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Spatial analysis and potential exposure implications of microplastic contamination in urban street dust in Urmia

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Microplastics (MPs) are ubiquitous environmental contaminants detected across water, air, and soil, posing a major threat to organisms and presenting a critical global ecosystem challenge. This study assesses microplastic contamination in the street dust of Urmia city, Iran. Samples were collected from various points across the city to investigate the microplastic concentration, physical characteristics, and polymer composition. The results showed that microplastic concentration in Urmia's street dust ranged from 500 to 17,000 particles per kilogram, indicating a high level of pollution. The most common form of MPs found were fibers, with a predominant size between 100 and 500 micrometers. In terms of color, transparent (40%) and black (22%) microplastics were the most abundant types. Scanning Electron Microscope (SEM) analysis of the particles revealed irregular shapes and rough surfaces, which are typical signs of physical and mechanical degradation processes like fragmentation and weathering. The polymer composition was determined by μ-Raman, revealing common types such as PS, POM, PES, PET, PE, PP, EP and PVC. Finally, the potential exposure of microplastic ingestion were analysed. Based on the estimations, an adult in a normal scenario ingests between 37 and 1150 particles annually, while in an acute scenario, this number can reach up to 2894 particles. The observed high contamination levels, fiber predominance, and greater estimated ingestion exposure in children highlight significant microplastic presence in Urmia street dust, emphasizing the importance of local mitigation strategies and further exposure research.

Keywords Microplastics, Contamination, Street dust, Urmia, Health exposure

Plastics have achieved widespread application in daily life, with manufacturing sectors mass-producing these materials due to their cost-effective production processes and exceptional durability[1]. Microplastics (MPs) are small plastic particles that contribute to environmental contamination. MPs are small plastic particles less than 5 mm in size, which can be fragments, fibers, films, pellets, or other shapes and belong to specific polymer types (e.g., PE, PP, PS, PET)[1–3]. Today, plastics have various applications in industries and daily life. With a global production of 400 million tons of plastic per year, it is estimated that by 2025, approximately 11 billion tons of plastic will accumulate in the environment[4,5]. Once released into the environment, plastics undergo physical and chemical processes such as weathering, photo-oxidation, biodegradation, and mechanical forces, which alter their structure and lead to fragmentation[6–8]. MPs exhibit a wide variety in terms of chemical composition, diameter, shape, density, and color factors that play a key role in their distribution and environmental impact[9,10].

Primary microplastics are intentionally manufactured at small sizes (< 5 mm) and include microbeads in personal care products (e.g., exfoliants) and industrial pellets/nurdles from manufacturing processes[11,12]. In contrast, secondary microplastics result from the mechanical wear and fragmentation of larger plastics, such as synthetic fibers released from clothing during washing and use, tire wear particles, and degradation of macroplastics[13].

In recent years, microplastic contamination has become a global concern, as their presence has been documented in marine environments, freshwater lakes, rivers, the atmosphere, and even atmospheric deposition[14,15]. Atmospheric MPs are primarily fibrous in nature, as synthetic textiles are a major source[16]. During

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the production and daily use of textiles, a significant amount of microfibers is released into the air. Additionally, microplastics already present in the environment can be transported into the air through various pathways, with major examples including abrasion of plastic products and construction materials, waste incineration, industrial emissions, vehicle exhaust, resuspension of roadside dust, and tire wear particles[17,18]. Street dust accumulates microplastics from key urban sources including tire/road wear, vehicle emissions, synthetic textile abrasion, and construction dust, making it an important matrix for studying contamination and potential human exposure via ingestion in densely populated cities[19].

Street dust refers to particulate matter composed of mineral and organic particles that accumulates on urban road surfaces[20,21]. Previous studies in Iranian cities have reported significant microplastic contamination in urban street dust, yet data remain limited for northwestern regions and mid-sized cities with high traffic and dust influx[22,23]. MPs can infiltrate soil and water, potentially affecting plant growth and animal development, while some species (e.g., fish) may ingest MPs as food, resulting in intestinal blockages, reduced feeding, and mortality[24,25]. Moreover, MPs can act as carriers for other pollutants, such as heavy metals and organic chemicals, amplifying their harmful effects on ecosystems[26,27].

MPs could enter the human body primarily through ingestion of contaminated dust particles, while dermal contact has also been identified as a potential exposure pathway, particularly for smaller particles in occupational or highly contaminated environments, with studies reporting their accumulation in human lungs, intestines, placenta, and bloodstream[26,28,29]. While the long-term health effects of microplastic exposure are not yet fully understood, there are concerns about potential respiratory, gastrointestinal, and even carcinogenic risks[30,31].

Furthermore, microplastics often contain chemical additives such as plasticizers (phthalates), bisphenols, flame retardants, and stabilizers, which can leach during environmental degradation and potentially contribute to endocrine disruption, reproductive toxicity, and other adverse health effects[32,33]. In addition, microplastics act as efficient vectors for adsorbing and concentrating environmental contaminants, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and pesticides from surrounding media, thereby increasing the bioavailability and potential toxicity of these pollutants upon human exposure through ingestion[34,35]. These characteristics highlight the importance of assessing microplastic contamination in urban street dust not only in terms of particle abundance and morphology but also regarding associated chemical loads that may exacerbate exposure risks.

Although a previous study in northwestern Iran has investigated micro rubber particles and vanadium contamination in urban street dust[36], to the best of our knowledge, no comprehensive research has yet examined the concentration, physical characteristics, polymer composition, and potential human exposure risks of microplastics specifically in street dust of Urmia city.

Accordingly, the present study aimed to quantify microplastic concentration in Urmia street dust, characterize their physical (size, shape, color, morphology) and chemical (polymer composition) properties, and estimate potential human exposure risks via ingestion, filling a critical gap in microplastic research for this region.

Materials and methods

Study area

Urmia, the capital of West Azerbaijan Province in northwestern Iran, is located at 37.45° N latitude and 45.07° E longitude, at an altitude of 1,332 m above sea level, with a total urban area of approximately 100 km^2[37]. The city has a population exceeding 800,000 people, and lies about 30 km west of Lake Urmia, which has undergone near-complete desiccation in recent decades, contributing to increased regional dust storms, particulate matter transport, and saline dust influx from neighboring countries[38]. Urmia features a semi-arid climate with cold winters (average January temperature ~ −2 °C), hot summers (average July ~ 24 °C), and low annual precipitation (~ 350 mm), resulting in dry conditions that promote dust resuspension and pollutant accumulation on road surfaces.

As Fig. 1A and B land-use and traffic density distribution in Urmia is predominantly residential and commercial in the central and southern parts, with high traffic density on major roads and intersections, limited industrial zones in the northern periphery, and open/green spaces surrounding the city area. These urban characteristics combined with heavy vehicle traffic, road surface abrasion, fossil fuel combustion, construction activities, and occasional regional dust influx make street dust a critical environmental matrix for assessing microplastic contamination in this setting[38]. In the summer of 2024, street dust sampling was conducted from main and secondary streets of Urmia (Fig. 1). Sampling sites were selected based on traffic volume, population density, urban land-use patterns (residential, commercial, and high-traffic zones), and proximity to potential sources such as roads and construction areas to ensure representative coverage of the city.

Sampling

In accordance with Fig. 1, a total of 30 street dust samples were systematically collected from diverse urban locations in Urmia during the summer of 2024 (July–August) for microplastic analysis. Sampling was performed under dry weather conditions to avoid the influence of precipitation on dust accumulation and ensure consistency. All samples were taken exclusively from the asphalt surfaces adjacent to the roadside (curb-side edges) of main roads, secondary streets, and high-traffic intersections. No other surfaces (e.g., concrete sidewalks, soil, or unpaved areas) were sampled.

One discrete single point grab sample was collected per site. No field replicates were taken at individual locations due to logistical constraints and the priority of achieving broad spatial coverage across the city. The number and distribution of sampling sites (30 locations) were determined using a stratified approach based on traffic volume (high, medium, low), land-use patterns (residential, commercial, and high-traffic zones), population density, and proximity to potential microplastic sources (major roads, intersections, and construction

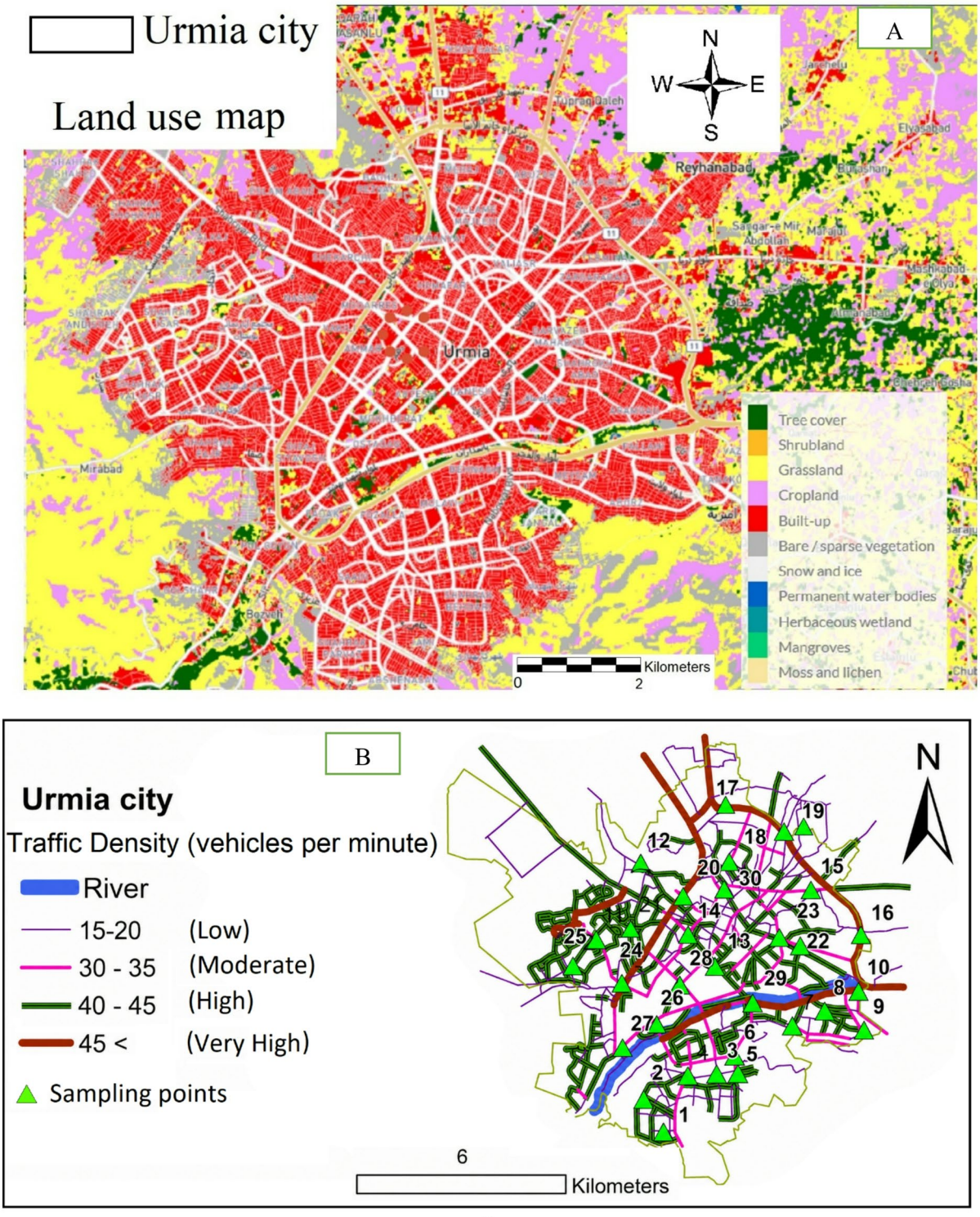


Fig. 1. (**A**) Land-use and land-cover map of Urmia City derived from the ESA WorldCover 2021 dataset (10 m spatial resolution). The map was processed and visualized using ArcGIS 10. 8. 2 (ESRI, Redlands, CA, USA). Source: ESA WorldCover 2021 (© ESA WorldCover project 2021 / Contains modified Copernicus Sentinel data processed by the ESA WorldCover consortium. (**B**) Traffic density map of Urmia city showing the spatial distribution of the 30 sampling sites. Sampling points were selected using a stratified approach based on traffic density (Low: 15–20, Moderate: 30–35, High: 40–45, and Very High: >45 vehicles per minute) and major land-use categories. This design aimed to ensure representative coverage of different urban environments and potential microplastic sources. Source: Generated by the authors using ArcGIS Desktop 10.8.2 (ESRI, Redlands, CA, USA) based on field surveys and the study sampling framework.

areas), as shown in Fig. 1A and B. This design aimed to provide reasonable representativeness of the urban environment.

At each site, a standardized 1 m^2 area was defined on the asphalt surface. The entire collected volume (~ 200 g) was thoroughly homogenized by manual stirring and shaking in the collection container to minimize within-site heterogeneity before subsampling. Then, a 50-gram representative subsample was taken for further processing. This mass (200 g) was collected as a representative subsample from the defined area, regardless of the total dust available on the surface, to maintain uniformity across sites and avoid bias from varying dust thickness. The collected dust was immediately transferred into pre-cleaned, sealed, labeled non-plastic (stainless steel) containers and transported to the laboratory under controlled conditions to prevent external contamination[22,36,39].

Microplastic concentrations are reported as numbers particles per gram of dry dust. Although the fixed 1 m^2 sampling area allows for future conversion to particles per unit area, the lack of field replicates at each site means that small-scale spatial heterogeneity within sites could not be quantified. This limitation is acknowledged and further discussed in the discussion section.

Preparation, extraction, and enumeration of microplastics

First, the collected street dust sample (~ 200 g per site) was thoroughly homogenized by manual stirring and shaking in the sealed container to ensure uniformity and minimize heterogeneity before subsampling. Then, a 50 gram subsample was taken and sieved using a 5 mm stainless steel sieve to remove larger components such as rocks, vegetation, and coarse debris. A 5 mm stainless steel sieve was used as the upper size limit to align with the widely accepted definition of microplastics (< 5 mm in at least one dimension)[40,41]. Due to the fine nature of street dust, larger particles (> 5 mm) were extremely limited (classified as coarse debris), and no particles in the 2–5 mm range were observed during sieving or subsequent visual examination, confirming that the sieve size did not substantially affect the microplastic fraction.

This subsampling approach prior to sieving was employed to optimize laboratory processing efficiency, reduce reagent volumes (e.g., H_2O_2 and $ZnCl_2$), and minimize handling-related contamination or loss, while the prior homogenization step ensured the subsample remained representative of the original material[22,26,42].

To eliminate organic matter, 15 g of the sieved dust were mixed with 35 mL of 30% hydrogen peroxide (H_2O_2) and incubated at room temperature for up to eight days (or until visible bubbling ceased and organic material was fully digested). The extended digestion time was necessary due to the high content of complex organic matter (e.g., humic substances, plant debris, soot) in street dust samples, which required prolonged exposure for complete removal. This approach is consistent with protocols used for complex matrices in previous studies[26,42,43]. The 15 g subsample was selected to balance effective organic digestion in high-organic-content street dust while preventing filter overloading during subsequent filtration steps. The entire sample was processed in one batch; after digestion, it was vacuum-filtered in two stages (coarse filtration to remove residues and final 0.45 µm filtration after density separation), and the complete filter surface was systematically examined under the binocular microscope (up to 200× magnification) without subsampling, ensuring all suspected microplastics were counted and characterize.

Residual H_2O_2 was removed by vacuum filtration through filter papers. For microplastic separation, 50 mL of zinc chloride ($ZnCl_2$) solution (density 1.6 g/cm^3) was added to each sample in a new beaker. The mixture was stirred at 350 rpm for five minutes and allowed to settle for 90 min to enable heavier materials to sink. The supernatant was centrifuged at 4,000 rpm for three minutes, vacuum-filtered through a 0.45 µm filter paper, and rinsed with distilled water to prevent $ZnCl_2$ crystal formation. Filters were dried in a metal cabinet at room temperature for several days to minimize contamination. Dried filters were transferred to Petri dishes, and microplastics were counted and measured under a binocular microscope (up to 200× magnification). Particles were classified based on visual and physical characteristics (shape, hardness, luster, and color)[22,23,42,44].

- Shape: Classified into four categories: fiber, film, fragment, or sphere.
- Color: Grouped into: white-transparent, yellow-orange, red-pink, blue-green, or black-grey.
- Size: Measured and classified based on length using a 250 micrometer probe.

Morphology of microplastics

The morphology (shape and appearance) of the MPs was determined using a Scanning Electron Microscope (SEM). This device, operating at a magnification of 300x to 2400x, provides a detailed view of the particles' features.

Polymer types of the identified microplastics were confirmed using micro-Raman spectroscopy, with representative spectra. This technique records the chemical spectrum of the particles by illuminating them with two lasers. These spectra are then compared with the Open Specy online database to identify the specific polymer type. For the Raman analysis, approximately 10% of the particles that visually resembled MPs were selected. These particles were meticulously transferred to a copper adhesive and sent to the Iran color research institute for analysis. While a specific recovery rate test was not performed within this study, the reliability of the employed SEM–µ-Raman methodology is supported by findings in the broader scientific literature. Previous research utilizing similar analytical approaches has established robust recovery rates, indicating the general efficacy and precision of these techniques for microplastic analysis. Visually identified candidate microplastic particles were subjected to further chemical characterization using µ-Raman spectroscopy. Due to the large number of candidates, a representative subset, approximately 10% of the total visually identified particles, was selected for Raman analysis. The selection of this subset was based on [e.g., particle

size, morphology, color, spatial distribution across the sample] to ensure it was representative of the entire population of visually identified particles. Raman spectroscopy confirmed the chemical identity of these selected particles as microplastics. The confirmation rate observed within this analyzed subset was then extrapolated to the total count of visually identified particles to estimate the overall microplastic abundance. This extrapolation assumes that the chemical composition of the non-analyzed visually identified particles is similar to that of the analyzed subset.

Quality control and blank sample analysis

To ensure the accuracy and reliability of the MP quantification, all sample preparation and extraction steps were conducted under strict contamination control protocols within a dedicated laboratory environment. To minimize potential contamination from plastics and environmental fibers, work surfaces were meticulously cleaned with ethanol, and all windows and doors were kept closed during sample processing. Researchers consistently wore lab coats, disposable gloves, and face masks. All reagents and distilled water used were pre-filtered, and all glassware and equipment were thoroughly washed and acid-rinsed.

Crucially, to assess for potential secondary contamination originating from the laboratory air, two open containers, each holding 100 mL of filtered water, were strategically placed in the workspace throughout the entire sample processing and extraction procedure. These open containers served as air blank samples. Following the completion of the sample extraction, the filtered water from these blank containers was subjected to the exact same microscopic observation and analytical procedures as the actual environmental samples.

Analysis of these air blank samples revealed a negligible amount of one microplastic particle, smaller and morphologically different from those found in the environmental samples, which was excluded from the final count. This finding indicates that contamination from the laboratory air during the study period was minimal and did not impact the accuracy of the microplastic counts derived from the street dust samples. These rigorous measures, including the analysis of blank samples, collectively guarantee the validity and dependability of the reported data.

Human potential exposure risks

Potential exposure to MPs through dust ingestion was estimated for adults and children under normal and acute exposure scenarios. The assessment was based on standard dust ingestion rates reported in previous studies, including 100 and 330 mg day^{-1} for adults and 200 and 1000 mg day^{-1} for children. Daily exposure was calculated by multiplying the MPs concentration measured at each sampling site by the corresponding ingestion rate, while annual exposure was estimated by multiplying daily exposure values by 365 days[22,45]. The daily and annual intake of microplastics was estimated using the ingestion rates recommended by the USEPA[46], which specify average values of 200 mg/day for children aged 1–6 years and 100 mg/day for adults (Eq. 1). These ingestion rates correspond to typical exposure conditions, while for acute exposure scenarios, a value of 1 g/day was proposed for children during outdoor activities. Additionally, based on the soil screening guidance provided by Harris and Harper (2004), an ingestion rate of approximately 330 mg/day was considered for construction and outdoor workers. Using these reference values, together with an assumed average of 200 working days per year, the annual occupational exposure to microplastics was calculated[22,45]. However, the health risk assessment in this study was exclusively based on ingestion counts and conducted as a preliminary screening and exposure risk by MPs. Equation (1):

$$\text{Ingested MPs (per day)} = (\text{MPs Abundance}/1000\ \text{mg}) \times \text{IngestionRate (mg/day)} \quad (1)$$

Data analysis

The statistical analysis of data collected at sampling stations and their interrelationships involved descriptive statistics, including minimum, maximum, percentile, median, mean and standard deviation analysis using Stata 14.

The normality of microplastic abundance data was evaluated using the Shapiro–Wilk test. Sampling stations were categorized into traffic intensity groups (low, moderate, and high traffic) based on the urban traffic map of Urmia city. Differences in microplastic abundance among traffic categories were assessed using the Kruskal–Wallis test. Comparative interpretations were considered statistically significant at $p < 0.05$.

Additionally, spatial analysis was performed using ArcGIS 10.8.2, employing the kriging interpolation method to generate independent raster layers for visualization and further analysis.

Results and discussion

Quantity, size distribution, and color of microplastics

In the present study, according to Table 1, a total of 4,875 microplastic particles ranging in size from 100 to 5,000 µm were visually identified and counted per kilogram of collected samples. The mean abundance of total MPs in street dust samples was 0.97 ± 2.02 particles/g, with a coefficient of variation (CV) of 207%, indicating a high degree of spatial variability. Among different shapes, fibers were the most dominant type, showing an average concentration of 1.3 ± 2.6 particles/g, accounting for 79% of the total MPs, while fragments exhibited a lower mean value of 0.42 ± 1.3 particles/g (21%).

Shapiro–Wilk analysis demonstrated that microplastic abundance data did not follow a normal distribution ($p < 0.05$). Accordingly, non-parametric analyses were performed. Kruskal–Wallis testing revealed significant differences in microplastic abundance among traffic intensity categories ($p < 0.05$), with higher concentrations generally observed at stations located within high-traffic urban zones. This pattern suggests that traffic related urban activities may contribute substantially to microplastic accumulation in the study area.

MPs properties	%	Total (*N*)	Min (*N*)	Max (*N*)	Mean (*N*)	Med. (*N*)	S.D.	CV (%)
All MPs	100	289	0	17	0.97	0	2.02	207
Shape								
Fiber	79	227	0	17	1.3	0.5	2.6	171
Fragment	21	62	0	9	0.42	0	1.3	305
Color								
White-Transparent	71	204	0	17	3.65	2.5	3.35	71
Yellow-	3	10	0	2	0.17	0	0.35	3
Blue-green	8	23	0	2	0.38	0	0.51	136
Red	7	21	0	4	0.34	0	0.69	7
Black-gray	11	32	0	5	0.53	0	0.90	11
Size (μm)								
L < 100	13	37	0	1.23	5	1	1.65	134
100 ≤ L < 250	25	72	0	2.48	10	2	2.58	104
250 ≤ L < 500	29	84	0	2.87	11	2	2.67	93
500 ≤ L < 1000	16	45	0	1.50	5	1	1.41	94
1000 ≤ L	18	51	0	1.70	10	1	2.10	124

Table 1. Descriptive statistics of microplastic counts based on shape, size, and color (N: Number MPs per g street dust).

Regarding color distribution, white-transparent MPs had the highest mean abundance (3.65 ± 3.35 particles/g, 71%), followed by black-gray (0.53 ± 0.90 particles/g, 11%), blue-green (0.38 ± 0.51 particles/g, 8%), red (0.34 ± 0.69 particles/g, 7%), and yellow (0.17 ± 0.35 particles/g, 3%). The distribution of colors showed the following decreasing order of abundance: colorless > black > red > green > blue > yellow. The predominance of colorless microplastics area may be attributed to their widespread use in packaging and transportation of both consumable and non-consumable goods. A comparison with other studies provides valuable context. In Assaluyeh, a total of 220 airborne fibrous MPs were collected, with an almost equal distribution between urban and industrial zones. After normalization to airflow and screening with $PM_{2.5}$ filters, microplastic concentrations ranged between 0.3 and 1.1 particles per cubic meter of air. The dominant color in Assaluyeh was transparent white, accounting for more than 70% of the particles in industrial areas and 53% in urban regions. Only a small fraction of blue–green and yellow–orange MPs were observed. A key difference between the two areas was the higher presence of black MPs in the industrial zone (33 particles) compared to the urban zone (9 particles)[23].

In Urmia as Fig.s 2 and 3, the most frequent MPs were also colorless (40%), followed by black (22%), consistent with the findings from Assaluyeh city. Microplastic particles were clearly observed on all filters examined under the microscope, though their fragile and fine structure imposed limitations in precise quantification and classification. In Urmia, microplastic concentrations ranged from 100 to 17,000 items per 1,000 g of street dust, indicating a higher level of contamination compared to the airborne samples in Assaluyeh. Such discrepancies are likely influenced by environmental conditions, human activities, and sampling methodologies. As shown in Figs. 2 and 3, the MPs were visually identified under a binocular microscope and their morphology was analyzed using SEM.

To identify the polymer types of microplastics, μ-Raman spectroscopy was performed on representative particles. As shown in Fig.S1, eight different polymer types were detected, including Polystyrene (PS), Polyoxymethylene (POM), Polyester (PES), Polyethylene terephthalate (PET), Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC), and Ethylene-Propylene copolymer (EP). Fibers were predominantly composed of polyester and polypropylene, while fragments mainly consisted of polyethylene and polystyrene. It appear, the identified polymers are consistent with common sources such as textile fibers, packaging materials, automotive components, and plastic waste, which are prevalent in urban environments. The diversity of polymer types identified in this study reflects the multiple sources of microplastics in Urmia, including traffic-related (tire wear, road paint), domestic (textiles, packaging), and construction activities. The predominance of polyester and polypropylene in fibrous particles is consistent with the widespread use of synthetic textiles in the region.

According to Fig. 3, studying the morphology of MPs using SEM images provides precise information about their physical characteristics, such as shape, size, and surface texture. These images reveal that the MPs in question have irregular shapes and uneven surfaces with deep cracks, which are the result of physical and mechanical processes like breakage, abrasion, and weathering. Additionally, the detailed texture of peeling surfaces and fragmented layers at higher magnifications indicates severe degradation and erosion of these particles. This analysis contributes to a better understanding of the origin and fate of these pollutants in the environment.

Further comparison with Bushehr highlights additional differences. In that study, MP and dust particles were analyzed separately by size, shape, and color using fluorescence microscopy. Reported color proportions included red/pink (56.21%), black/gray (20.20%), white/transparent (11.9%), blue/green (7.77%), and yellow/orange (3.9%). The highest concentration reached 876 microplastic items per 10 g of dust, which is markedly

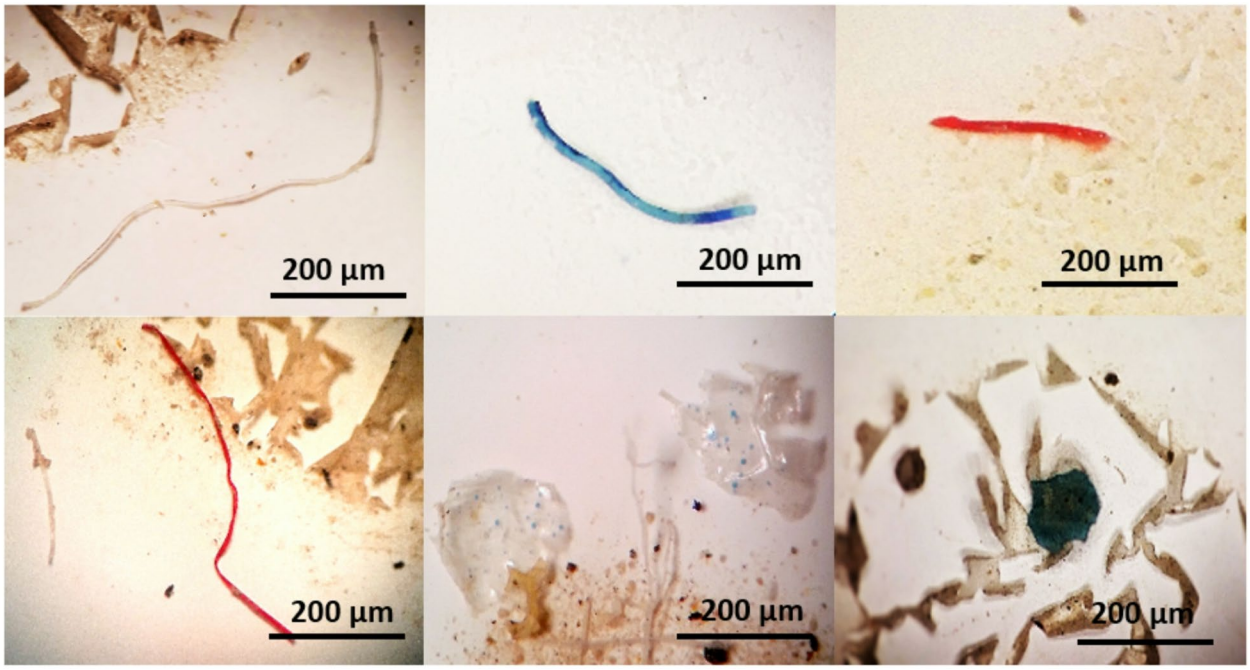


Fig. 2. Representative images of microplastics identified using an optical microscope.

higher than the levels observed in Urmia[39]. Importantly, over 75% of the identified MP in Bushehr were fibers, likely originating from textiles and household materials such as carpets, curtains, and clothing. Spatial distribution analysis indicated that northern Bushehr, characterized by higher traffic, industrial activity, and commercial density, exhibited greater microplastic contamination than the predominantly residential southern part.

Overall, the data suggest that microplastic contamination levels vary substantially across urban and industrial settings, driven by local environmental conditions, anthropogenic pressures, and analytical techniques. Since all sampling sites were located on street surfaces, traffic-related sources (such as tire wear, brake abrasion, and vehicle related plastic debris) are likely to play an important role in the observed distribution. However, because traffic and commercial activities are spatially correlated in urban settings, distinguishing the specific contribution of each factor requires further source apportionment studies. These findings underscore the necessity of continuous monitoring and the development of management strategies to mitigate microplastic contamination in both urban and industrial environments.

Elevated microplastic concentrations in central Urmia, particularly near major roads and commercial zones, suggest that traffic and intensive human activities are important contributing factors. The dominance of fibers and the presence of various colors (especially transparent) along with polymers such as polyester and polypropylene (identified in one representative sample) indicate synthetic textiles and urban waste as notable sources. Overall, traffic-related emissions and improper plastic waste management appear to be the main drivers of microplastic pollution in Urmia street dust.

The data collected from Urmia city revealed microplastic concentrations in dust ranging from 100 to 17,000 particles per kilogram, which is higher than values reported in Victoria (529 particles/kg) and even industrial samples from Melbourne (1,130 particles/kg)[47]. This discrepancy may be attributed to differences in pollution sources, population density, agricultural practices, and waste management. In both Urmia and Australian studies, fibers were the dominant shape, with particle sizes mostly below 2 mm; however, in Urmia more than 60% of fibers were smaller than 500 µm. In comparison, a study in Tehran showed particle sizes between < 100 µm and 5 mm, with 33.7% in the 250–500 µm range and 25.7% larger than 1000 µm, while color distribution also varied, as black and transparent were dominant in Urmia, whereas black, yellow, and transparent were most common in Tehran. Shape composition differed as well, with granules (65.9%) and fibers (33%) prevailing in Tehran, while Urmia samples were mostly fibers. Furthermore, advanced techniques such as FTIR and GC–MS-Pyr were applied in Tehran, enabling detailed polymer identification (e.g., PET, PVC, PP), while in Urmia polymer types remain to be characterized. Overall, both Urmia and Tehran[22].

Spatial variations in microplastic distribution

The microplastic abundance map was generated using GIS software with the Ordinary Kriging interpolation method. This technique allowed us to estimate microplastic concentrations in unsampled locations, thereby depicting the spatial distribution of contamination. The interpolation was performed in ArcGIS Desktop 10.8.2 (ESRI, Redlands, CA, USA) using microplastic concentration data collected from the sampling sites in the present study.

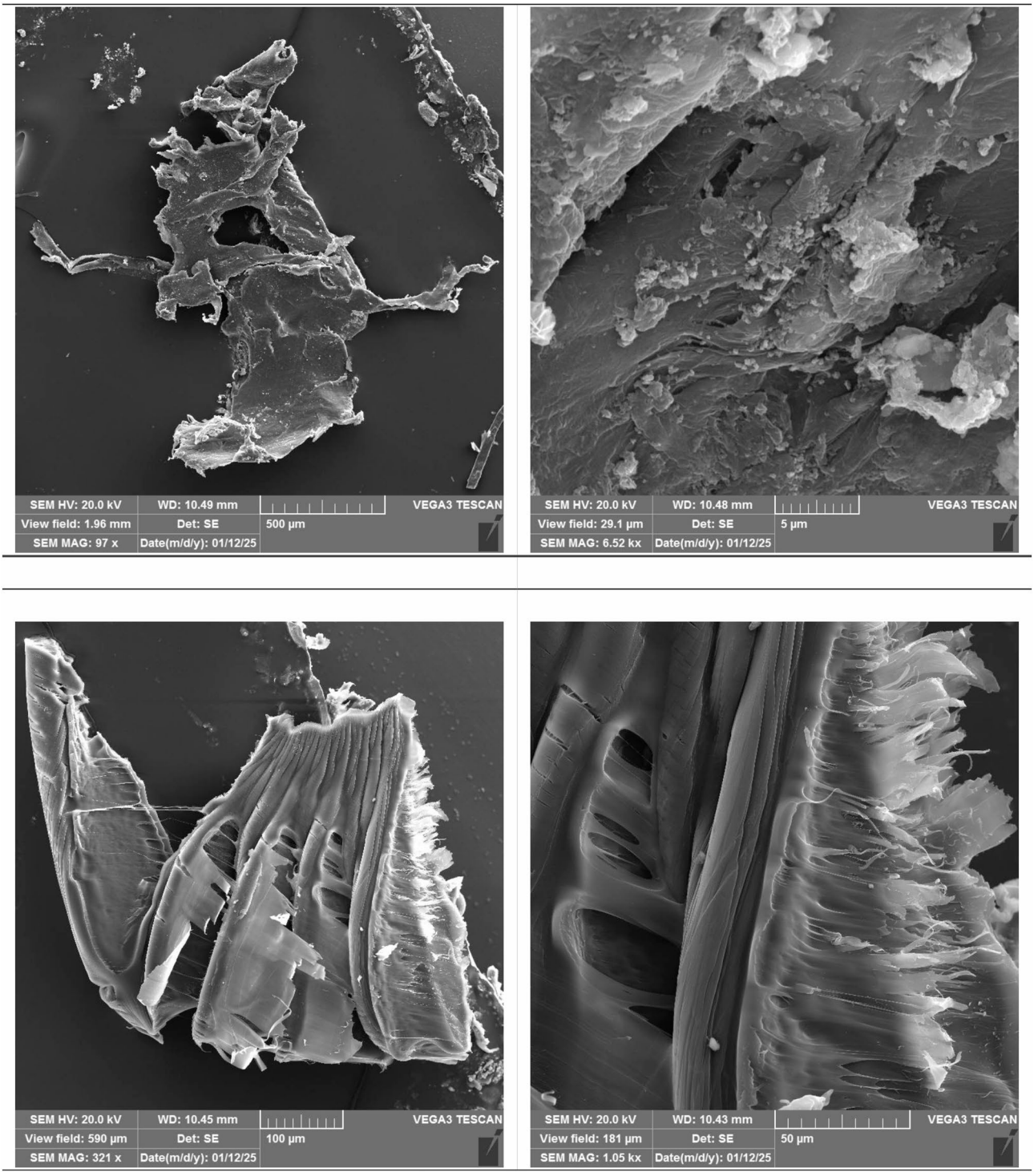


Fig. 3. SEM micrographs showing the morphology of identified microplastics.



Fig. 3. (continued)

For the classification of values into high and low categories displayed by color gradients, we employed a equal interval classification approach. Specifically, values such as 12 particles/g were designated as high and 1 particles/g as low because these represent significant concentrations compared to other sampled sites. According to Fig. 4A and B, this microplastic zoning map shows the concentration distribution in Urmia city using raster data and color classification, clearly illustrating the pollution pattern. It is important to acknowledge that spatial interpolation inherently entails a degree of uncertainty driven by sampling point distribution and intrinsic data variance. To quantify this uncertainty and validate the reliability of the Kriging model, a cross-validation approach was employed. The resulting Root mean square error (RMSE) was found to be reasonably low relative to the overall range of the measured dataset, demonstrating an acceptable level of accuracy and confidence for the generated spatial maps. High-concentration points, marked in dark red and intense orange, are mainly located in the city center, especially along the river and main road networks. These areas show the highest level of MPs, likely due to dense human activity and heavy traffic. In contrast, low-concentration points, marked in yellow, are mostly found on the northern and southern outskirts of the city. In these areas, the level of MPs reaches its lowest point. This geographical distribution clearly indicates that microplastic concentration increases from the outskirts toward the city center, with the highest pollution risk concentrated in busy and populated areas.

Also, results showed a statistically significant difference in total MPs abundance between traffic density groups ($p = 0.012$). Subsequent Dunn's post-hoc test indicated that high and very high traffic zones had significantly higher microplastic concentrations compared to low traffic areas ($p = 0.008$). A similar pattern was observed between commercial/mixed land-use areas and residential outskirts ($p = 0.019$).

Factors such as sampling methods, environmental differences, and potential sources of pollutants can explain spatial variations in MPs distribution. For example, in Urmia, agricultural activities, waste disposal, and urban plastic use are likely to play significant roles (Fig. 4A). In contrast, the dominant colors reported in Bushehr (red/pink and black/gray) suggest different sources or types of pollution compared to Urmia[39]. The results from Bushehr highlight the strong influence of traffic and industrial activities on microplastic abundance, whereas in Urmia, agricultural inputs and waste accumulation may be more relevant. These findings emphasize the need for localized actions and region-specific policies to reduce pollution. Moreover, they demonstrate that the composition and sources of MPs can vary greatly between cities and regions. Advanced techniques such as fluorescence and polarized light microscopy, which were applied in Bushehr, could also be used in future studies in Urmia to improve identification accuracy.

Another study in Australia reported that roads and transportation are major sources of microplastic release into aquatic environments. The primary sources identified included tire wear particles, thermoplastic elastomers used in road markings, and polymers incorporated into asphalt. Research conducted in various Australian cities, including Melbourne, Brisbane, and urban and rural areas of Victoria, showed that microplastic concentrations in urban road samples were higher than those in rural areas[48]. Overall, more than 40% of microplastic inputs into aquatic environments have been attributed to road dust and street litter[49].

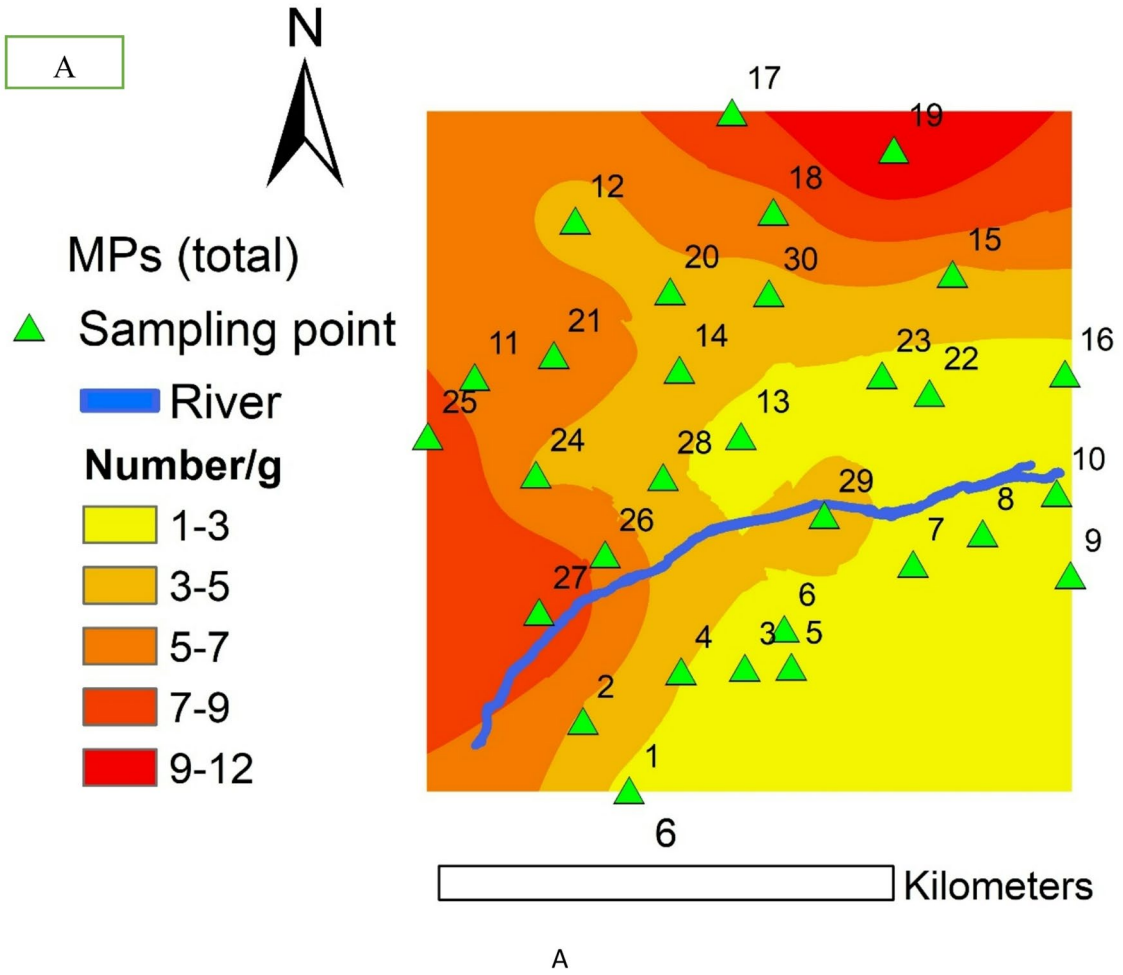


Fig. 4. Spatial distribution of total MPs (**A**) and transparent MPs (**B**) concentrations (numbers per gram of dry dust) in street dust across Urmia city using Ordinary Kriging interpolation. Maps were generated by the authors in ArcGIS Desktop 10.8.2 (ESRI, Redlands, CA, USA) based on microplastic concentration data collected from the sampling sites in the present study.

While the Urmia study indicated very high concentrations of MPs in soils, the results from Australia placed greater emphasis on transportation and road-related sources as the main contributors to contamination. These differences highlight the importance of localized and site-specific actions for reducing environmental pollution. In Urmia, focusing on waste management, reducing single-use plastics, and investigating agricultural and urban sources could provide effective mitigation strategies. The study of MPs in Tehran street dust revealed unique characteristics, including distinct distributions of particle size, shape, and color. Notably, the limited use of advanced analytical techniques in this study was remarkable. In Tehran, microplastic sizes ranged from less than 100 µm to 5 mm, with a large proportion (33.7%) falling within the 250–500 µm range, while particles larger than 1000 µm accounted for about 25.7%[22].

Estimation of microplastic potential exposure risks

To assess the potential exposure risks associated with microplastic ingestion, it is necessary to estimate the number of particles ingested on a daily and annual basis[22,50,51]. These estimations are based on assumptions such as the amount of dust present on hands and the frequency of hand-to-mouth transfer. As Table 2, the results indicate that, under the normal scenario, adults ingest between 37 and 1,150 particles annually, while in the acute scenario this increases to between 244 and 2,894 particles per year. For children, the maximum ingestion levels under the normal and acute scenarios are estimated at 2,301 and 11,505 particles per year, respectively. The annual ingestion in children under acute conditions is nearly four times higher than in adults, highlighting their greater risk. In comparison, a study conducted in Tehran reported values approximately three times higher, which aligns with the findings of the present study[22]. Particle size also plays an important role in this risk; smaller particles (< 50 µm) have a greater likelihood of unintentional ingestion. In this study, most MPs were found within the size range of 100–500 µm. Furthermore, MPs can adsorb heavy metals and organic pollutants.

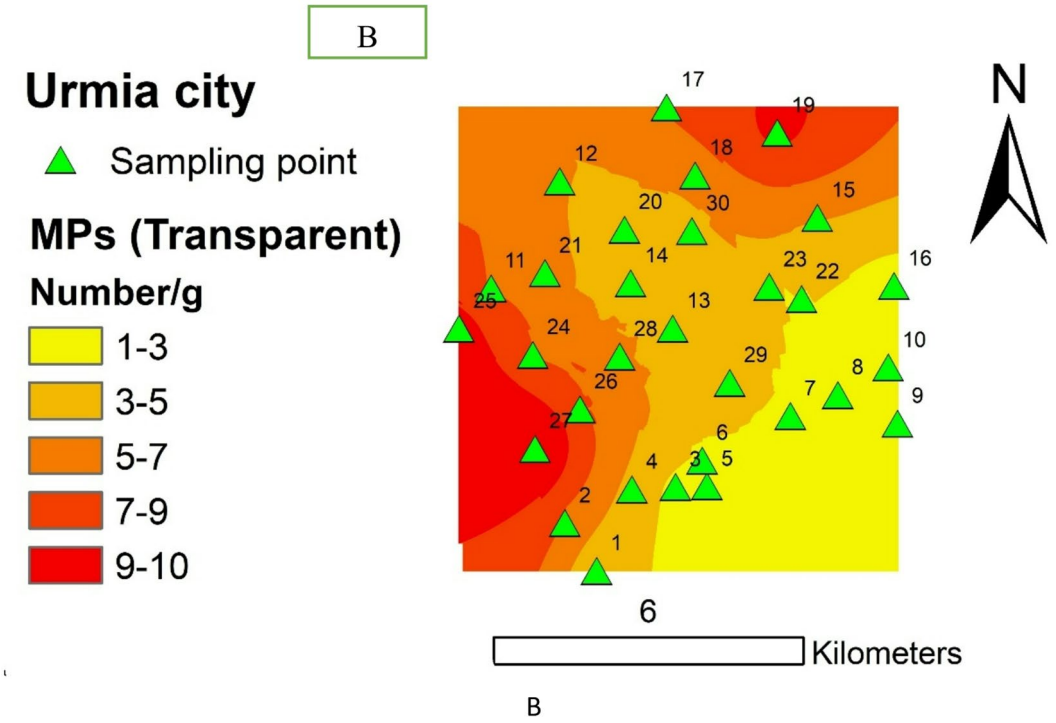


Fig. 4. (continued)

However, the current knowledge regarding the toxicity and digestion of plastic additives and polymers in the human body remains very limited.

The primary limitation of this study is its focus solely on ingestion counts for health risk assessment as a preliminary screening, which may not provide a comprehensive picture of potential exposures.

A limitation of the present study is the lack of field replicates at each sampling site. Although the collected samples were homogenized before subsampling to improve representativeness, small-scale spatial heterogeneity within each 1 m^2 area may still exist in street dust due to variable traffic patterns and local sources. Therefore, the results should be interpreted with caution regarding fine-scale spatial variability. Future studies are recommended to include replicate sampling at each location to enhance data reliability.

This study revealed that street dust in Urmia is heavily polluted with MPs, with this pollution being concentrated in the city center and high-traffic areas, posing a serious health risk, especially for children. To combat this issue, it is recommended to improve plastic waste management programs, reduce the use of single-use plastics, and increase public awareness about waste segregation and the dangers of microplastic pollution.

Conclusion

This study revealed that street dust in Urmia is heavily polluted with MPs, highlighting significant urban environmental degradation. The morphological characteristics and spatial distribution patterns clearly indicated that high-traffic zones and areas with dense human activity act as major hotspots for MP accumulation. Furthermore, the health risk assessment demonstrated that children are disproportionately vulnerable to MP ingestion compared to adults, raising critical public health concerns.

These findings underscore the urgent need for targeted municipal policies to mitigate MP pollution. Implementing strategies such as optimizing street sweeping practices, upgrading urban waste management infrastructure, and enforcing stricter regulations on single-use plastics are essential at both local and regional levels. Given the identified health risks, future research should prioritize investigating the long-term ingestion toxicity of urban dust MPs and monitoring their seasonal variations to develop more effective environmental and public health interventions.

	MPs adults				MPs children			
	Normal exposure (100 mg day^{-1})		Acute exposure (330 mg day^{-1})		Normal exposure (200 mg day^{-1})		Acute exposure (1000 mg day^{-1})	
Sampling site	Per day	Per year	Per day	Per year	Per day	Per year	Per day	Per year
1	0.6	219	2.0	723	1.2002	438	6	2190
2	0.8	292	2.6	964	1.6004	584	8	2921
3	0.3	110	1.0	362	0.6006	219	3	1096
4	0.7	256	2.3	844	1.4008	511	7	2556
5	0.9	329	3.0	1085	1.801	657	9	3287
6	0.6	219	2.0	723	1.2012	438	6	2192
7	0.4	146	1.3	483	0.8014	293	4	1463
8	0.7	238	2.1	784	1.3016	475	7	2375
9	0.6	219	2.0	724	1.2018	439	6	2193
10	0.4	146	1.3	483	0.802	293	4	1464
11	0.5	183	1.7	604	1.0022	366	5	1829
12	0.6	219	2.0	724	1.2024	439	6	2194
13	0.1	37	0.3	122	0.2026	74	1	370
14	1.4	512	4.6	1688	2.8028	1023	14	5115
15	0.5	183	1.7	604	1.003	366	5	1830
16	0.6	220	2.0	725	1.2032	439	6	2196
17	1.8	658	5.9	2170	3.6034	1315	18	6576
18	0.7	256	2.3	845	1.4036	512	7	2562
19	3.2	1150	10.4	3797	6.304	2301	32	11,505
20	0.9	329	3.0	1086	1.804	658	9	3292
21	1.8	658	5.9	2171	3.6042	1316	18	6578
22	0.8	293	2.6	966	1.6044	586	8	2928
23	0.6	202	1.8	665	1.1046	403	6	2016
24	0.2	74	0.7	244	0.4048	148	2	739
25	2.4	877	7.9	2894	4.805	1754	24	8769
26	1.6	585	5.3	1930	3.2052	1170	16	5849
27	2.4	877	7.9	2894	4.8054	1754	24	8770
28	0.6	220	2.0	726	1.2056	440	6	2200
29	1.4	512	4.6	1690	2.8058	1024	14	5121
30	1.0	366	3.3	1208	2.006	732	10	3661
Mean	1.0	352.8	3.2	1164.2	1.9	705.6	9.7	3527.9
Median	0.7	264.3	2.4	872.2	1.4	528.6	7.2	2643.1

Table 2.. Estimated potential exposure to MPs through dust ingestion for adults and children under normal and acute exposure scenarios.

Data availability

The datasets generated and analyzed during the current study were available from the corresponding author on reasonable request.

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Author contributions
PA; writing, investigation, formal analysis. SH; writing – original draft, validation, software. RF; writing – review & editing, methodology, investigation. AM; writing – review & editing, writing – original draft, visualization, validation, supervision, software, resources, project administration, methodology, investigation, funding acquisition, formal analysis, data curation, conceptualization.

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Declarations

Competing interests
The authors declare no competing interests.

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