limited infiltration rates[39]. However, climatic and seasonal factors, such as rainfall patterns and temperature fluctuations, can accelerate fragmentation and redistribution [41]. Improper landfill waste management often results in microplastics coexisting with other contaminants, including heavy metals [42] and pesticide residues [43, 44]. In this study, morphological analysis identified multiple microplastic forms, such as fibers, filaments, fragments, and granules, in soil, leachate, and well water, consistent with other landfill studies [45]. A further study of landfill sites has demonstrated that the majority of microplastics are of a fibrous and fragmentary nature [46], a finding that is in accordance with the present study.

The concentration of microplastic in the present study is consistent with the levels observed in other regions. However, further analysis is required to determine whether these levels are consistent across different regions and to what extent this consistency is influenced by the PLI value. The microplastic contamination levels observed in this region are lower than those recorded in other areas, as evidenced by previous studies conducted in Yogyakarta. This discrepancy can be attributed to the larger size of the Piyungan landfill site in Yogyakarta, which serves as a more significant concentration point for microplastics. [47]. The present study demonstrates a higher concentration of microparticles than was observed in any other region, including Mojokerto city. In Mojokerto City, the landfill site is of a smaller size than that of Pakusari. Furthermore, the sampling site differs in two respects. First, in Mojokerto, the sampling was collected at the leachate treatment plant (LTP). Second, at the LTP, the aerobic biological process is applied to reduce the concentration [48]. Consequently, the concentration of microparticles at landfill sites can have implications for the methodology and geographical location of sampling.

The Pollutant Load Index (PLI) assessment revealed elevated contamination levels across all sample types. Leachate samples recorded a PLI of 3.46 (high risk), soil samples reached 6.08, and monitoring wells exhibited the highest PLI of 6.78—categorized as very high risk (PLI > 5). The average PLI across the study area was 3.67, placing the site in Class IV contamination (PLI > 3). PLI is defined as the potential for microplastic accumulation. The PLI was calculated based on the MPs concentration [49, 50]. The presence of microplastics has been proven to result in an elevated PLI. This phenomenon is attributed to the inherent characteristics of microplastics that facilitate significant aggregation, thereby contributing to a substantial escalation in PLI. A high PLI value signals a strong potential for emerging contaminants with the capacity for bioaccumulation, persistence, and adverse health impacts [51]. Environmental factors, such as water flow, seasonal variation, and wind, can enhance microplastic mobilization. Before directly impacting human health, these particles may enter the food chain via drinking water, agricultural produce, or other consumables [52-54]. Chronic exposure to microplastics is increasingly linked to cancer risk [55]. Furthermore, landfill studies have shown that microplastics can harbor harmful microorganisms, such as Acidobacteria and Proteobacteria, which may become pathogenic upon exposure [56].

Public health implications

The direct public health implications for the local community are of particular concern. The public health risks in the Pakusari landfill area are

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heightened by the reliance on local wells for daily water consumption. Of the 14 active household wells identified, eight (57.1%) were used without any treatment, while the remaining six (42.9%) underwent basic processing (e.g., boiling). Each well typically serves between one and four households. The detection of microplastics in these water sources represents a direct exposure pathway for residents. Microplastics can enter the human body through water consumption. The extant research demonstrates that exposure to microplastics, whether in the long or short term, has the potential to induce oxidative stress and inflammatory responses [57, 58]. A study on mice has suggested a potential link between microplastic exposure and cognitive decline, specifically the presence of a marker for dementia in the hippocampus. Further research indicates that microplastics can bioaccumulate in the brain, potentially impacting cognitive function [59, 60]

The presence of *Acinetobacter* and *Pseudomonas* further increases the risk of opportunistic infections in the community, particularly in vulnerable populations. Given these findings, immediate interventions in waste management, leachate treatment, and safe water provision are critical to protect environmental and human health. Previous research has shown that microplastics in water systems can act as vectors for pathogens and potentially contribute to antimicrobial resistance [61, 62]. As demonstrated in previous studies, the 16S rRNA gene sequencing of microbial communities in water has been shown to reveal the presence of the Acinetobacter and Pseudomonas genera, both of which have been associated with antimicrobial resistance [63]. This has the potential to have a significant impact on public health.

Strategy and future prospects for waste management

In Indonesia, waste from various sectors is typically collected in the morning and transported from urban collection points to larger centralized facilities. The largest waste processing center in Jember Regency is located in Pakusari, East Java. The waste management process involves initial collection from urban areas, households, and other sectors, followed by sorting at the processing facility. At the study site, waste was categorized as organic and inorganic materials. Organic waste was processed into compost, whereas inorganic materials were sent to a central facility for destruction or recycling into new products.

Figure 9 shows the current condition of the waste management system at the Pakusari landfill. One of the main challenges identified was that waste is not sorted from the beginning of the collection and transportation process. Sorting is only performed upon arrival at the landfill. Moreover, issues related to household-level waste management need to be addressed, as sorting of household-level waste is not a common practice among the community. Environmental issues are closely connected to social and behavioral aspects [64, 65]. Currently, the use of incinerators for waste destruction in Indonesia is limited. Additionally, the time taken for waste transportation can lead to physicochemical changes in the waste, which increases the potential for microplastic dispersal. Despite these challenges, there are ongoing efforts to raise public awareness regarding the importance of waste sorting[53]. Communities can be educated and motivated to participate in secondary waste processing, such as upcycling waste into reusable products [66]. Promoting community-based waste management strategies offers a promising pathway toward reducing environmental pollution and mitigating microplastic contamination at the source [67]. Therefore, the government must be supported by effective waste management policy[68]. It is imperative that government policy encompasses a multifaceted approach, encompassing legal, operational, technical, institutional and community dimensions.

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Figure 9: Current waste processing conditions and sample collection points at Pakusari landfill. *Notes: a) Leachate, b) household well, c) monitoring well, and d) soil.*

Conclusions

The total microplastic abundance identified in the Pakusari landfill (TPA Pakusari) was 89.5 ± 64.4 particles, collected from multiple sources, including well water, soil, leachate, and monitoring wells. The types of microplastics detected included fibers, filaments, fragments, and granules. FTIR analysis confirmed the presence of polymer compounds containing polyethylenimine (PEI). Based on the PLI assessment, the overall contamination level at the Pakusari landfill was classified as high (Class IV, PLI > 3).

This study presents a comprehensive profiling of microplastics within the waste management process. The presence of microplastics poses a threat not only to the environment but also to human health. This investigation aimed to assess the effectiveness of the current waste processing system in relation to contamination levels. The findings from laboratory analyses can serve as a scientific basis for formulating optimized waste management strategies that minimize contamination risks and protect public health.

CRediT authorship contribution statement

K. K.: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review and editing. S. A. B.: Conceptualization, Resources, Investigation, Writing – review and editing. R. S. P.: Methodology, Investigation, Data curation, Writing – review and editing. F. K. A.: Methodology, Validation, Writing – original draft, Writing – review and editing. F. M.A. R.: Software, Visualization, Writing – review and editing. KA: Data curation, validation, writing, and review. J-J.J: Methodology, Validation, Writing – review and editing. MAR : Writing-review, revising and editing

Declaration of competing interest

All authors declare no conflicts of interest.

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Conflict of Interest

The author declare there is no conflict of interest

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Ethical Considerations

The ethical clearance was officially recognised by the Faculty of Dentistry.

Code of Ethics

The ethical clearance was officially recognised by the Faculty of Dentistry, bearing the reference

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Authors' Contributions

K.K: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review and editing. S.A.B: Conceptualization, Resources, Investigation, Writing – review and editing. R.S.P: Methodology, Investigation, Data curation, Writing – review and editing. F.K.A: Methodology, Validation, Writing – original draft, Writing – review and editing. F.M.A.R: Software, Visualization, Writing – review and editing. KA: Data curation, Validation, Writing-review. J-J.J: Methodology, Validation, Writing – review and editing. MAR : Writing-review, revising and editing

Data availability

Data will be made available on request.

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