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Microplastic and POP contamination in rural waste-dumping sites, India

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Persistent organic pollutants (POPs) are highly toxic and long-lived environmental contaminants that easily adsorb onto the surfaces of microplastics (MPs). While urban and industrial environments have been extensively studied, rural areas, especially in developing countries, have received limited attention. In such regions, uncontrolled waste dumping exacerbates the contamination of water and soil systems by MPs and associated POPs, causing significant environmental and health concerns. This study quantified MP pollution in soil and water near unregulated waste-dumping sites in Tamil Nadu, India. A total of 20 environmental samples (10 soil and 10 water) were collected from two active rural dump sites. MPs were extracted using density separation and characterized by stereomicroscopy and Fourier transform infrared spectroscopy. MPs were detected in all samples, with polypropylene (PP) and polyethylene (PE) identified as the dominant polymer types. Soil samples contained 49.87% PP and 21.62% polyethylene terephthalate, while water samples comprised 57.14% PP and 28.57% PE. These polymers were particularly effective at adsorbing and transporting POPs through environmental media. The presence of MPs and POPs in drinking water sources and agricultural soils poses a significant threat to the ecological integrity of these rural areas and the health of their communities. The present results underscore the urgent need for enhanced waste management practices and robust water protection policies to mitigate the long-term health impacts and environmental degradation in these regions.

KEYWORDS

microplastics, persistent organic pollutants, rural waste, soil and water contamination, FTIR analysis

Introduction

Over the centuries, human activities such as mining have led to the overexploitation of natural ecosystems and the generation of massive amounts of waste (Ullah et al., 2025). The composition and quantity of this waste have changed dramatically over recent decades due to rapid urbanization, increased consumerism, and industrialization (Voukkali et al., 2024).

Global waste generation increased from approximately 1.3 billion tonnes in 2010 to 2.0 billion tonnes in 2016 (Awino and Garland, 2025), with projections indicating further increases to 2.2, 2.6, and potentially 3.4–3.8 billion tonnes annually by 2025, 2030, and 2050, respectively. Of particular concern is that more than 2 billion people worldwide lack access to formal waste collection systems, while over 3 billion continue to dispose of waste through unregulated open dumping or burning (Rodić and Wilson, 2017). Although high-income nations generate the highest *per capita* waste volumes, low- and middle-income countries are disproportionately affected due to inadequate waste management infrastructure (Noah et al., 2025; Mmereki et al., 2023; Whiteman et al., 2025). Around 100 million tonnes of waste are illegally dumped in uncontrolled areas annually (Tisserant et al., 2017), contributing to more than 3 million potentially contaminated sites worldwide. In India specifically, 13 major cities alone produce approximately 55 million tonnes of municipal solid waste annually, with projections indicating exponential growth to 165 million tonnes by 2030 and 436 million tonnes by 2050. Waste production in million-plus cities has doubled since 2004, indicating deteriorating waste management conditions in urban India. Thousands of active open dumps operate across India, Turkey, and other developing countries (Canavati et al., 2022). These sites typically lack environmental monitoring despite posing substantial risks to surrounding air, water, and soil quality (Cisternas et al., 2022).

The threat is particularly acute in rural regions, where informal and unregulated waste dumping remains the primary disposal method due to the absence of organized waste collection and treatment systems. Over recent years, the use of synthetic materials in rural areas has increased significantly, including plastic packaging, disposable household items, multi-layer films, and chemically treated products (Emami et al., 2024; Shah et al., 2024). Without proper disposal infrastructure, these materials are discarded in open areas where they undergo slow degradation. Physical breakdown occurs through ultraviolet radiation, microbial activity, and thermal processes, releasing toxic leachates and gaseous emissions into the environment (Campanale et al., 2020). In contrast to urban centers, which have partial segregation and collection networks, rural waste management is hampered by several critical deficiencies: the absence of door-to-door collection systems, unsegregated dumping in open fields and water bodies, communal burning of mixed agricultural and household wastes including plastics, and inadequate local regulatory infrastructure with limited enforcement and monitoring capabilities.

The incommode collection is frequently contaminated with microplastics (MPs)-broken-down pieces of synthetic polymers used as consumer packaging, apparel, and as agricultural films. This seepage of contaminants disrupts the soil's physical structure and microbial balance. Runoff, both surface and infiltrated, introduces dissolved pollutants into local water bodies and amplifies the risk of water contamination through soil pathways. The open burning of mixed plastic waste, which is usually carried out as a space-clearance or volume-reduction exercise, emits hazardous pollutants, including dioxin, furan, and volatile organic compounds into the atmosphere (Nayanathara et al., 2024; Sheriff et al., 2025). This further worsens atmospheric pollution and poses an inhalation risk to the local population.

MPs, in turn, serve as efficient carriers of persistent organic pollutants (POPs) (Kinigopoulou et al., 2022). These contaminants originate from larger pieces of plastic waste or are released directly from industrial and consumer products. POPs are among the most hazardous contaminants associated with unregulated waste dumping (Akinrinade et al., 2024; Bamotra et al., 2025). These synthetic compounds are characterized by diverse chemical structures and demonstrate high environmental persistence and cause severe ecosystem damage (Pan et al., 2025). Their toxicity and bioaccumulation potential are exacerbated by unregulated disposal practices. Important examples of POPs include flame retardants, perfluoroalkyl substances, polybrominated diphenyl ethers, and polychlorinated biphenyls (PCBs) (Weber et al., 2025). These pollutants resist natural degradation processes such as photolysis, oxidation, and microbial breakdown, enabling prolonged persistence in soil, water, and air (Muir et al., 2025). Furthermore, POPs can move dynamically across environmental compartments through atmospheric transport, groundwater infiltration, and soil accumulation, thereby increasing the likelihood of entry into the food chain via ingestion, inhalation, or dermal contact. Once released into biological systems, they accumulate in fatty tissues and provide continuous exposure risks. POPs have been linked to adverse health effects including endocrine disruption, reproductive disorders, immunotoxicity, neurodevelopmental impairment, and carcinogenicity, with their environmental persistence posing long-term risks to human health and ecological balance (Monteiro-Alves et al., 2024).

Recent studies have consistently shown that MPs are widespread in environments affected by waste. Vairamuthu et al. (2024) reported high levels of MP contamination, with polyethylene (PE) and polypropylene (PP) being the predominant polymer types. Akca et al. (Uzampur et al., 2023) found high MP concentrations around open dumps and scrapyards in Turkey and demonstrated the importance of soil characteristics as conditioning factors. Przydatek et al. (2025) documented the leakage of chemicals and MPs from a closed landfill in Poland and suggested long-term contamination risks. Shirazi et al. (Ghorbaninejad Fard Shirazi et al., 2023) detected hazardous concentrations of MPs and mesoplastics in Tehran landfill soils, with contamination levels ranging from minor to critical. Regarding landfill-mined soil reuse in Delhi, Haritwal et al. (2024) observed high MP concentrations, indicating potential risks upon reuse. Chamanee et al. (2024) documented high levels of MPs and plasticizers in landfill leachates in Sri Lanka, which led to a concern over the usage of drinking water. Amal and Devipriya, (2024) reported post-fire surges in MP concentrations in freshwater near the Brahmapuram landfill in India. Zhang et al. (2023), Wang et al. (2023), Arab et al. (2024), and Jin et al. (2022) have demonstrated that deposited MPs can significantly alter the physicochemical properties of soil, including porosity, bulk density, water retention capacity, and evaporation dynamics. Despite these findings, informal rural dumpsites remain critically understudied, which is the main motivation for the present study.

Although there is growing global concern about POP contamination in industrial and urban areas, rural settlements, particularly in developing countries, remain significantly understudied. These regions are equally susceptible to contamination by hazardous agents due to unregulated waste

disposal practices, yet systematic environmental monitoring is often absent. This study aims to investigate the occurrence and spatial distribution of MP pollution in rural garbage dumps in Tamil Nadu state, India. The study characterizes the morphology and polymer composition of MPs in water and soil samples, and identifies their likely sources, using Fourier transform infrared (FTIR) spectroscopy. The results provide valuable data on the behavior of pollutants in low-infrastructure environments and can inform targeted waste management policies, guide regulatory frameworks, and support community-level interventions to reduce exposure to hazardous pollutants among vulnerable rural populations. Despite the increased use of plastic in rural India, there is limited understanding of how informal dumping contributes to MP contamination in soil and water systems, with respect to their potential role as POP carriers.

Materials and methods

This study selected unregulated solid waste dumping sites from rural settlements in Tamil Nadu, India, specifically those located near natural water bodies such as irrigation canals and ponds. Sites were chosen based on visible plastic waste accumulation, community-reported dumping activity, accessibility, and environmental diversity. From ten assessed field sites, Siruvani Bridge (10.940586°N, 76.727223°E) and Karunya Nagar (10.940124°N, 76.749391°E) were identified as representative active dumpsites based on extensive plastic waste exposure, proximity to freshwater ecosystems, and inter-site differences in land use and vegetation cover. The two sites possessed distinct environmental characteristics including soil texture, waste distribution patterns, and waste composition, making them suitable for comparative analysis. Temperature, humidity, and landscape slope were recorded during sample collection to contextualize environmental conditions. Qualitative assessment of soil permeability, vegetation density, and surface plastic density was also conducted, as these variables correlate site physical parameters with MP distribution.

A total of 20 environmental samples were collected from two sites, comprising 10 soil and 10 water samples to ensure both horizontal and vertical representation. These samples were selected based on their higher visible plastic particle load, turbidity, and proximity to active dumping zones, representing the most contaminated subsets for FTIR characterization. Soil samples were collected using sterile steel augers at two depths: five from the surface layer (0–5 cm) and five from the subsurface layer (20–30 cm). Water samples were collected in sterile polypropylene bottles that had been pre-cleaned with deionized water at the corresponding depths: the surface layer (0–10 cm) and the mid-column (20–30 cm). All bottles were pre-cleaned with deionized water and labeled with the sampling depth, collection date, and location code. From the 20 samples, 4 (2 soil and 2 water) were selected for detailed FTIR and stereomicroscopic analysis based on high plastic particle load, elevated turbidity, and proximity to the most active dumping zones. The soil samples were sun-dried for 72 h to reduce moisture content and minimize microbial variability, while the water samples were stored at 4 °C in light-protected containers and periodically exposed to natural light to simulate

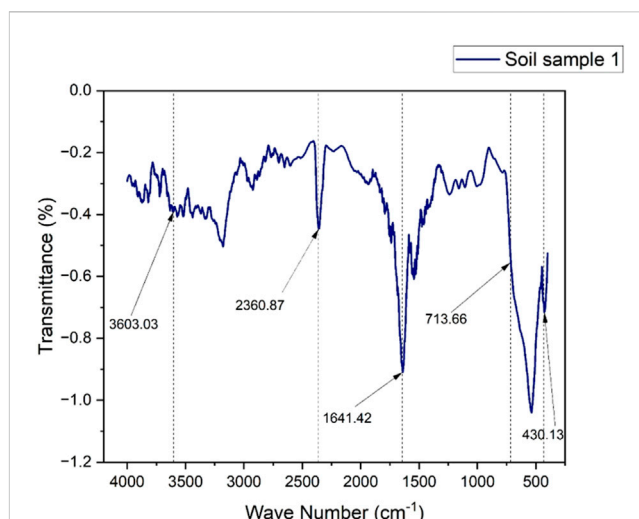


FIGURE 1
FTIR spectrum of Soil Sample 1 demonstrating microplastic contamination with labeled absorption peaks corresponding to various synthetic polymer functional groups (O-H, C=C, and C-H vibrations).

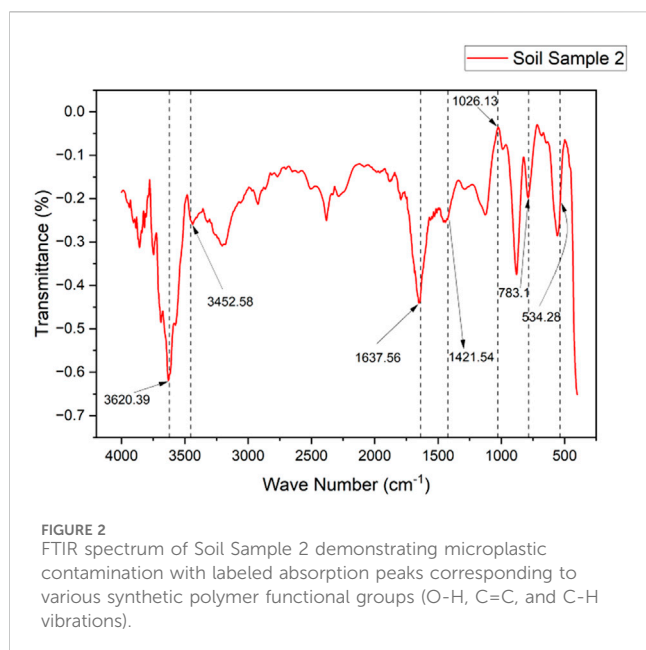
MP-biofilm interactions. To minimize contamination, all instruments were pre-cleaned, procedural blanks were analyzed, nylon gloves were used, and filtration was conducted under covered conditions.

MP extraction was performed using the methodology of density separation. Approximately 250 g of dry soil and 500 mL of water samples were each treated with saturated NaCl solution. The suspensions were stirred and allowed to settle, after which floating fractions were recovered and filtered through 0.45 μm nylon membranes using vacuum filtration. The filtered materials were then dried under controlled laboratory conditions. Particle counting and visual inspection were conducted using stereomicroscopy based on particle size, quantity, morphology (fibers, fragments, films, and foams), and color. FTIR spectra were obtained in ATR mode over 4,000–600 cm^{-1} with a spectral resolution of 4 cm^{-1} and 32 scans per sample. Polymer identification was confirmed by matching sample spectra with reference library spectra (similarity index $\geq 90\%$). Characteristic absorption peaks confirmed the presence of PE, PP, and PS as the most prevalent polymers in both soil and water samples. This methodology enabled the effective recovery and detection of MPs from the two rural waste sites. Polymer identification was achieved through FTIR analysis, while particle morphology was characterized by stereomicroscopy. The following section presents the results and their implications for assessing rural contamination and developing waste management strategies.

Results and discussion

FTIR spectral analysis of soil sample

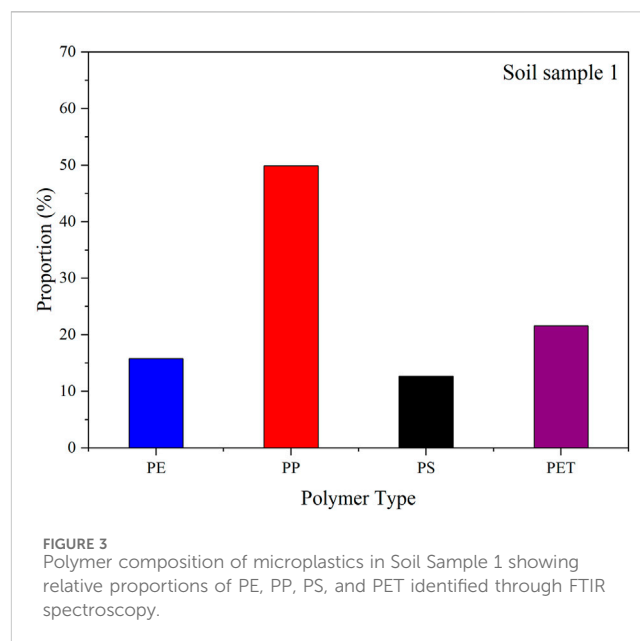
Figure 1 displays the FTIR spectrum of Soil Sample 1, confirming the presence of synthetic polymeric contaminants. A strong, broad absorption band at 3,603.03 cm^{-1} corresponds to O-H



stretching vibrations, which are typically associated with surface-bound moisture or hydroxyl groups (Hsiao et al., 2025). The absorption at $2,360.87\text{ cm}^{-1}$ indicates C=C functional groups, commonly found in polymer additives (Mohd Nasir et al., 2025). A sharp peak at $1,641.42\text{ cm}^{-1}$ represents C=C stretching, characteristic of unsaturated hydrocarbon structures. Significant signals at 713.66 cm^{-1} and 430.13 cm^{-1} reflect C-H bending vibrations and potential traces of halogenated compounds. These spectral features are consistent with PE, PP, PET, and PS and confirm MP infiltration into unregulated rural soils. The results demonstrate the persistent presence of packaging-related polymers in terrestrial environments and suggest the urgent need for rural waste management policy development.

Figure 2 shows the FTIR spectrum of Soil Sample 2, representing several absorption bands that are characteristic of MP polymers. A broad maximum at $3,620.39\text{ cm}^{-1}$, accompanied by a shoulder at $3,452.58\text{ cm}^{-1}$, indicates O-H stretching vibrations, attributable to moisture or hydroxyl groups from biofilm formation or natural soil organics (Hsiao et al., 2025; Thombare et al., 2023). The band at $1,637.56\text{ cm}^{-1}$ denotes C=C stretching, characteristic of polyolefin plastics. Strong absorption at $1,026.13\text{ cm}^{-1}$ indicates C-O stretching vibrations, typical of oxidized plastic surfaces or degraded polyester materials (Ramadoss et al., 2024).

Peaks at 783.1 cm^{-1} and 534.28 cm^{-1} correspond to aromatic ring bending and C-Cl vibrations, respectively, suggesting the presence of PET and degraded PS. The peaks in the fingerprint region are broader and more defined compared to Soil Sample 1, indicating greater polymer diversity and advanced weathering processes. These results confirm the presence of extensive MP pollution in rural soils and demonstrate the chemical diversity of plastic degradation products in dumping site environments. Polymer composition data are summarized using descriptive statistics (percentage contribution). Inter-site variation is evaluated through relative percentage differences and visualized using bar charts.

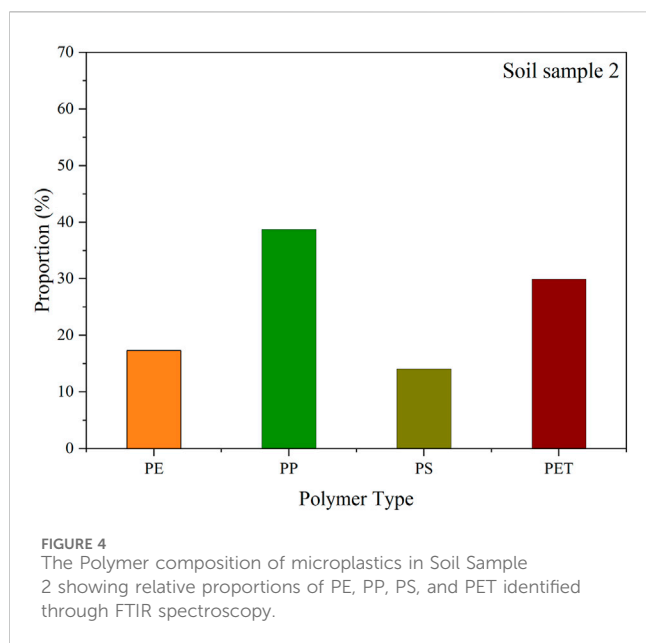


Polymer composition in soil sample

Figure 3 shows the polymer composition of the MPs identified in Soil Sample 1. PP is the dominant polymer, comprising 49.87% of the identified particles. This high proportion reflects the extensive rural consumption of PP-based consumer products including packaging films, woven sacks, and disposable containers. PE represents 15.79% of the particles and is commonly associated with plastic bags and agricultural films. PET contributes 21.62% and is likely to originate from beverage bottles and synthetic textiles. PS is the least represented at 12.72%, probably derived from food packaging and thermal insulation materials. The abundance of polyolefins (i.e., PP and PE) indicates the dominance of low-density, lightweight plastics that are more prone to fragmentation and widespread distribution in surface environments. These polymer distributions are consistent with FTIR results and demonstrate that local dumping activities generate a diverse yet consistent combination of plastic contaminants in rural soil matrices.

Figure 4 shows the polymer composition of the MPs identified in Soil Sample 2. PP remains the most prevalent polymer at 38.72% of fragments, indicating its widespread use in rural consumer goods and packaging materials. The differences in land use, waste type, slope, and vegetation between Siruvani Bridge and Karunya Nagar are likely to have influenced the diversity of polymers and the abundance of MPs.

PET is the second most abundant contributor at 29.91%, likely originating from beverage bottles, textiles, and food containers. PE comprises 17.31% of particles and is typically derived from carry bags and agricultural mulch films. PS accounts for 14.06%, probably resulting from foam packaging and household disposables. This distribution shows increased polymer diversity at this location, with the higher proportions of PET and PS indicating contributions from both domestic and semi-urban



waste sources (Liu et al., 2023). These proportions, confirmed by FTIR spectral analysis, demonstrate the complexity of plastic contamination in rural soils with diverse land use patterns. Compared to Soil Sample 1, Soil Sample 2 shows a 8.29% higher PET content (29.91% vs. 21.62%) and a 1.34% higher PS content (14.06% vs. 12.72%), representing a greater diversity of waste and contributions from a semi-urban source. The broader FTIR peak patterns observed in Sample 2 suggest enhanced polymer weathering, likely attributable to increased surface runoff and slope exposure at this location.

FTIR spectral analysis of water sample

Figure 5 shows the FTIR spectrum of Water Sample 1, which displays clear absorption bands indicative of multiple polymer types. The sharp peak at $3,454.51\text{ cm}^{-1}$ is attributed to O-H stretching, which suggests the presence of hydrophilic groups associated with PET or weathered polyolefins. Absorption bands between $2,073.48$ and $2,074.90\text{ cm}^{-1}$ likely correspond to overtones and combination bands typical of nitrile or C=C bonds, often present as additives or degradation byproducts. The strong peak at $1,639.49\text{ cm}^{-1}$ represents C=C stretching or carbonyl bending, characteristic of PET and oxidized PE/PP. The sharp C-O stretching peak at $1,047.35\text{ cm}^{-1}$ indicates ester groups, further supporting PET identification. The band at 665.44 cm^{-1} corresponds to out-of-plane aromatic ring bending, typical of polystyrene or oxidized aromatic compounds.

These spectral features confirm the presence of PET, PP, and PS-derived MPs (Senathirajah et al., 2022; Chen et al., 2021). The prominent PET signatures suggest that discarded beverage bottles and textile waste are significant contributors to pollution of rural water ecosystems, a problem that is may exacerbated by uncontrolled waste management practices and refuse overflowing into bodies of water.

Figure 6 displays the FTIR spectrum for Water Sample 2, with distinct absorption peaks at $3,614.6\text{ cm}^{-1}$, $3,452.58\text{ cm}^{-1}$, $2,926.01\text{ cm}^{-1}$, $2,071.55\text{ cm}^{-1}$, $1,745.58\text{ cm}^{-1}$, $1,643.35\text{ cm}^{-1}$, $1,460.11\text{ cm}^{-1}$, $1,159.22\text{ cm}^{-1}$, and 715.59 cm^{-1} . The absorption band at $2,926.01\text{ cm}^{-1}$ corresponds to C-H stretching in aliphatic hydrocarbons, indicating PP presence. The sharp peak at $1,745.58\text{ cm}^{-1}$ is characteristic of ester carbonyl groups in PET. Additional peaks at $1,159.22\text{ cm}^{-1}$ and 715.59 cm^{-1} correspond to the fingerprint regions of PS and PET, respectively. The broader

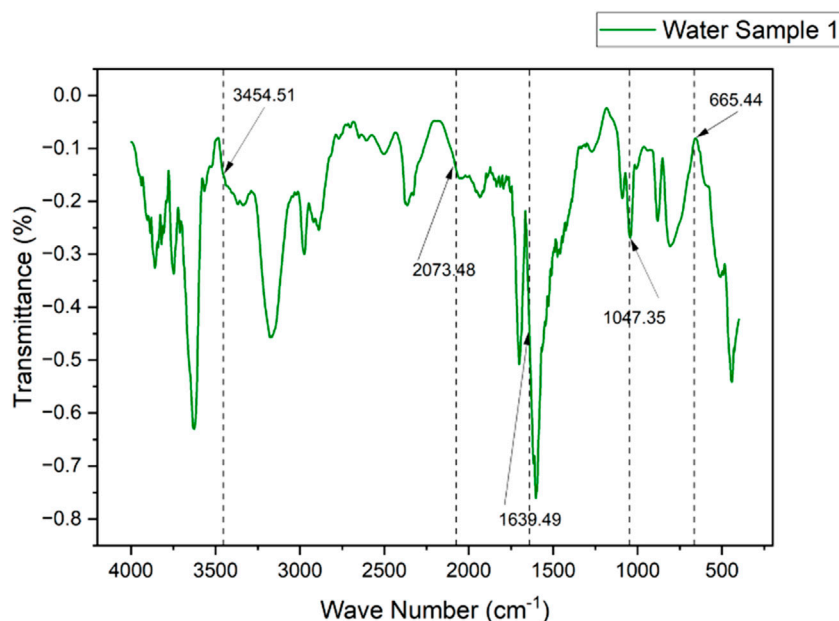


FIGURE 5
The FTIR spectrum of Water Sample 1 demonstrating microplastic contamination with labeled absorption peaks corresponding to various synthetic polymer functional groups (O-H, C=C, and C-H vibrations).

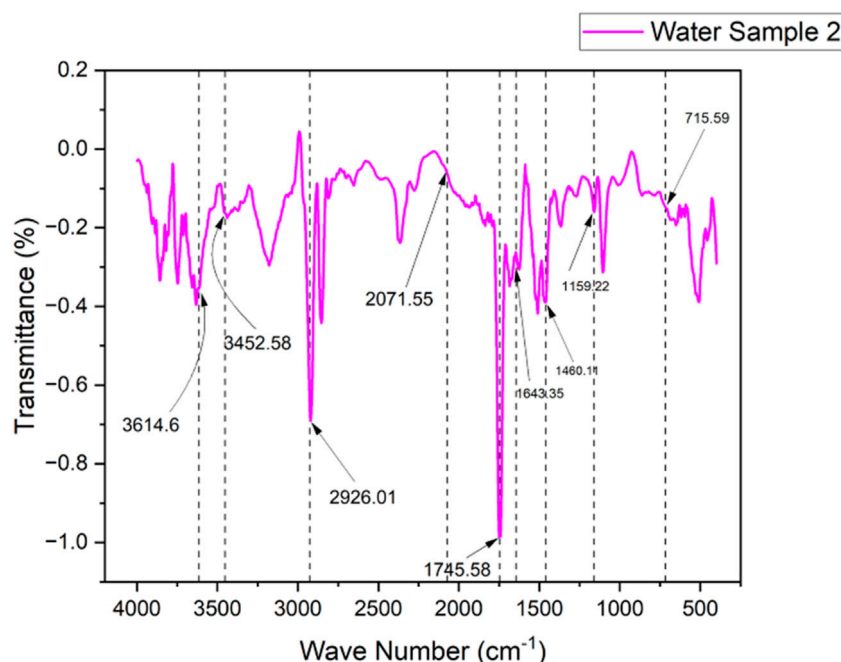


FIGURE 6

The FTIR spectrum of Water Sample 2 demonstrating microplastic contamination with labeled absorption peaks corresponding to various synthetic polymer functional groups (O-H, C=C, and C-H vibrations).

peaks in the 3,450–3,615 cm^{-1} region suggest O-H stretching, possibly from adsorbed moisture or oxidized plastic surfaces. These spectral features confirm that Water Sample 2 contains a complex mixture of MP polymers, predominantly PP, PET, and PS. The increased PET signals may indicate textile-derived contamination, while PS is likely linked to packaging materials.

This diversity of polymers suggests the variety of waste sources in the aquatic environment, demonstrating the infiltration of both domestic refuse and synthetic fibers into rural water bodies.

Polymer composition in water sample

Figure 7 shows the polymer distribution of MPs in Water Sample 1. PP is the most abundant polymer, comprising 53.4% of total MP particles. This dominance indicates the widespread presence of PP-based packaging and containers in rural waste streams. PET constitutes 26.01% and is likely to originate from beverage bottles, food wrappers and textile effluents. PE accounts for 12.69%, primarily derived from plastic bags and agricultural film residues. PS represents a smaller fraction at 7.9%, possibly from disposable cutlery, foam packaging, or insulation materials (Freitag et al., 2024). The predominance of polyolefins (PP and PE) demonstrates the impact of lightweight plastic materials that fragment into persistent particles in water bodies. These percentages are consistent with FTIR spectral verification and suggest the significant contribution of domestic waste leakage as a major source of MP contamination in rural surface waters (Bond et al., 2018; Sharma et al., 2024). This distribution supports the hypothesis that the composition of polymers in aquatic samples is determined by terrestrial waste disposal practices

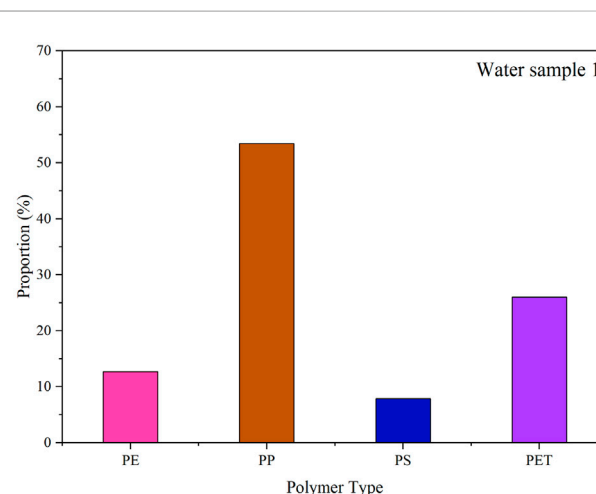


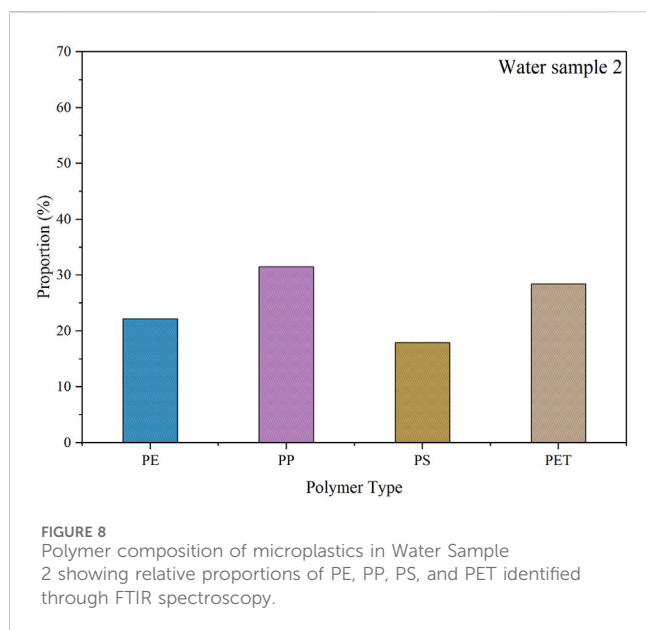
FIGURE 7

The Polymer composition of microplastics in Water Sample 1 showing relative proportions of PE, PP, PS, and PET identified through FTIR spectroscopy.

combined with the buoyancy and degradation characteristics of different materials.

Figure 8 shows the MP polymer distribution identified in Water Sample 2. With a contribution of 31.5%, PP is the dominant polymer, indicating its widespread use in consumer packaging, sacks and various plastic products.

PE constitutes 22.17% and is likely to have come from degraded plastic bags and agricultural films. PET constitutes 28.42%, corresponding to textile waste and beverage bottles. PS accounts



for 17.91% and possibly originates from disposable products and thermal insulation materials. Compared to Water Sample 1, the more balanced distribution of this sample, with relatively higher percentages of PS and PE, suggests spatial variation in waste sources and hydrodynamic dispersion within rural aquatic systems. The co-dominance of PP and PET is consistent with FTIR results and emphasizes the persistence of commodity plastics in surface water environments. This compositional profile indicates the need for targeted waste segregation policies and monitoring systems in rural areas. The percentages of PET and PS in Water Sample 2 are 2.41% and 10.01% higher, respectively, than in Sample 1, indicating increased contamination from textiles and foams. This more uniform polymer distribution suggests spatial heterogeneity in

waste inputs and hydrodynamic dispersion throughout the dump-influenced aquatic system. As the primary focus was on polymer identification, only descriptive comparisons were applied. Future studies with expanded datasets will include inferential statistical tests such as ANOVA for inter-site validation.

Microscopic identification of fibrous microplastics

Figure 9 presents microscopic images of fibrous MPs found in rural water samples. The fibers display red and pink coloration with irregular, curved morphologies characteristic of synthetic textile-derived MP debris, commonly originating from domestic washing effluents or degraded fishing equipment. The presence of MPs and POPs near agricultural fields and rural water sources indicates possible transfer to crops and household water, posing chronic exposure risks to rural communities dependent on these systems. Their elongated structure and coloration provide evidence of PE, PP, or PET polymer composition, consistent with FTIR analysis. These polymers are of particular environmental concern due to their capacity to adsorb and transport POPs. For example, PET demonstrates high affinity for phthalates and PAHs owing to its polar ester functional groups. Being hydrophobic and non-polar, PE and PP readily absorb hydrophobic POPs such as PCBs, dioxins, and organochlorine pesticides (Ali et al., 2020). Through van der Waals forces and partitioning mechanisms, these hydrophobic POPs adsorb onto plastic surfaces, transforming MPs into carriers of toxic chemicals (Prajapati et al., 2022; Wang et al., 2020). This MP-POP association allows toxicants to be transported long distances and persist, raising concerns about bioaccumulation and biomagnification in aquatic organisms, food webs and ultimately human populations.

Such contamination pathways present significant ecotoxicological and public health risks in rural systems with

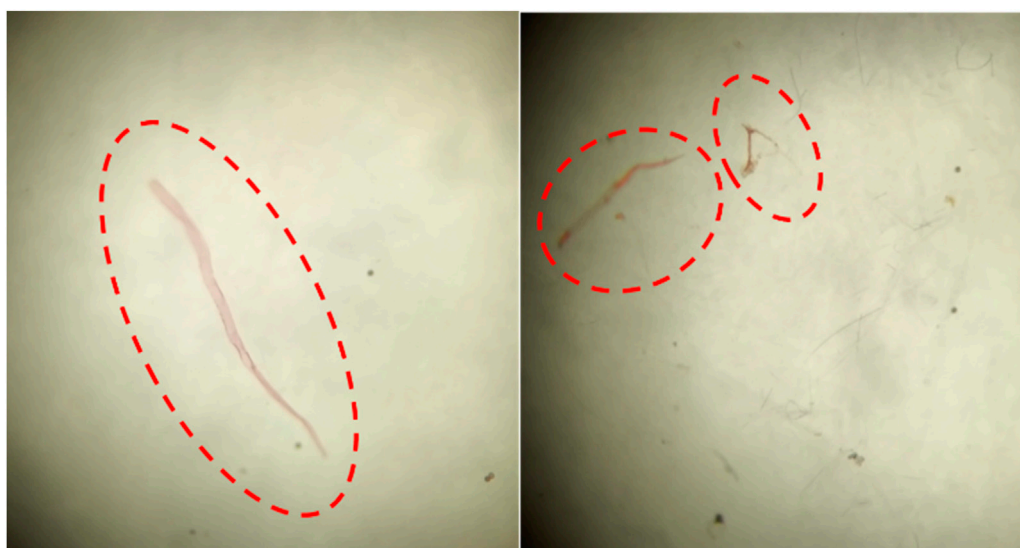


FIGURE 9
Microscopic confirmation of fibrous microplastics in rural water samples, highlighted with red dashed circles.

inadequate waste regulation. The simultaneous occurrence of visually identifiable fibers and FTIR-confirmed polymer types suggests the need for the control and monitoring of plastic pollutants and their associated chemical hazards at source. The identified polymers, particularly PP, PE, and PET, have a high affinity for hydrophobic POPs such as PCBs and PAHs, potentially leading to oxidative stress and endocrine disruption in exposed organisms (Ullah et al., 2025; Uzamur et al., 2023).

Limitations

This study qualitatively identified the potential for interaction between MP and POP, but did not include an analysis of the quantitative concentration of POP. Future investigations may include chromatographic quantification to validate adsorption levels. This study was limited to 20 samples from two representative rural sites, which restricts the scope for spatial generalization. It is recommended that future studies cover a wider rural gradient.

Conclusion

POPs are globally recognized as toxic, persistent, capable of long-range transport, and bioaccumulative. MPs have emerged as significant vectors in rural settings by facilitating the adsorption and transport of POPs through soil and water systems. This study demonstrates MP contamination in soil and water samples, showing diverse polymer types and morphologies of environmental concern that increase the risk of POP transmission. This provides compelling evidence of enhanced contamination pathways in rural environments.

Soil Sample 1 contained 49.87% PP, followed by 21.62% PET, 15.79% PE, and 12.72% PS. In Soil Sample 2, PP remained the dominant polymer at 38.72%, followed by PET at 29.91%, PE at 17.31%, and PS at 14.06%. These polymer types are commonly found in agricultural films, synthetic textiles and domestic waste, which are prevalent components in rural waste streams. Similar trends were observed in water samples. Water Sample 1 displayed a high PP content of 57.14%, followed by PET at 28.57%, PE at 28.57%, and PS present in low concentrations. Water Sample 2 displayed a more balanced distribution with PP (31.5%), PET (28.42%), PE (22.17%), and PS (17.91%). FTIR spectra confirmed the presence of the characteristic functional groups of these polymers, with characteristic peaks at $3,452.58\text{ cm}^{-1}$, $2,926.01\text{ cm}^{-1}$, and $1,643.35\text{ cm}^{-1}$, corresponding to hydroxyl, methylene, and carbonyl groups, respectively. Microscopic examination at $\times 100$ magnification showed predominantly fibrous MP particles in both the water and soil samples. Their morphology and coloration are consistent with degradation products from local packaging, textile, and waste materials, which supports the identified polymer types. The high prevalence of hydrophobic polyolefins (PP and PE) and PET, which preferentially associate with POPs, suggests that these materials could act as long-term environmental carriers of persistent organic pollutants. In rural agricultural and household contexts, this

increases risks to soil health, groundwater quality, and ultimately human and animal welfare.

This study confirms severe MP pollution in rural agricultural soils and waterways, with dominant polymer types demonstrating an established capacity for POP adsorption. FTIR and microscopy analyses confirmed consistent profiles with high concentrations of PP, PE, PET, and PS, suggesting the urgent need for targeted waste management and environmental controls in rural areas. These results advocate for waste management strategies specifically tailored to rural contexts. Given the high prevalence of MPs in aquatic environments and their chemical affinity for POPs, integrated approaches combining waste management systems, water security measures, and pollution prevention strategies are necessary. The results also suggest that routine POP monitoring of rural drinking water and agricultural soils may be warranted. Future work should quantify POP concentrations on MPs and examine their biological uptake and toxicity to evaluate ecological and health risks in rural systems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. BR: Conceptualization, Methodology, Software, Writing – original draft, Writing – review and editing. LA: Conceptualization, Resources, Validation, Writing – original draft. JH: Investigation, Methodology, Writing – original draft. AK: Project administration, Resources, Writing – original draft. LgK: Data curation, Methodology, Writing – original draft. LmK: Data curation, Methodology, Writing – original draft. C-HH: Resources, Validation, Visualization, Writing – review and editing.

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Conflict of interest

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References

- Akinrinade, O. E., Agunbiade, F. O., Alani, R., and Ayejuyo, O. O. (2024). Implementation of the Stockholm convention on persistent organic pollutants (POPs) in Africa - progress, challenges, and recommendations after 20 years. *Environ. Sci. Adv.* 3, 623–634. doi:10.1039/d3va00347g
- Ali, H. R., Emam, A. N., Koraney, N. F., Hefny, E. G., and Ali, S. F. (2020). Combating the prevalence of water-borne bacterial pathogens using anisotropic structures of silver nanoparticles. *J. Nanoparticle Res.* 22, 47. doi:10.1007/s11051-020-4760-6
- Amal, R., and Devipriya, S. P. (2024). Severe microplastic pollution risks in urban freshwater system post-landfill fire: a case study from Brahmapuram, India. *Environ. Pollut.* 352. doi:10.1016/j.envpol.2024.124132
- Arab, M., Yu, J., and Nayeib, B. (2024). Microplastics in sludges and soils: a comprehensive review on distribution, characteristics, and effects. *ChemEngineering* 8, 86. doi:10.3390/chemengineering8050086
- Awino, F. B., and Garland, G. (2025). Occurrence of emerging and persistent organic pollutants in dumpsite environments: a review. *Environ. Challenges*. 18 doi:10.1016/j.envc.2025.101094
- Bamotra, S., Yadav, S., and Tandon, A. (2025). Air pollution from dumping sites in India: implications on environmental health. *Soil Pollut.* 236, 624. doi:10.1007/s11270-025-08036-5
- Bond, T., Ferrandiz-Mas, V., Felipe-Sotelo, M., and van Sebille, E. (2018). The occurrence and degradation of aquatic plastic litter based on polymer physicochemical properties: a review. *Crit. Rev. Environ. Sci. Technol.* 48, 685–722. doi:10.1080/10643389.2018.1483155
- Campanale, C., Massarelli, C., Savino, I., Locaputo, V., and Uricchio, V. F. (2020). A detailed review study on potential effects of microplastics and additives of concern on human health. *Int. J. Environ. Res. Public Health*. 17, 1212. doi:10.3390/ijerph17041212
- Canavati, A., Toweh, J., Simon, A. C., and Arbic, B. K. (2022). The world's electronic graveyard: what is the solution to Ghana's e-waste dilemma? *World Dev. Perspect.* 26 doi:10.1016/j.wdp.2022.100433
- Chamane, G., Sewwandi, M., Wijesekara, H., and Vithanage, M. (2024). Occurrence and abundance of microplastics and plasticizers in landfill leachate from open dumpsites in Sri Lanka. *Environ. Pollut.* 350 doi:10.1016/j.envpol.2024.123944
- Chen, Y., Awasthi, A. K., Wei, F., Tan, Q., and Li, J. (2021). Single-use plastics: production, usage, disposal, and adverse impacts. *Sci. Total Environ.* 752 doi:10.1016/j.scitotenv.2020.141772
- Cisternas, L. A., Ordóñez, J. I., Jeldres, R. I., and Serna-Guerrero, R. (2022). Toward the implementation of circular economy strategies: an overview of the current situation in mineral processing. *Min. Process. Extr. Metall. Rev.* 43, 775–797. doi:10.1080/08827508.2021.1946690
- Emami, N., Baynes, T. M., Kaushik, T., Singh, M., Bhattacharjya, S., Locock, K., et al. (2024). Plastics in the Indian economy: a comprehensive material flow analysis. *J. Mater. Cycles Waste Manag.* 26, 3584–3595. doi:10.1007/s10163-024-02060-z
- Freitag, N., Schneider, J., Decotignies, V., Fell, T., Kucukpinar, E., and Schlummer, M. (2024). Waste study on flexible food and non-food packaging: detailed analysis of the plastic composition of European polyethylene-containing waste streams. *Mater. (Basel)* 17, 3202. doi:10.3390/ma17133202
- Ghorbaninejad Fard Shirazi, M. M., Shekooiyan, S., Moussavi, G., and Heidari, M. (2023). Microplastics and mesoplastics as emerging contaminants in Tehran landfill soils: the distribution and induced-ecological risk. *Environ. Pollut.* 324 doi:10.1016/j.envpol.2023.121368
- Haritwal, D. K., Singh, P., Ramana, G. V., and Datta, M. (2024). Microplastic migration from landfill-mined soil through earth filling operations and ecological risk assessment: a case study in New Delhi, India. *Environ. Sci. Pollut. Res.* 31, 65002–65021. doi:10.1007/s11356-024-35545-3
- Hsiao, K.-Y., Chung, R.-J., Chang, P.-P., and Tsai, T.-H. (2025). Identification of Hydroxyl and polysiloxane compounds via infrared absorption spectroscopy with targeted noise analysis. *Polym. (Basel)* 17, 1533. doi:10.3390/polym17111533
- Jin, T., Tang, J., Lyu, H., Wang, L., Gillmore, A. B., and Schaeffer, S. M. (2022). Activities of microplastics (MPs) in agricultural soil: a review of MPs pollution from the perspective of agricultural ecosystems. *J. Agric. Food Chem.* 70, 4182–4201. doi:10.1021/acs.jafc.1c07849
- Kinigopoulou, V., Pashalidis, I., Kalderis, D., and Anastopoulos, I. (2022). Microplastics as carriers of inorganic and organic contaminants in the environment: a review of recent progress. *J. Mol. Liq.* 350 doi:10.1016/j.molliq.2022.118580
- Liu, Z., Ren, X., Duan, X., Sarmah, A. K., and Zhao, X. (2023). Remediation of environmentally persistent organic pollutants (POPs) by persulfates oxidation system (PS): a review. *Sci. Total Environ.* 863 160818. doi:10.1016/j.scitotenv.2022.160818
- Mmereki, D., Emery David Jr, V., and Wreh Brownell, A. H. (2023). The management and prevention of food losses and waste in low- and middle-income countries: a mini-review in the Africa region. *Waste Manag. Res.* 42, 287–307. doi:10.1177/0734242X231184444
- Mohd Nasir, N. A., Wan Mohamad Kamaruzzaman, W. M. I., Lee, O. J., and Mohd Ghazali, M. S. (2025). Effects of Carica papaya leaves extract as an additive in waterborne polyurethane coatings for stainless steel 316L protection in artificial seawater. *J. Adhes. Sci. Technol.* 39, 2192–2213. doi:10.1080/01694243.2025.2489503
- Monteiro-Alves, P. S., Captivo Lourenço, E., Ornellas Meire, R., and Godoy Bergallo, H. (2024). Is banning persistent organic pollutants efficient? A quantitative and qualitative systematic review in bats. *Perspect. Ecol. Conserv.* 22 250–259. doi:10.1016/j.pecon.2024.07.001
- Muir, D., Gunnarsdóttir, M. J., Koziol, K., von Hippel, F. A., Szumińska, D., Ademollo, N., et al. (2025). Local sources versus long-range transport of organic contaminants in the Arctic: future developments related to climate change. *Environ. Sci. Adv.* 4, 355–408. doi:10.1039/d4va00240g
- Nayanathara, P., Thattharani, G., Pilapitiya, C., and Ratnayake, A. S. (2024). The world of plastic waste: a review. *Clean. Mater.* 11 doi:10.1016/j.clma.2024.100220
- Noah, A. O., David, O. O., and Osakwe, C. N. (2025). Electronic waste effects of ICT: does income level matter? *Discov. Sustain.* 6, 412. doi:10.1007/s43621-025-01194-w
- Pan, S., Li, Z., Rubbo, B., Quon-Chow, V., Chen, J. C., Baumert, B. O., et al. (2025). Applications of mixture methods in epidemiological studies investigating the health impact of persistent organic pollutants exposures: a scoping review. *J. Expo. Sci. Environ. Epidemiol.* 35, 522–534. doi:10.1038/s41370-024-00717-3
- Prajapati, A., Narayan Vaidya, A., and Kumar, A. R. (2022). Microplastic properties and their interaction with hydrophobic organic contaminants: a review. *Environ. Sci. Pollut. Res.* 29, 49490–49512. doi:10.1007/s11356-022-20723-y
- Przydatek, G., Ciula, J., Barsan, N., Mirila, D., and Mosnegutu, E. (2025). Groundwater quality analysis: assessing the impact of a closed landfill—A case study on physico-chemical and microplastic contaminants. *Appl. Sci.* 15, 8223. doi:10.3390/app15158223
- Ramadoss, P. K., Mayakrishnan, M., and Arockiasamy, F. S. (2024). Discarded custard apple seed powder waste-based polymer composites: an experimental study on mechanical, acoustic, thermal and moisture properties. *Iran. Polym. J.* 33, 461–479. doi:10.1007/s13726-023-01266-6
- Rodić, L., and Wilson, D. C. (2017). Resolving governance issues to achieve priority sustainable development goals related to solid waste management in developing countries. *Sustainability* 9, 404. doi:10.3390/su9030404

- Senathirajah, K., Kemp, A., Saaristo, M., Ishizuka, S., and Palanisami, T. (2022). Polymer prioritization framework: a novel multi-criteria framework for source mapping and characterizing the environmental risk of plastic polymers, *J. Hazard. Mater.* 429 doi:10.1016/j.jhazmat.2022.128330
- Shah, M. Z., Quraishi, M., Sreejith, A., Pandit, S., Roy, A., and Khandaker, M. U. (2024). Sustainable degradation of synthetic plastics: a solution to rising environmental concerns, *Chemosphere*. 352. doi:10.1016/j.chemosphere.2024.141451
- Sharma, S., Chauhan, A., Ranjan, A., Mathkor, D. M., Haque, S., Ramniwas, S., et al. (2024). Emerging challenges in antimicrobial resistance: implications for pathogenic microorganisms, novel antibiotics, and their impact on sustainability. *Front. Microbiol.* 15, 1403168–17. doi:10.3389/fmicb.2024.1403168
- Sheriff, S. S., Yusuf, A. A., Akiyode, O. O., Hallie, E. F., Oduma, S., Yambasu, R. A., et al. (2025). A comprehensive review on exposure to toxins and health risks from plastic waste: challenges, mitigation measures, and policy interventions, *Waste Manag. Bull.* 3. doi:10.1016/j.wmb.2025.100204
- Thombare, N., Mahto, A., Singh, D., Chowdhury, A. R., and Ansari, M. F. (2023). Comparative FTIR characterization of various natural gums: a criterion for their identification. *J. Polym. Environ.* 31, 3372–3380. doi:10.1007/s10924-023-02821-1
- Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., et al. (2017). Solid waste and the circular economy: a global analysis of waste treatment and waste footprints, *J. Ind. Ecol.* 21 628–640. doi:10.1111/jiec.12562
- Ullah, F., Wang, P.-Y., Saqib, S., Zhao, L., Ashraf, M., Khan, A., et al. (2025). Toxicological complexity of microplastics in terrestrial ecosystems. *iScience* 33, 111879. doi:10.1016/j.isci.2025.111879
- Uzamurera, A. G., Zhao, Z.-Y., Wang, P.-Y., Wei, Y.-X., Mo, F., Zhou, R., et al. (2023). Thickness effects of polyethylene and biodegradable film residuals on soil properties and dryland maize productivity. *Chemosphere* 329, 138602. doi:10.1016/j.chemosphere.2023.138602
- Vairamuthu, M., Nidheesh, P. V., and Tangappan Sarasvathy, A. S. (2024). Microplastic pollution unveiled: the consequences of small unregulated dumping in villages, spanning from soil to water. *Environ. Monit. Assess.* 196, 1161. doi:10.1007/s10661-024-13296-5
- Voukkali, I., Papamichael, I., Loizia, P., and Zorpas, A. A. (2024). Urbanization and solid waste production: prospects and challenges. *Environ. Sci. Pollut. Res.* 31, 17678–17689. doi:10.1007/s11356-023-27670-2
- Wang, F., Zhang, M., Sha, W., Wang, Y., Hao, H., Dou, Y., et al. (2020). Sorption behavior and mechanisms of organic contaminants to nano and microplastics. *Molecules* 25, 1827. doi:10.3390/molecules25081827
- Wang, Z., Li, W., Li, W., Yang, W., and Jing, S. (2023). Effects of microplastics on the water characteristic curve of soils with different textures, *Chemosphere*. 317. doi:10.1016/j.chemosphere.2023.137762
- Weber, R., Girones, L., Förstner, U., Tysklind, M., Laner, D., Hollert, H., et al. (2025). Review on the need for inventories and management of reservoirs of POPs and other persistent, bioaccumulating and toxic substances (PBTs) in the face of climate change. *Environ. Sci. Eur.* 37, 48. doi:10.1186/s12302-025-01060-6
- Whiteman, A. D., Hennessy, N., and Wilson, D. C. (2025). Rethinking waste and resource management for underserved communities. *Oxf. Dev. Stud.*, 1–17. doi:10.1080/13600818.2025.2473957
- Zhang, P., Yuan, Y., Zhang, J., Wen, T., Wang, H., Qu, C., et al. (2023). Specific response of soil properties to microplastics pollution: a review, *Environ. Res.* 232 doi:10.1016/j.envres.2023.116427