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**Citation:**

ZIA, Amna, SAQIB, Zulfiqar Ahmad, UL HAQ, Muhammad Anwar and ASLAM, Zubair (2026). Microplastics build-up in soils - spatial distribution patterns across different land uses and associated health risks. *Environmental Earth Sciences*, 85 (10): 244. [Article]

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# Microplastics build-up in soils - spatial distribution patterns across different land uses and associated health risks

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Received: 8 August 2025 / Accepted: 25 April 2026 / Published online: 8 May 2026  
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## Abstract

Microplastic (MP) pollution in soil is an emerging environmental concern due to the extensive use and persistence of plastics, which degrade soil quality and pose potential risks to human health through accidental ingestion; however, the extent and implications of MP in soil environments remain poorly understood. This study assessed the extent, composition, distribution patterns, and potential hazards of MP across major ten Land Use types in five districts of Punjab, Pakistan to support environmental sustainability and policy design. Microplastics were extracted from soil samples by treating organic matter with 30% H<sub>2</sub>O<sub>2</sub> in the presence of FeSO<sub>4</sub> as a catalyst, followed by density separation with saturated NaCl solution. The supernatant was filtered through 0.45 µm cellulose nitrate membranes to isolate MP. Visual classification was performed under a stereomicroscope, and polymer types were identified using FT-IR spectroscopy based on spectral library matching. The MP concentrations in soil significantly varied across cities and Land Use types, ranging from 18 to 1872 MP/kg. Greenhouse soils showed the highest contamination (1867±32 MP/kg), followed by residential (751±19) and industrial soils (693±18) and Fish farm (18±2) showed lowest values. Microplastic characterization revealed the dominance of fibrous and film shaped MP, particularly in agricultural and residential soils, with larger size MP particles 1–5 mm linked to fragmentation of agricultural mulching films and wastewater inputs. The FTIR spectra identified nine polymers, with HDPE and polypropylene as the most abundant, sourced primarily from mulching films, while Nylon and ABS were associated with textile effluents. Igeo values indicated severe contamination in Greenhouse>Residential>Land-fill>Industrial>Roadside>Sewage irrigated>Mulching> Cropland>Fish farm, with Rawalpindi and Lahore most contaminated and Bahawalpur least. Principal Component Analysis (PCA) linked industrial and roadside soils to large durable fragments, agricultural soils to films and fibers, with urban density and climatic conditions. MP particles were found in all soils, even areas with minimal direct plastic use contained MP particles, emphasizing the role of atmospheric deposition and hydrological transport in shaping spatial heterogeneity. Microplastic particles adsorb pollutants, and may leach into groundwater, posing ecological and human health risks. These findings underscore the urgent need for robust policies, improved plastic waste management, and expanded research across diverse Land Use systems and environmental contexts.

**Keywords** Plastic contamination · Soil Contamination · Soil Pollutant · Human Health

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## Introduction

Microplastics are now recognized as a global threat due to their harmful impacts on human health, such as stillbirths, neurodevelopmental disorders, and lung cancers, arising from their toxic, mutagenic, and carcinogenic nature (Landrigan et al. 2023). Global plastic production in 2023 was estimated at 413.8 million tons (Ainyanbhor et al. 2025). In 2017, Asia generated about 121 million tons (Mt) of plastic waste, including 79 Mt from municipal solid waste and 42 Mt from industrial sources (Liang et al. 2021). China, Japan, and South Korea produce nearly 700,000 tons of high-density polyethylene (HDPE) annually (Huang et al., 2020). About 3 million tons of solid plastic ends up in landfills and water bodies in Pakistan (UNDP 2021).

In developing countries, plastic use in agriculture is widespread. Mulching is used for specific crops, and farmers rely on organic inputs such as compost, manure, and fertilizers (Singh et al. 2024). Plastic irrigation pipes and agricultural equipment also contribute to soil plastic waste (Liu et al. 2023). Tillage operations and water infiltration integrate MP into soil layers, increasing plastic residues formation and mobility (Kader et al. 2017). Ramos et al. (2015) found that polyethylene (PE) residues polluted about 10% of agricultural land in Buenos Aires, Argentina. Biowastes such as household refuse and energy crops also increase MP in soils (Weithmann et al. 2018). Modern agricultural practices including mulching, soil amendments, sewage irrigation, and atmospheric deposition are major sources of soil MP (Huang et al., 2020). In 2020, agriculture used 11.7 million tons of plastics (3.2% of global production), mainly as films for greenhouses, mulching, and silage, with Asia being the main consumer (Briassoulis 2023). In Europe, 54 million tons of plastics are produced annually, with 0.083 million tons used for mulching films (Kim et al. 2015).

The lack of proper monitoring and management of plastic waste has created major environmental challenges, leading to increasing plastic pollution in oceans (Ateia and Karanfil, 2020) and soils (Tun et al. 2022). These plastic residues degrade into small particles under UV radiation, high temperatures, and oxygen, forming small plastic less than 5 mm known as MP (Zhao et al. 2022). Microplastic enter in environment through waste including, urban storm runoff, and landfills (Kabir et al. 2023). Textile industry is a significant source of airborne MP, with about 65% released during garment drying and wearing, which later deposit into soils (Munhoz et al. 2022). Whereas abundance of MP varies depending on population density, Land Use and sewage treatment efficiency (Desforges et al. 2014), while wind, road traffic, and human activities further enhance their mobility and alter their fate (Nor and Obbard, 2014). Hot climatic

conditions enhance MP fragmentation and redistribution and effects on soil nutrient cycling and microbial activity (Afzal et al. 2025). Especially, high urban temperatures (>35 °C) significantly accelerate the generation, release, and airborne transport of traffic-derived MP, increasing human inhalation exposure especially for children (Wu et al. 2025). However, the size and type of plastic also influence their environmental behavior and toxicity (Gunaalan et al. 2020). Moreover, meta-analysis of 60 studies shows that MP significantly increase soil greenhouse gas emissions (50–60%), with fibers, films, and larger-sized particles driving the strongest rises in CH<sub>4</sub> and N<sub>2</sub>O. These shape and size dependent effects highlight MP as an emerging contributor to global warming potential (Iqbal et al., 2024).

Microplastic pollution in agricultural soils is an emerging concern because MP particles act as vectors for harmful contaminants like heavy metals and persistent organic pollutants (POPs) (Wang et al. 2020) posing possible risks to agricultural products and farmers. While extensive research has focused on MP in aquatic environments, their presence and impact on agricultural and urban soils have received far less attention. This is concerning, as agriculture is a major pathway for MP accumulation in air, water, and soil. Microplastic may leach into groundwater, run off into surface water, or disperse through dust, eventually reaching humans (Rillig 2012). Microplastic pose ecotoxicological threats to soil organisms by altering behavior, impairing ecosystem functions, and reducing productivity (Wu et al. 2020). Their small size and large surface area increase mobility, while soil properties such as ionic strength and organic matter influence their fate (Wang et al. 2020). Soil organisms such as earthworms can transport MP to deeper layers and even groundwater (Rillig 2012). Microplastic can bioaccumulate in plants, entering the food chain and posing risks to

humans. Humans ingest or inhale MP through food, water, and air, which can accumulate in organs (Wibowo et al. 2021) causing inflammation, oxidative stress, cellular damage, and other health disorders (Kibria 2024). Moreover, MP contain over 16,325 chemicals from various functional classes, including colorants, processing aids, fillers, lubricants, plasticizers, antioxidants, and flame retardants, with more than 4,200 chemicals identified as persistent, bioaccumulative, mobile, and toxic, which can migrate easily into the environment (Monclús et al. 2025). Although various factors contribute to MP accumulation in urban and peri-urban soils, data on their distribution across different Land Use types and extend to expose to human remain limited.

Therefore, this study was designed to evaluate the extent, composition, distribution patterns, potential health risks, and environmental drivers of MP across diverse Land Uses and soil environments in multiple districts of Pakistan. This

study represents the comprehensive investigation of soil MP in the region and provides essential baseline data to support future policy formulation and regulatory frameworks for MP as emerging global contaminants. Specifically, this study offers: (a) a systematic, multi-district and land use-based assessment of MPs in soil; (b) an integrated analysis of polymer types coupled with *geo-accumulation index (I<sub>geo</sub>)* based risk evaluation and health hazards; and (c) insights into how Land Use patterns shape MP characteristics and their sources, and an assessment of the extent, composition, distribution patterns, health risks, and environmental drivers of MPs across diverse land use types and soils.

## Materials and method

### Study area and soil sampling

The study was conducted in five major districts of Pakistan based on population and area (Figure-1; Table-1&2). The study area has a hot semi-arid climate, where annual temperature varies from 15 °C in winter to 40 °C in summer. A total of 220 samples from six distinct Land Use types of each of these districts were collected at depths of 15–20 cm with the help of soil auger. Minimum 1 to 5 samples were collected as replicated depending on the size and variability

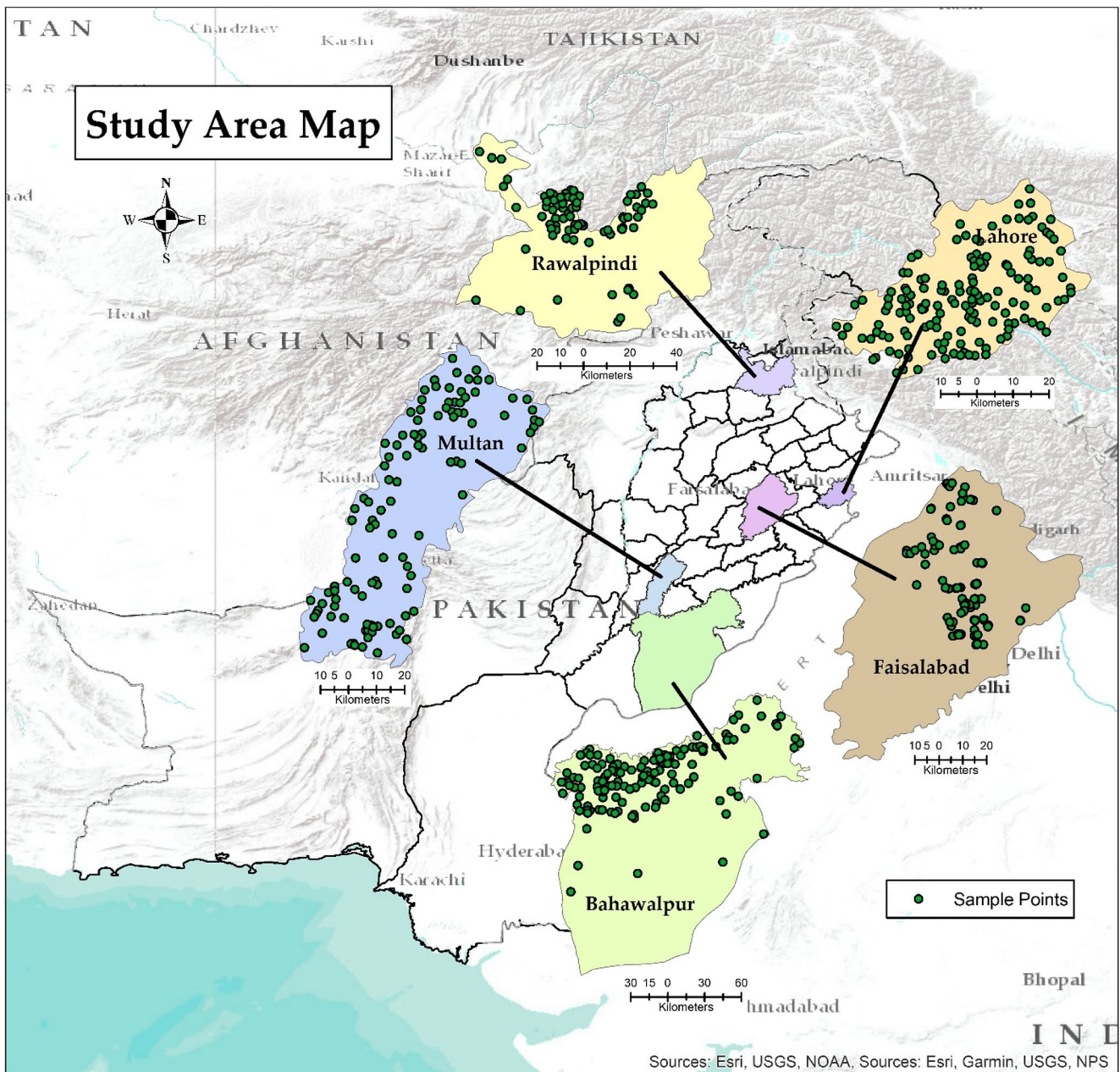


Fig. 1 Study area map showing the sampling sites (see Table-S1 for details)

**Table 1** Climatic and demographic characteristics of the study districts

Districts	Population (millions)	Solid Waste Generation (tons/day)	Mean Annual Temperature	Mean Annual Precipitation (mm/year)
Lahore	10.0	7,690	>40 °C	~625–760
Faisalabad	7.5	5,017	~40 °C	~600
Rawalpindi	5.9	4,500	~47 °C	~1,250
Multan	5.2	3,680	~41 °C	~150–200
Bahawalpur	0.9	282	~45 °C	~150 s

Source; Pakistan bureau of statistics and EPA

**Table 2** Description and sources of MP in various Land Use

Land Cover	Current Land Use	Description and MP Source
Vegetation	Crops	Compost, fertilizer bag, plastic films, packing bag, pesticide bottle etc.
	Mulched Soils	Agriculture soils using mulching for more than five years
	Composted Soils	Soils which are frequently using commercial composts and organic waste as amendment
	Greenhouses	Using white/green plastic sheet for greenhouse effect with or without mulching practice
	Sewage Irrigated soils	Peri-urban areas where wastewater having both municipal and industrial effluents is used for irrigation
Urban Areas	Fish Farm soil	Soil around fish farm
	Landfills	Contain dumping municipal and industrial solid waste such as plastic bags, bottles, packaging materials, and construction debris containing plastic.
	Residential areas/Parks	Household waste zones and public parks where plastic bags, bottles, toys, and food packaging are commonly discarded.
	Roadsides	Areas adjacent to roads and highways are affected by vehicle and pedestrian activities.
	Industrial Soils	Surroundings of factories, workshops, and production units.

of the site. About one kg of soil was collected, packed and stored at 25 °C for further laboratory analyses. Soil samples were then air dried and sieved through 5 mm and 0.1 mm mesh sizes to remove large debris and unwanted particles (Rafique et al. 2020). To remove organic debris, 35% hydrogen peroxide and 0.5 M ferrous sulphate was added in the soil and placed on a hot plate set to 60 °C for 72 h (Fig. 2).

### MP Isolation, Identification and Quantification

After organic matter removal, density separation was performed by adding 600 mL of NaCl solution (30% w/v) to the sample and placed in a density separator, operated at 150–200 RPM to ensure effective mixing. The soil was allowed to settle in the separator for 12 h, allowing the MP, which

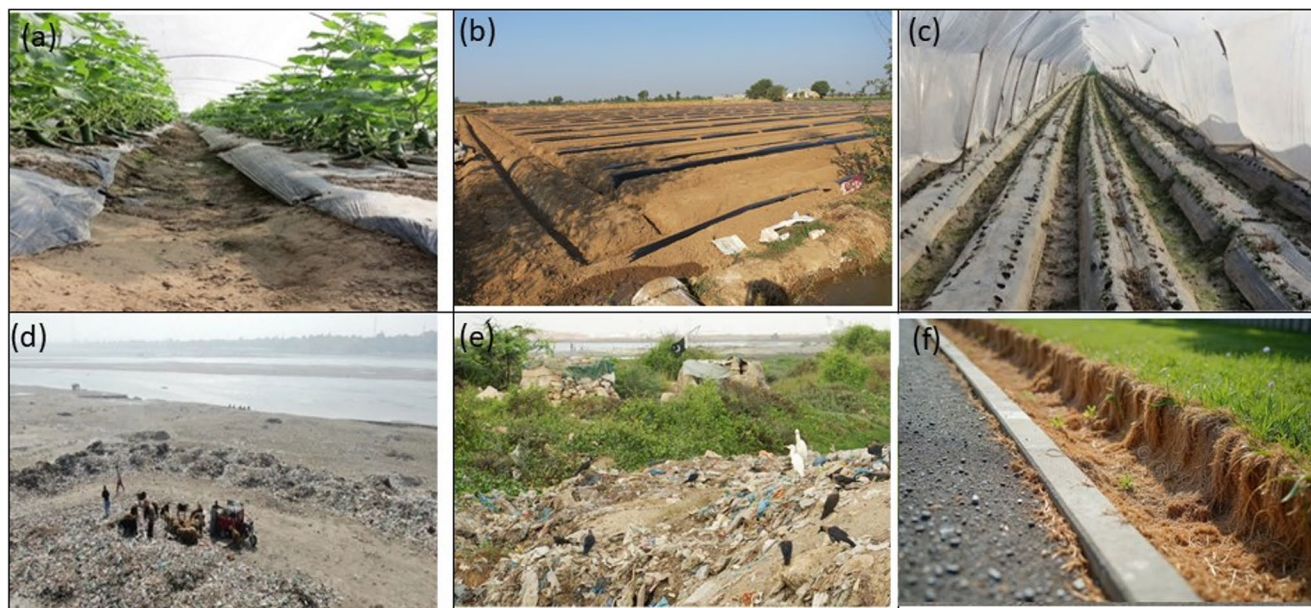
are less dense, to float to the top and the supernatant was carefully collected and filtered through 0.45 µm filter (Sartorius, Germany) using vacuum filtration assembly (Song et al. 2017) to isolate the MP from the soil solution (Rafique et al. 2020). After filtration, the filter papers were immediately stored in clean glass petri dishes and examined by using stereomicroscope (IRMECO GmbH, Model IM-SZ-500) and hot needle test was also done to confirm the presence of plastic particles (Rafique et al. 2020). In this test, a heated needle or metal point is brought close to the particles, to confirm the presence of plastic particles, which melt, while non-plastic particles either do not melt or burn to ashes. However, because this test relies solely on visual observation, it can be subjective and may result in misidentification; therefore, all suspected particles were confirmed using Fourier Transform Infrared (FTIR) spectroscopy. Microplastic particles were categorized based on colour (white, black, red and blue), shape (fibres or elongated, fragmented, films, and beads) (Jabeen et al. 2017). The MP were also categorized into three size ranges: 0.1–0.3 mm, 0.3–1.0 mm, and 1–5 mm (Yu et al. 2021) using ImageJ software. The MP polymers were identified using FTIR spectrometer (Nicolet-380, Thermo Fisher Scientific, USA) equipped with a diamond Attenuated Total Reflectance (ATR) accessory, spectral range of 4000–400 cm<sup>-1</sup>. Spectra were acquired in absorbance mode with 64 scans per sample at a resolution of 4 cm<sup>-1</sup> to ensure optimal spectral clarity. Data analysis and polymer identification were performed using OMNIC software version 9.1.

### Human exposure analysis

Human exposure to MP through soil ingestion was assessed by estimating the daily intake (EDI) for different age groups, specifically infants (1–5 years) and adults (≥ 20 years), using Eq. (1).

$$EDI_{\text{ingestion}} = \frac{C \times AMIMP \times M_{\text{ingestion}}}{BW} \quad (1)$$

$M_{\text{ingestion}}$  showed the soil and dust ingestion rate (mg/day), with values of 55 mg/day for infants and 30 mg/day for toddlers (USEPA, 2017); BW denotes body weight for infants



**Fig. 2** Sampling for different Land Use types. images (a–c) represent mulching, greenhouse, and sewage/compost soils, while images (d–f) show residential soil and roadside sampling sites

and adults as 5 kg and 63 kg respectively;  $C$  refers to the concentration of MP in the soil. Average Mass of an Individual Microplastic Particle (AMIMP) was estimated following Senatirajah et al. (2021) for different sizes ranging from 0.1 to 0.3 mm, 0.3–1.0 mm, and 1–5 mm and assuming spherical geometry and applying polymer density, particle counts were converted into mass.

### The geo-accumulation index ( $I_{geo}$ )

The geo-accumulation index ( $I_{geo}$ ) as given in equation-2 was originally defined by Müller (1969) and is applied to determine contamination of material by comparing current concentrations with pre-industrial levels, however, as there is no systematic and standardized method that is completely applicable to assess MP pollution status and its potential ecological risks. Therefore, this method with minor modification as described by Feng et al. (2019) was used as preliminary assessment method to better understand the MP pollution status and potential ecological risks.

$$I_{geo} = \log_2 \left( \frac{C_i}{1.5 \times C_o} \right) \quad (2)$$

Where  $C_o$  represents the background concentration (MP/kg). Ideally,  $C_o$  should reflect MP levels in soils prior to the widespread use of synthetic polymers. However, because such historical data are unavailable for the study area, the lowest observed level (18 MP/kg) in fish-farm soils suitable proxy for the background value ( $C_o$ ) in the  $I_{geo}$  calculation,

as recommended by Feng et al. (2019). The site represents a relatively isolated and minimally disturbed environment with limited anthropogenic input. Where  $C_i$  represents the concentration of various plastic polymers (MP/kg). Based on  $I_{geo}$  values, MP pollution was categorized into four levels, Uncontaminated ( $I_{geo} \leq 0$ ), moderately contaminated ( $0 < I_{geo} \leq 2$ ), heavily contaminated ( $2 < I_{geo} \leq 4$ ) and extremely contaminated ( $I_{geo} > 4$ ).

### Statistical analysis

Abundance of MP is reported as mean  $\pm$  standard error. Differences among Land Use types and districts were assessed using two-way Analysis of Variance (ANOVA) at the 95% confidence level ( $p < 0.05$ ). Principal component analysis (PCA) was applied to evaluate correlations between Land Use, climate, and population. Graphical analyses and basic statistical tests were conducted in MS Excel 2010<sup>®</sup>, sampling sites were mapped in ArcGIS 10.5 (Esri, USA), and all figures were generated using Origin Pro 2026 (Origin Lab Corporation, Northampton, MA, USA).

## Result

### Abundance and distribution characteristics of MP

Microplastic concentrations in soil varied markedly across land-use types. Greenhouse soils exhibited the highest contamination ( $1872 \pm 32$  MP/kg), followed by residential

(751±19) and industrial soils (693±18). Landfill and roadside soils showed moderate levels (421–561 MP/kg), while fish farm (18±2) and compost soils (46±3) recorded the lowest values. Spatially, Rawalpindi, Lahore, and Faisalabad had the greatest contamination, whereas Bahawalpur consistently showed the lowest across most land-use categories. Statistical analysis confirmed that both location ( $p=0.03$ ) and land-use type ( $p=0.02$ ) significantly influenced MP concentrations ( $p<0.05$ ), underscoring the role of urbanization and anthropogenic activities in shaping MP distribution within terrestrial environments.

Regarding the color of MP (Figure-3b), white MP were most dominant in fish farm soils (75%) and sewage-irrigated soil (60%), while red and blue MP were the lowest (less than 26%) in all soil types, even absent in fish farms soils. Red color MP was highest (33%) in greenhouse soils, while blue MP was most common in industrial soils (40%). Four different shapes of MPs were observed in the study (Figure-3c & Figure-4). Fibers MP were predominantly in most of the sites including fish farms, crops, roadside, sewage irrigated, and industrial soils, while film-shaped MP were prevalent in mulched and greenhouse soils, accounting around 50% of the MP in these soils. Bead shaped MP were also found, but generally less common across all soil types, with the highest proportion (33%) observed in greenhouse soils.

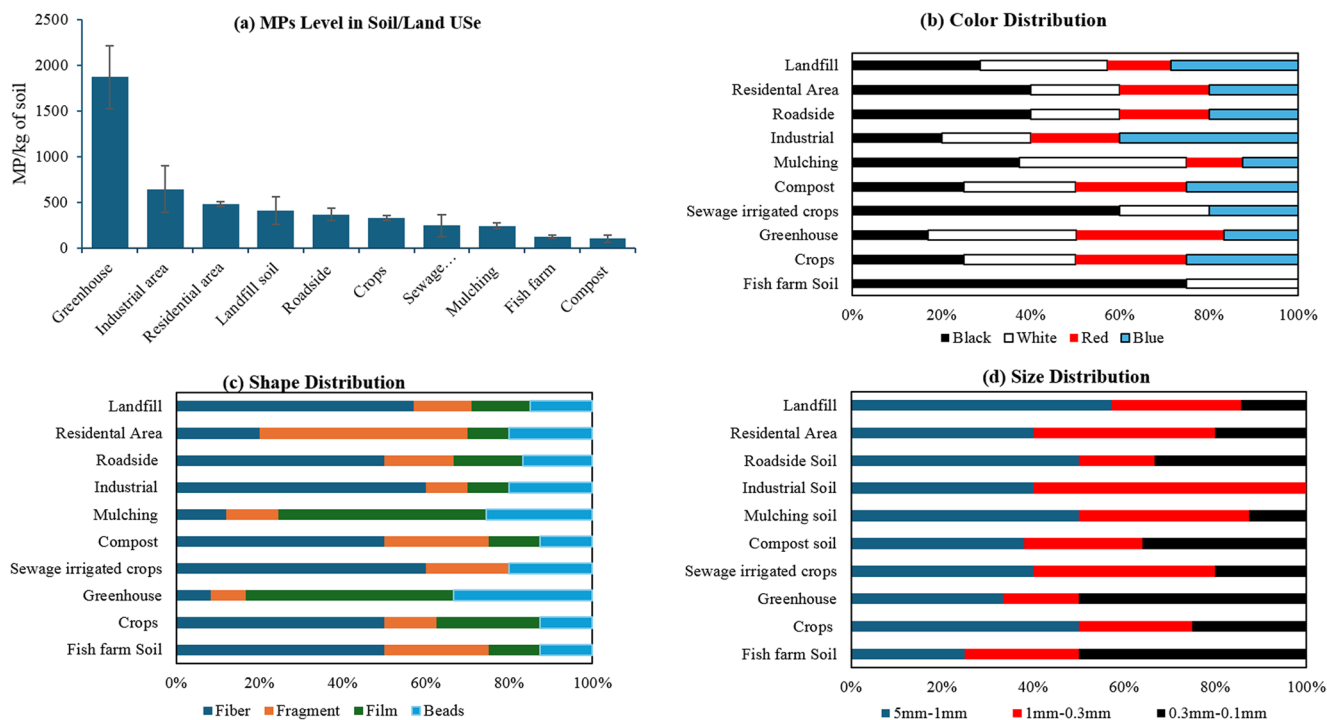
Microplastics were also categorized into three types based on their size and those between 1 and 5 mm size MP were most prevalent in landfills, roadside, crops, and mulching

soils, accounting for approximately 50–60% of the total MP in soil. While fish farm and greenhouse soils contained 50% of MP in the 0.3 to 0.1 mm size range and only 25% of MP from 1.0 to 5.0 mm category, and interestingly there was no MP of 0.3 to 0.1 mm size range in industrial soils (Figure-3d). Sewage-irrigated, industrial, and residential soils contain 40–60% of MP from 1 to 0.3 mm size range.

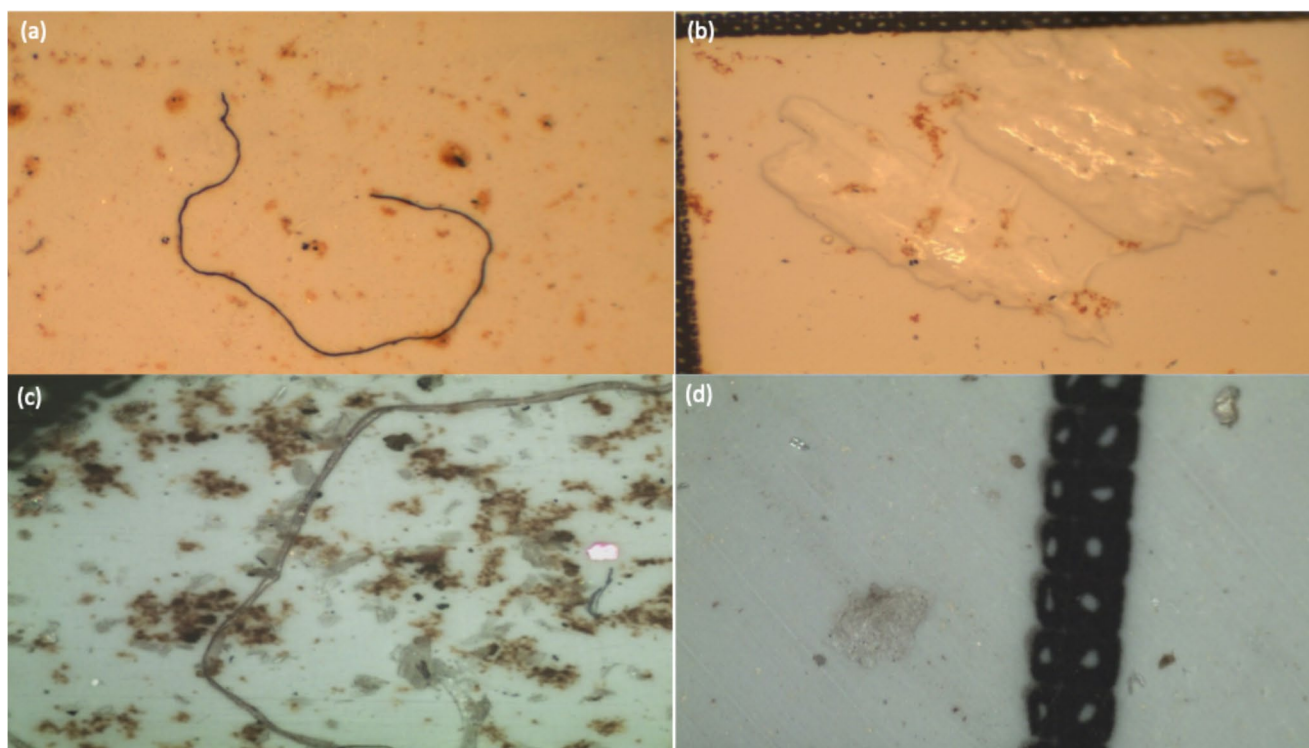
### Characteristics and chemical composition of MP

Regarding the chemical composition of MPs, nine different types of polymers were observed and the highest one was HDPE (20±3) followed by Nylon (14±1), PVC (12±1), PP (12±1), and PS (10±1), while PE (11±2), PET (7±1), ABS (6±1) and PU (5±1) were relatively less in numbers (Fig. 4a). The HDPE accounted for the highest share (29%); likewise, Nylon (27%) was the dominant polymer in industrial zones and greenhouses (20%). In sewage-irrigated and compost-amended soils, PE and PS together made up over 30%; while, PVC peaked in landfill sites (26%) and residential areas (17%), PP was notably high in crop fields (26%).

The MPs polymers observed in soil using (ATR-FTIR) spectroscopy (Figure-4c), HDPE was observed with its prominent C–H stretching vibrations around 2915 and 2849  $\text{cm}^{-1}$ ,  $\text{CH}_2$  bending at  $\sim 1470 \text{ cm}^{-1}$ , and  $\text{CH}_2$  rocking vibrations near 730–720  $\text{cm}^{-1}$ , confirming its linear aliphatic structure and non-polar nature. Similarly, PE and PP displayed strong C–H stretching in the same range and bending



**Fig. 3** Abundance of MP (a), color distribution (b), shape distribution (c), and size distribution (d) of microplastics in five districts



**Fig. 4** Images of various shapes of MP observed under stereomicroscope, namely fiber(a, c), Film (b), fragments (c), beads (d)

vibrations near  $1463$  and  $1375\text{ cm}^{-1}$ , indicating aliphatic hydrocarbon chains. Polystyrene and ABS exhibited prominent aromatic  $\text{C}=\text{C}$  stretching near  $1600\text{ cm}^{-1}$  and complex deformation bands in the fingerprint region ( $900\text{--}600\text{ cm}^{-1}$ ), typical of aromatic ring structures. PET, PU, nylon and PVC showed distinct carbonyl ( $\text{C}=\text{O}$ ) stretching vibrations between  $1730$  and  $1630\text{ cm}^{-1}$ . Notably, PVC also displayed a strong  $\text{C}-\text{Cl}$  stretching band near  $600\text{ cm}^{-1}$ , while nylon and PU were further identified by broad  $\text{N}-\text{H}$  stretching bands around  $3300\text{ cm}^{-1}$ .

### Human exposure to MP

Due to increasing concerns about the impact of MP on human health, it is imperative to focus this aspect during such studies along with monitoring the amount of MP in various environments. The most common route of MP exposure is through accidental ingestion and entry via food chain (Fig. 5).

### The estimated daily intake (EDI) values

EDI for MP reveals key exposure patterns for infants and adults (Table 3). In residential areas, infants ingest up to  $23.6\text{ mg/day}$  of MP in the  $0.3\text{ mm}$  to  $1\text{ mm}$  size range, far exceeding the adult intake of  $0.6480\text{ mg/day}$  for the same size. This heightened vulnerability in infants is largely due

to their hand-to-mouth behaviors and lower body weight, which amplify the effects of MP exposure. Additionally,  $1\text{ mm}$  to  $5\text{ mm}$  MP are the most prevalent and contribute the highest intake across all Land Use types, with infants in greenhouses ingesting up to  $5.6\text{ mg/day}$ .

### The geo-accumulation index (*I*<sub>geo</sub>)

The *I*<sub>geo</sub> values and MP abundance revealed significant enrichment and ecological risks. Severe contamination (*I*<sub>geo</sub> > 4) was found in greenhouses, residential areas, landfills, and industrial soils, while, district wise situation followed order with highest levels in Rawalpindi, followed by Lahore, Faisalabad, Multan, and Bahawalpur. Fish farm soil area and compost soils showed minimal contamination (*I*<sub>geo</sub> = 0–2). Overall, contamination ranked: Greenhouse > Residential > Landfill > Industrial > Roadside > Sewage irrigated > Mulching > Cropland > Fish farm, with Rawalpindi bearing the highest district-level burden.

### The relationships between MP characteristics and their distribution across different Land Use types and geographic locations

The PCA biplot (Fig. 6a) illustrates relationships between Land Use and MP characteristics, with PC1 and PC2 explaining  $24.61\%$  and  $22.33\%$  of the variance, respectively ( $47\%$

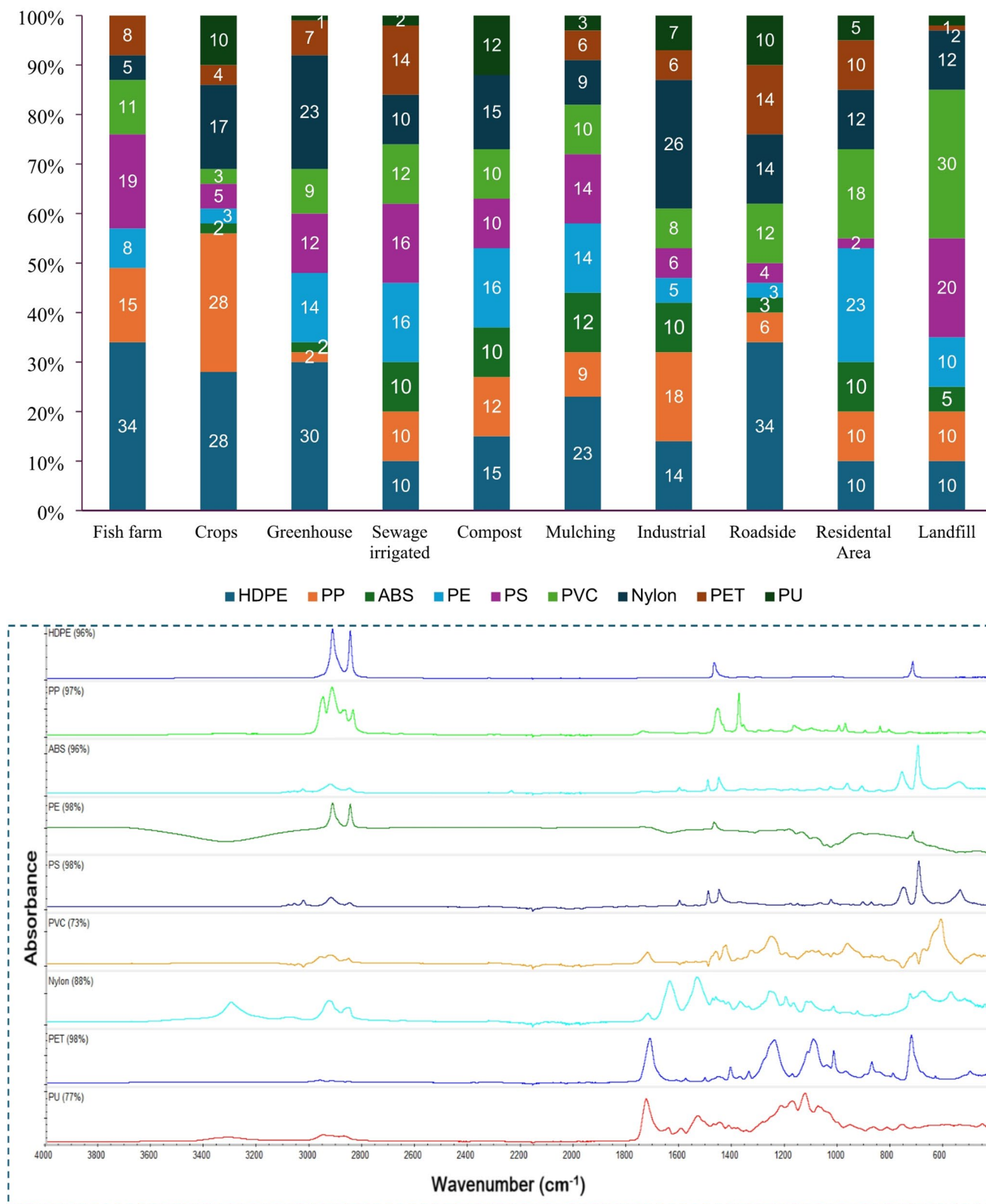


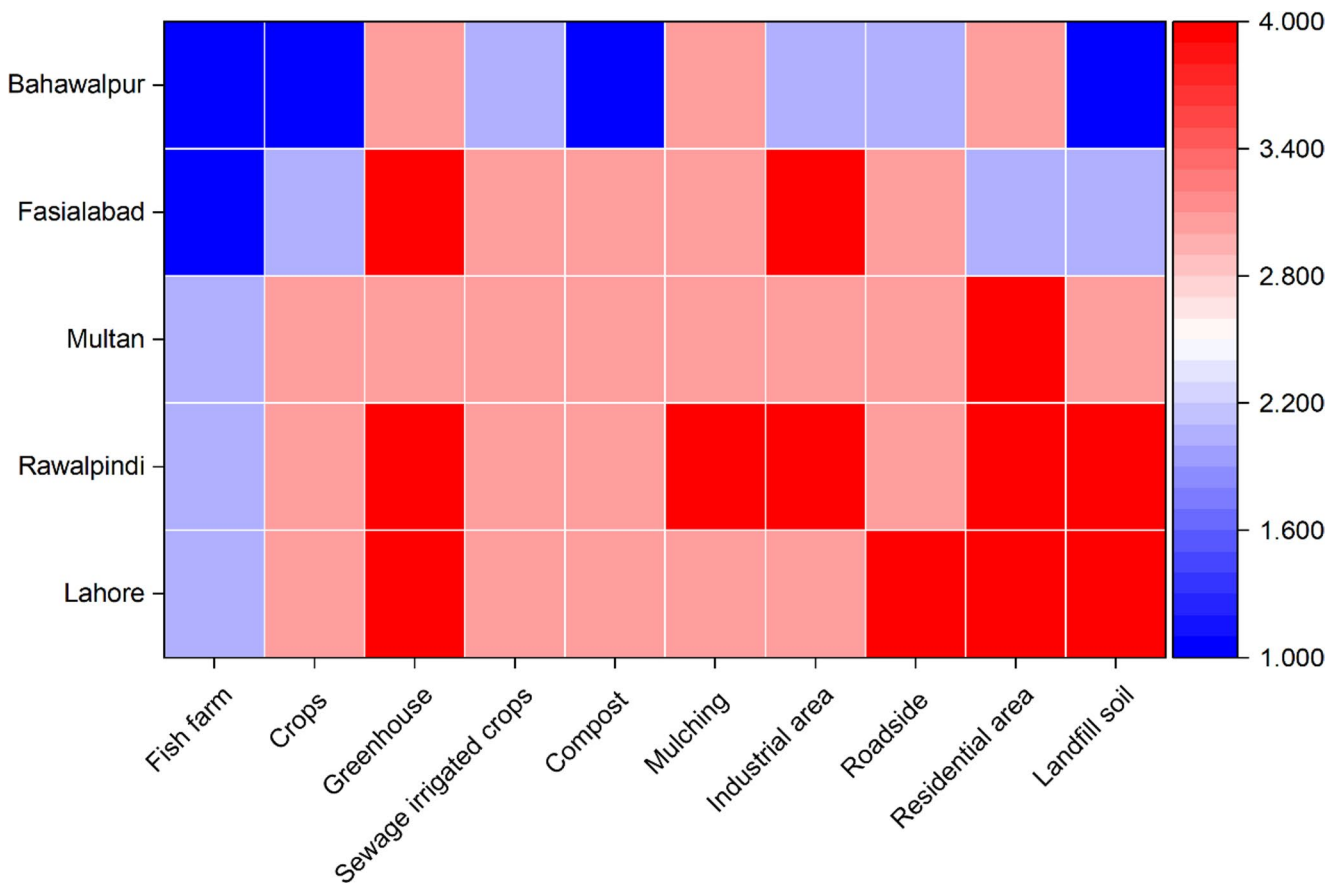
Fig. 5 (a) The MPs types/polymer distribution (%) in different Land Use (b) FTIR-ATR spectra of MP polymers identified in the study area

**Table 3** Average EDI (mg/kg body weight/day) of different size MP at various locations

Land Use	Age Group	MP Size		
		0.1–0.3mm	0.3–1 mm	1.0–5.0mm
Residential Area	Infants	0.0189	0.6480	1.6200
	Adults	0.2376	23.100	5.4310
Crops	Infants	0.0038	0.1315	0.3288
	Adults	0.0482	4.6889	1.1024
Fish Farm	Infants	0.0010	0.0357	0.0891
	Adults	0.0131	1.2709	0.2988
Landfill	Infants	0.0151	0.5202	1.3005
	Adults	0.1907	18.544	4.3599
Roadside	Infants	0.0057	0.1973	0.4932
	Adults	0.0723	7.0334	1.6536
Greenhouse	Infants	0.0192	0.6612	1.6531
	Adults	0.2424	23.571	5.5419
Sewage Irrigated	Infants	0.0016	0.0543	0.1357
	Adults	0.0199	1.9348	0.4549
Compost	Infants	0.0045	0.1554	0.3885
	Adults	0.0570	5.5403	1.3026
Mulching Soil	Infants	0.0099	0.3404	0.8511
	Adults	0.1248	12.135	2.8532
Industrial Soil	Infants	0.0017	0.0601	0.1502
	Adults	0.0220	2.1421	0.5036

total). Industrial, Roadside, Compost, and Landfill samples cluster near vectors for larger fragments (5–1 mm), black particles, PVC, and polyurethane (PU), reflecting urban and industrial inputs. Compost and Mulching are associated with fibers, films, and smaller fragments, consistent with plastic residues from organic waste and agricultural practices. Fish farms and sewage-irrigated crops align with beads, red particles, and fine size classes (0.3–0.1 mm), indicating wastewater and aquaculture contributions. Greenhouse and Crops cluster with HDPE, PE, and films, pointing to agricultural plastics such as covers and mulch films.

The PCA biplot (Fig. 6b) illustrates relationships between urban locations and MP characteristics, with PC1 and PC2 explaining 40.12% and 30.01% of the variance, respectively (70% total). Lahore and Faisalabad cluster near vectors for population, precipitation, and polymers such as PS and PVC, reflecting dense urban environments with strong wastewater and industrial inputs. Multan and Bahawalpur align with fragments, beads, and red particles, suggesting contributions from agricultural plastics and localized waste management practices. Rawalpindi is associated with fibers, films, and blue particles, consistent with household and



**Fig. 6** Heatmap of geo-accumulation index (Igeo) Across Land Use Types and five districts of Pakistan

textile sources. Together, the biplots reveal spatial patterns and source-specific MP pollution across urban and semi-urban environments (Fig. 7).

### Discussion

#### Abundance and spatial distribution of MP

Small-sized MP particles are a serious concern not only for human health but also for terrestrial and aquatic ecosystems (Huang et al., 2020). A study by WWF and The University of Newcastle estimated that every person ingests about 5 g of plastic per week, equivalent to the weight of a credit card (Senathirajah et al. 2021). These particles pose heightened ecological risks due to their large surface area, which facilitates adsorption of heavy metals, organic pollutants, and

pathogenic bacteria from the atmosphere (Yang et al. 2022). Consequently, agricultural and urban soils in Pakistan are emerging as key sinks of MP pollution, strongly influenced by industrial activities and unsustainable plastic management practices.

In this study, MP pollution in soils was assessed across different Land Use types and districts, with implications for human health. Results showed Greenhouse soils showed the highest contamination ( $1867 \pm 32$  MP/kg), followed by residential ( $751 \pm 19$ ) and industrial soils ( $693 \pm 18$ ) and Fish farm ( $18 \pm 2$ ) showed lowest values. Comparable findings were reported by Hu et al. (2024), who observed the highest MP concentrations in farmland (3738 MP/kg) in a mining city. Redundancy analysis by Zhang et al. (2022a, b) further confirmed that MP pollution is closely associated with human activities, with grassland soils in urban parks showing contamination due to proximity to residential areas. Our

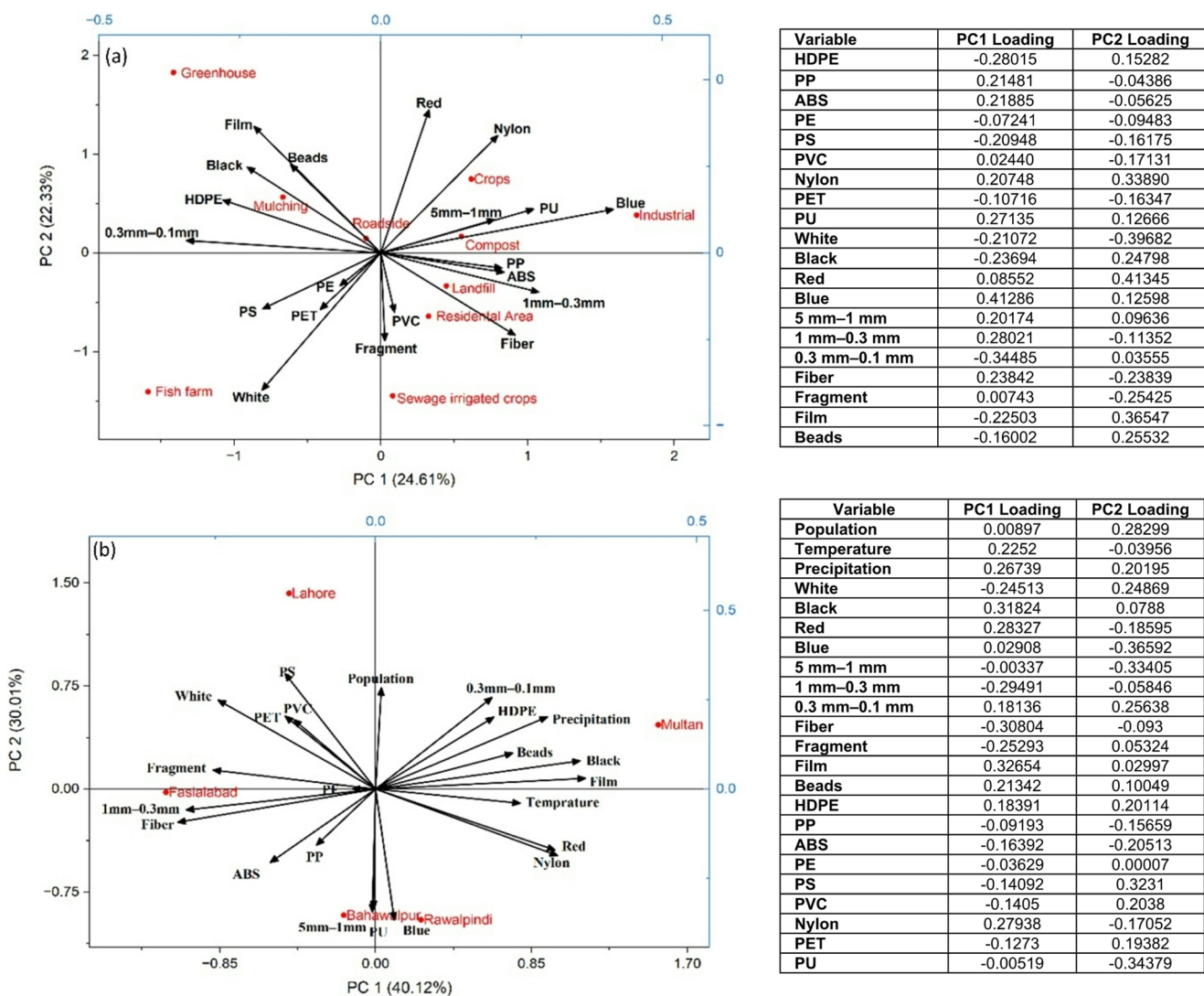


Fig. 7 (a) Principal Component Analysis (PCA) biplot with factor loading table showing the distribution of microplastic in different Land Use types and (b) different environmental variables across five districts in Punjab

results also support this, as Bahawalpur exhibited lower MP contamination due to its desert climate, which slows plastic fragmentation, and its limited rivers and water channels, reducing hydrological transport and deposition of MP particles.

Although a few surveys have examined MP contamination in Pakistani soils, no systematic work has addressed sources and geographical variability across both urban and agricultural Land Uses. Clear evidence of MP contamination was observed in all districts, with concentrations ranging from 18 to 1872 MP/kg, highest in residential and greenhouse soils and lowest in fish farm soils. These variations may reflect differences in sampling methods, preparation protocols, detection sensitivity, climatic conditions, population density, and Land Use type (He et al., 2018). Regional differences are further supported by international studies, such as Zhang et al. (2024) in China, who reported even higher MP levels ( $2285 \pm 1592$  MP/kg). Similarly, global reports show significant variability in MP concentrations across regions and countries (Table 4).

This study demonstrates that MP contamination in soils is shaped by a complex interplay of particle morphology, polymer composition, Land Use practices, and environmental

drivers. The dominance of MP particles in the 0.3–0.1 mm size range raises concern due to their enhanced mobility and inhalation risk, as such particles can become airborne, enter the human body via dust inhalation, and potentially reach the bloodstream (Nawab et al. 2024). Their small size also facilitates long-distance transport through air and water, contributing to contamination even in soil without direct plastic inputs (Sajedi et al. 2025). Shape analysis revealed that fibers accounted for nearly half of all MP particles, followed by films, with fibrous MP particularly abundant in agricultural soils. These findings align with reports from China, though regional differences exist, with some studies noting fragment dominance (Zhang et al. 2022a, b). Fibrous MP particles likely originate from diverse sources including mulching materials, greenhouse sheets, textiles, atmospheric deposition, and household packaging waste (Zhang et al. 2020). Their persistence and bioaccumulation in organisms highlight significant ecological and health risks (Browne et al. 2011).

Color distribution further supports source heterogeneity. White MP particles were most dominant, consistent with previous studies, and are often linked to bottles and bags. Film-shaped MP particles were prevalent in greenhouse and mulching soils, reflecting weathering of agricultural plastics, while fibrous MP particles dominated in landfills, roadsides, and croplands, suggesting localized degradation. Smaller MP particles (0.1–0.3 mm) were more abundant in fish farm and industrial soils, indicating migration from external environments and representing aged particles. The detection of MP particles in all soils, including unmanaged lands, underscores the role of atmospheric deposition and surface runoff in dispersing MP particles across terrestrial ecosystems (Senathirajah et al. 2021).

Polymer analysis revealed nine distinct types, with HDPE accounting for 85% of the total composition, consistent with earlier findings (Massaccesi et al. 2025). HDPE and polypropylene were strongly linked to mulching films, while croplands showed elevated PP levels (28%) from pipes, bottles, and agricultural plastics (Zhang et al. 2020). Industrial soils were dominated by Nylon (26%), reflecting synthetic fiber fallout and effluents (Deng et al. 2020). Compared to European and East Asian studies, MP concentrations in Pakistan were comparable or higher, particularly for HDPE and Nylon, likely driven by unregulated waste disposal, limited recycling infrastructure, and intensive agro-industrial activity. The widespread presence of Nylon and ABS across Land Use types further implicates textile effluents as a major source of MP particles.

Multivariate PCA analysis reinforced these findings by linking MP characteristics to Land Use and urban contexts. The first biplot (47%) highlighted distinct MP profiles: industrial, roadside, and landfill soils clustered with larger

**Table 4** Reported Concentrations of Microplastics in Soils of different Countries and Land Use

Country	Land Use	Contamination Level (MP/Kg)	Reference
Pakistan	Soil	1867±32	Present Study
		4483±2315	Rafique et al. 2020
Chile	Soil	0.6–10.4	Corradini et al., 2019
China	Soil	7100–42,960	He et al., 2018
	Agricultural field	0.54	Zhang et al. 2018
	Tree-planted soil	7100–42,960	
China	Farmland soils	62.50±12.97	Liu et al., 2018
	Multiple Farmland	50 to 3450	Zhang et al. 2018
Germany	Soil	1000–24,000	Bläsing and Amelung (2018)
	Farmland soil	0–1.25	Piehl et al. 2018
Mexico	Home garden soil	0.87	Lwanga et al. 2017
Denmark	Agricultural soil	82,000	Vollertsen and Hansen (2017)
Australia	Industrial soil	300–67,500	Fuller and Gautam (2016)
Argentina	Farmland Soil	30±19	Ramos et al. 2015
Switzerland	Floodplain soils	<593	Scheurer and Bigalke (2018)

fragments, black particles, PVC, and PU, reflecting traffic and waste-derived inputs. Compost and mulching soils aligned with fibers, films, and smaller fragments, consistent with agricultural degradation. Fish farm and sewage-irrigated crops were associated with beads and fine MP particles, pointing to wastewater and atmospheric sources, while greenhouse and cropland soils clustered with HDPE, PE, and films, reflecting agricultural plastics. The PCA analysis showed Lahore and Rawalpindi clustered near HDPE, PET, PS, and environmental variables such as population and temperature, underscoring the influence of urban density and climatic factors. Faisalabad and Multan aligned with fibers, fragments, and colored MP particles, likely from textile and domestic sources, while Bahawalpur grouped with beads and fine MP particles, reflecting agricultural runoff and wastewater inputs.

### Human exposure pathways and health implications of MP

Microplastic particles pose significant human-health risks due to their small ingestible size and their ability to adsorb co-contaminants such as heavy metals and persistent organic pollutants (Feng et al. 2019). Soil ingestion represents a major exposure pathway in urban, peri-urban, and agricultural settings (Van den Berg et al., 2020). This risk is heightened by the greater bio accessibility of smaller particles, as  $MP < 1$  mm are more readily ingested than larger size fractions (Senathirajah et al. 2021). In this study, the geo-accumulation index (*I<sub>geo</sub>*) revealed moderate to high MP contamination across Land Use categories, reflecting substantial anthropogenic pressure. The variation in *I<sub>geo</sub>* among sites highlights differences in plastic inputs, waste management, and Land Use intensity (Dehkordi et al. 2024), consistent with earlier research showing the localized nature of soil MP pollution (Nor and Obbard, 2014). Elevated MP levels in residential and landfill soils indicate strong influence from urban waste and legacy plastics, while consistently high concentrations in greenhouse soils correspond to extensive use of mulching films, tunnels, and coverings aligned with global evidence linking agricultural plastics and sludge amendments to increased MP loads (Ramage et al. 2025). Residential and greenhouse areas, particularly in Rawalpindi and Lahore, emerged as contamination hotspots due to high urbanization and waste generation. Incorporating a broader MP size range (0.3–5 mm) provides a more realistic representation of potential exposure, as smaller fractions are more relevant to ingestion and internalization (Barceló et al. 2023). This approach addresses a key limitation in many soil MP studies that rely solely on particle counts without linking them to exposure risk.

To better contextualize potential human exposure, this study extended beyond number-based MP abundance by estimating mass-based concentrations and calculating the estimated daily intake for size fractions most likely to be ingested during Land Use-specific activities. This highlights an elevated exposure risk for farmers, residents in urban parks, and particularly in children, who may face up to 20 times greater vulnerability in these environments. Together, these results highlight that human activities are the primary drivers of MP accumulation in soils, with agricultural plastics, textile effluents, and urban waste as dominant sources. Higher EDI values were observed in infants and toddlers compared to the adults, maybe due to high exposure to MP-contaminated dust through activities like playing on the floor and parks. Similar results were reported by Cohen et al. (2024) indicating higher dust ingestion among younger age groups due to greater hand-to-mouth activity. Moreover, particles size plays vital role in MP ingestion (Jeong et al. 2016). Our estimated EDI values also suggest that the risk of HDPE exposure is significantly higher in managed lands compared to unmanaged lands, most likely due to the extensive use of mulching sheets and other agricultural plastics. However, even areas with minimal direct plastic use contained MP particles, emphasizing the role of atmospheric deposition and hydrological transport in shaping spatial heterogeneity. This pattern is evident in Bahawalpur characterized by low population density, the absence of major rivers, and a desert climate which showed the lowest MP levels, indicating that limited hydrological connectivity and fewer water bodies reduce MP transport and deposition into soils. These findings highlight the urgent need for strengthened waste-management practices, stricter regulation of agricultural plastic use, and improved monitoring of airborne and waterborne MP pathways to mitigate ecological and human-health risks.

### Conclusions

This study provides clear evidence that microplastic (MP) contamination is widespread across both urban and agricultural soils in Punjab, offering new insights into regional MP pollution. Average abundances ranged from 18 to 1872 items/kg, with greenhouse soil most affected, followed by residential and industrial sites. Fibrous and film morphotypes dominated, largely originating from mulching films, textile effluents, and packaging materials, and were influenced by atmospheric deposition and hydrological transport. Pollution levels ranged from uncontaminated to severely contaminated, with the highest *I<sub>geo</sub>* values in Lahore, Faisalabad, and Rawalpindi, while Bahawalpur remained least impacted. Estimated Daily Intake (EDI)

suggested that residents in highly contaminated areas may face ~20 times greater exposure compared to those in less polluted sites, underscoring significant health risks. Overall, PP and HDPE were the most critical polymers contributing to soil MP pollution. Future research should prioritize MP contamination in agricultural and urban soils, focusing on interactions with co-occurring pollutants and their ecological consequences. Robust policies and improved plastic waste management are urgently needed to mitigate these risks.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s12665-026-12972-8>.

**Author contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Amna Zia and Zulfiqar Ahmad Saqib. The first draft of the manuscript was written by Amna Zia and Zubair Aslam, while initial review and statistical improvements were done by Anwar Ul Haq. All authors commented on previous versions of the manuscript. All authors read and approved of the final manuscript.

**Funding** The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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