Microplastic occurrence in urban and industrial soils of Ahvaz metropolis: a city with a sustained record of air pollution

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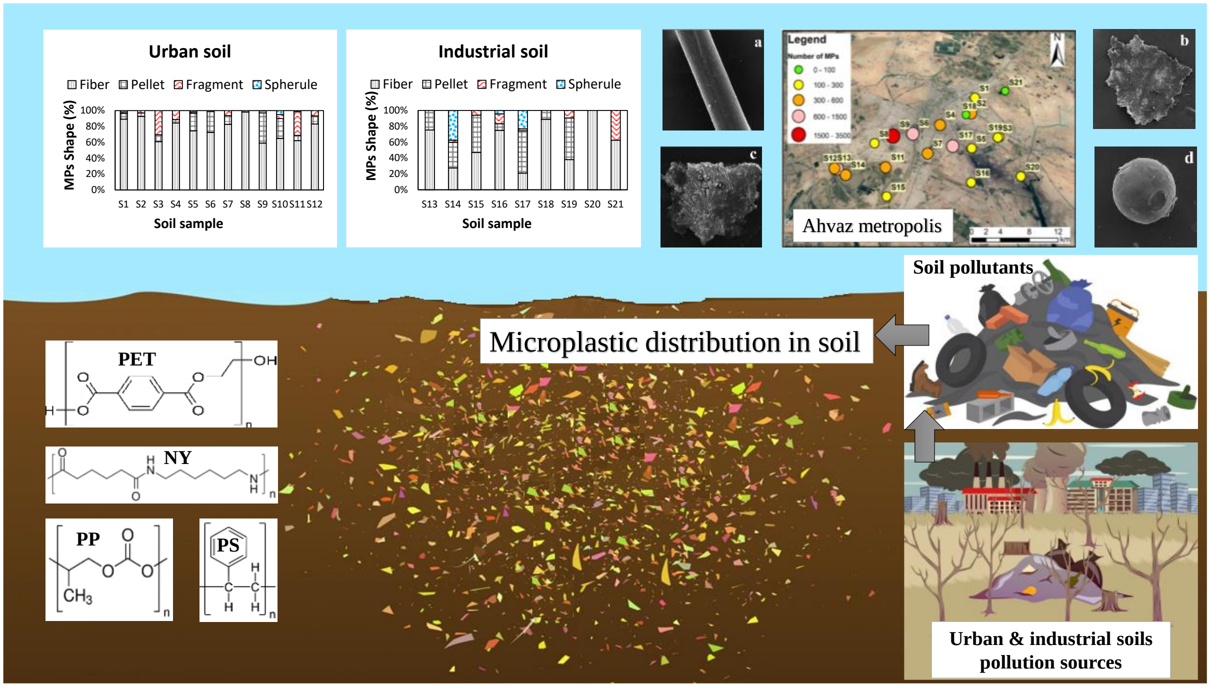
Abstract

This study investigates, for the first time, the concentration, distribution, fate and chemical composition of microplastics (MPs) in urban and industrial soils of Ahvaz metropolis, SW Iran. MP concentrations ranged from 100 to 3135 and 80 to1220 unit·kg^{-1} in urban and industrial soils, respectively, with corresponding means of 619 and 390 unit·kg^{-1}. The most contaminated urban sites were located in the city center. Precisely these areas were affected by insufficient sanitation infrastructure including sewer systems, surface runoff collection and sewage treatment, and also high traffic loading in a commercial zone. MPs were found in various shapes, colours and sizes. In particular, microfibres (white-transparent and < 250 µm) were the most abundant MPs found in urban (70%) and industrial (55%) soils. Based on the weathering observed in the MPs, a large number of them originated from the fragmentation of other plastics and could have been photobleached. Polyethylene terephthalate and nylon were the dominant polymers in the MPs found in both industrial and urban soils and they could originate from textiles and tyres.

Keywords: Microfibre; PET; Photobleached MPs; Textile; Iran

- Urban soils had higher concentration of microplastics than industrial soils.
- Fibre microplastics and those <250 µm were dominant.
- Microplastics had greater spatial distribution in the centre and west of Ahvaz.
- Polyethylene, terephthalate and nylon were main polymers in the microplastics.



1. Introduction

Microplastics (MPs), which can be defined as synthetic solid particles or polymer matrices with a size range of 1 µm - 5 mm and insoluble in water (Arthur et al., 2009), are emerging and ubiquitous contaminants that have become an environmental challenge (Afrin et al., 2020). MPs can enter the environment through processes that are in place to reduce pollution such as municipal wastewater treatment plants (Dris et al., 2016) and urban landfills (Afrin et al., 2020), among other sources. Plastics and MPs persist in the environment due to their relatively inert nature. However, physical weathering, photo-oxidation and slow biological decomposition can break down plastics into smaller particles (Ding et al., 2020), which can enhance the accumulation of nanoplastics (plastics with 1-1000 nm in size (Gigault et al., 2018)) in the environment. MPs degrading into nanoplastics could be a greater problem because nanoplastics can reach and affect the function of biological membranes, macromolecules, and biofilms, and overall, cause adverse effects to aquatic organisms (Kihara 2021). There is no sufficient data to compare the toxicity of micro and nanoplastics and their impact on humans (Kihara et al., 2021; Banerjee and Shelver, 2021). The toxicity of plastics is likely to be affected by their size although this aspect is still unclear and may vary with cell type (Banerjee and Shelver, 2021).

Soil can be a sink of MPs, though their fate in this medium has been scarcely evaluated (Rillig et al., 2012; Ding et al., 2020). Recent studies have found that MPs in soil can influence the soil-plant system by affecting the structure of the soil and the water dynamics in it, its microbial activity and availability of nitrogen (Liu et al., 2017; de Souza Machado et al., 2019; Iqbal et al., 2020; Yi et al., 2020; Leifheit et al., 2021). Overall, these changes caused by MPs impact plant growth (Qi et al., 2018; de Souza Machado et al., 2019). The extent of the effect of MPs on crops was different for different polymers (de Souza Machado et al., 2019). MPs can affect the structure of burrows made by earthworms and this can have implications in the leaching of MPs to groundwater (Lwanga et al., 2017). On the other hand, the presence of earthworms showed a marked positive impact on the growth of wheat in soil that had plastic residues (Qi et al., 2018).

The presence of MPs in urban and industrial soils was identified as an important gap in knowledge in 2012 and of special interest for policymakers and regulatory bodies (Rillig et al. 2012). Since then, studies have found the origin of MPs in these types of soils, and these involve a variety of anthropogenic activities and environmental processes: atmospheric deposition; littering; degradation of tyres; their presence in sewage sludge and wastewater effluents; and degradation of plastic mulches used in agriculture (Liu et al., 2017; De Souza Machado et al., 2018; Bläsing and Amelung, 2018; Zhang et al., 2020a; Mbachu et al., 2020; Huang et al., 2020). There has been the scarcity of quantitative data of MPs in soil caused in part by the analytical difficulty of their determination in soil (Rillig et al. 2012). In a study carried out in Campeche, Mexico, MPs were found an average concentration of 0.87 ± 1.9 MPs g^{-1} in urban residential soils (Huerta Lwanga et al., 2017). In Australian industrial soils, the average concentration of MPs was 4191 mg kg^{-1}, varying between 300 and 67500 mg kg^{-1} (Fuller and Gautam, 2016). The presence of MPs at Guiyu town, China, was 0 - 34100 MPs kg^{-1} (Chai et al. 2020) and found that e-waste dismantling sites were hotspots and main sources of MPs. Contamination of MPs in urban soils around a landfill site in Dhaka, Bangladesh confirmed the presence of low-density polyethylene (LDPE) and high-density polyethylene (HDPE) MPs and demonstrated that landfill can be a source of MPs dispersing to the surrounding soils (Afrin et al., 2020). MPs in soil can be transported and circulated to other environmental compartments and may reach water resources, sediments and living organisms (Facchinelli et al., 2001; Keshavarzi et al., 2019; Afrin et al., 2020). It is still unknown if MPs will be incorporated in the dynamic structure of the soil and if they will be bioaccessible and affect environmental health in a significant way (Rillig 2012, Afrin et al., 2020).

Ahvaz is a main industrial metropolis in Iran and is well-known for its oil fields. Various industrial activities in Ahvaz (e.g., extraction and refining of oil and gas, petrochemical industries, and steel industry) cause the emission of contaminants to the environment (Goudarzi et al., 2018; Effatpanah et al., 2020). Specifically, the oil industry, traffic, dust storms (Velayatzadeh, 2020), and <10 μm particles and ozone are problematic in Ahvaz (Hosseini et al., 2017). Ahvaz was once classed among the 10 cities with the worst air quality, based on the World Health Organization report in 2010, and has had episodes of acid rain (The Observer, 2013). Also, due to the lack of suitable infrastructures for waste disposal, domestic and industrial wastes are usually discarded in open dumps and thus harmful substances can contaminate and threaten the safety of urban ecosystems and beyond.

Most studies addressing MP sources and pathways have been carried out in aquatic ecosystems (e.g., Karlsson et al., 2017; Wen et al., 2018; Bottari et al., 2019; Capillo et al., 2020; Nematollahi et al., 2020, 2021a; Albano et al., 2021; Savoca et al., 2021). In contrast, fewer studies on MP pollution have been conducted in terrestrial ecosystems and consequently knowledge in such environmental compartment is limited (Kumar et al., 2020). Furthermore, studies of MPs in soil have been commonly conducted in agricultural soils (e.g., Harms et al., 2020; Wang et al., 2021; Yu et al., 2021) and studies in urban and industrial soils remain very limited (e.g., Fuller and Gautam, 2016; Chai et al., 2020; Corradini et al., 2021). In this study, we seek to gain an insight into the concentration, spatial distribution, fate, and possible sources of MP pollution in both urban and industrial soils of Ahvaz. It constitutes, to the best of our knowledge, the first study on MPs in Iranian urban and industrial soils.

2. Materials and methods

2.1. Site description

Ahvaz, the capital city of Khouzestan province, is situated in the east longitude of 48°40′ and the north latitude of 31°20′ (Fig. 1a). It has an area of 18,650 ha and an altitude of 12 m from sea level. Ahvaz, with a population of 1,303,000 people, is the 7th most populated city in Iran (Statistical center of Iran, 2016). Ahvaz is one of the warmest cities in Iran. It has hot and arid weather with a mean annual temperature of about 25.5 °C ranging from minus 5 °C in winter and 50 °C in summer (MOKP, 2017). Based on the synoptic weather stations, the city has a mean annual rainfall of 266 mm and predominantly westerly winds. The mean wind speed in Ahvaz is 8.3 m/h (MOKP, 2017) (Fig. 1b).

Ahvaz is a typical industrial metropolis in the Southwest of Iran with several Iranian industrial companies including the National Iranian South Oil Company, National Iranian Drilling Company, and Khouzestan Steel Company. In addition, carbon black manufacturing, cement manufacturing plants, machine manufacturing, paper making, electric and electronics, paints, and textile are among the important industries of Ahvaz (Statistical center of Iran, 2016).

2.2. Sampling, sample treatment, and experimental analyses

Sampling was conducted in Ahvaz metropolis during the dry season in June 2019. Sampling sites were selected to include both urban and industrial areas and covered the entire city (displayed in Figure 1a). Regarding the urban areas, soil samples were collected from populous areas and they included possible hotspots of MP pollution. The urban soil samples were collected from zones of the city with high traffic loads. Industrial soil samples were taken from the most important industrial areas of Ahvaz. Industrial soil samples were usually mixed with industrial debris and litter. A total of 21 topsoil samples (0 - 5 cm) from 12 urban (S1-S12) and 9 industrial (S13-S21) sites were taken (Figure 1a).

Detailed information on the location of sampling sites is given in Table S1. Soil samples were collected with a stainless steel shovel. The shovel was washed and cleaned after sampling at every site. From each of the 21 sites, about 1 kg of composite soil sample (comprised of a mixture of five subsamples) was collected and stored in sealed glass jars until further treatment.

In the laboratory, the soil samples were spread onto aluminum foil and air-dried at room temperature. Soil sample impurities such as leaves were removed with tweezers. In this study, the experimental methods presented in Nematollahi et al. (2021b) were used. Briefly, 200 g of soil samples were weighed, passed through a 5-mm metal sieve, and stored in glass beakers covered with aluminum foil. Soil samples were then mixed with an adequate amount of 30%

H_2O_2 solution to remove organic matter (Nuelle et al., 2014). The oxidation of the samples with H_2O_2 took place for several days (10 days) until the oxidation reaction was completed and organic matter was degraded. Then, beakers capped with aluminum foil were left in a sand bath at 80°C until complete dryness. The use of plastic was avoided during sampling, sample treatment, and analysis.

MPs were extracted using a flotation method (Löder and Gerdts, 2015). For this purpose, 200 ml of $ZnCl_2$ solution with a density of 1.6 g cm^{-3}, pre-filtered with a 2μm filter paper, was added to each beaker, the beakers were shaken (at 250 rpm for 15 min) using an orbital shaker, and left to rest for 24 h to completely separate the supernatant from the settlement. The supernatant with MPs was centrifuged (at 5000 rpm for 5 min) and filtered using S&S filter papers (2 μm pore size, blue band, grade 589/3). A different filter was used for every sample. Filters were covered with aluminum foil and finally left to dry in precleaned, sterilised cabinets in a clean room with low outside airflow. Dry MP debris on each filter was transferred to glass Petri dishes for subsequent analyses.

To identify and count the number of MPs, a binocular optical microscope (Carl-Zeiss, West Germany), an insulin needle and ImagJ software were used. Below the microscope, MPs were identified by their shape (fibre, fragment, sheetand spherule/beads); length (L) or size (50 μm ≤ L < 100 μm, 100 ≤ L< 250 μm, 250 ≤ L< 500 μm, 500 ≤ L< 1000 μm and 1000 ≤ L< 5000 μm); and colour (white/transparent, yellow/orange, red/pink, blue/green, and black/grey). Selected representative MPs with different sizes, colours and shapes were mounted onto one side of two-sided Cu adhesive tape stripes with the aid of an insulin needle. To characterise MPs' morphology and elemental composition, the Cu adhesive tape stripes with adhered representative MPs were mounted on the instrument stabs, coated with gold and analysed using a Scanning Electron Microscopy (SEM) from TESCAN Vega 3 (Czech Republic) equipped with an Energy Dispersive X-ray Microanalyzer (EDS) from TESCAN. MPs' polymer type was determined using a confocal Raman microscope (Lab Ram HR Evolution, Horiba Japan). In this case, non-coated Cu adhesive tapes (with adhered representative MPs) were mounted on glass microscopy prior the spectroscopy analysis. A laser irradiating at 785 nm was the excitation source, and the detection covered the range of 400 to 800 cm^{-1}. Finally, microplastic spetra derived from Raman were compared to reference spectra included in the Raman microscope's polymer database. A total of 4.6% of the extracted MPs were further characterized with confocal Raman spectroscopy and SEM-EDS.

Quality control of this study was considered by several controlling measures during performing sample treatments and analyses. Sample treatment and preservation were conducted in a cleanroom. Laboratory benches, instruments, and materials were cleaned using ethanol 96%. To wash glassware, phosphate-free soap was used. Firstly, glassware was rinsed twice with deionised water, then left in nitric acid (10%) for 24h, and finally rinsed three times with deionised water and left in precleaned cabinets in a cleanroom. All reagents used for sample treatment were previously filtered using 2-µm S&S filter papers to filter unwanted plastic debris. Plastic-made suits, gloves, and other plastic stuff were prohibited during laboratory works to minimise contamination of the samples. Contamination during sample treatment was assessed using the empty petri dishes left open in the lab as a blank control sample during the extraction, drying and identification stages (about three weeks). In addition, to reduce the MPs loss in the identification stage, the filter papers were also inspected with optical microscopy after having transferred the MPs to Petri dishes. Four blank and and one blind samples were analysed with Raman.

2.3. Data analysis and software

To plot maps and illustrate the spatial distribution of the data, Arc GIS 10.3 was used. The statistical tests were carried out with the software SPSS 22. Shapiro-Wilk (S-W) test was applied to statistically check the normality of the concentrations of MPs. Mann-Whitney U test was performed to find significant differences in MPs concentrations between urban and industrial soils. Image J was used to support the quantification of MPs with optical microscopy.

3. Results and discussion

3.1. MPs distribution and soil contamination

The level of MPs detected in both urban and industrial soil samples is given in Table 1. A total of 10940 MPs were found in 21 soil samples. Urban and industrial soil samples contained 68% and 32% of MPs found in the purified samples, respectively. The concentration of MPs in urban soils (S1-S12) nearly doubled the levels found in the industrial soil samples (S13-S21). Mean concentration of MPs in the urban and industrial soils was 619 ± 822 MPs kg^{-1} and 390 ± 368 MPs kg^{-1}, respectively. Normality test carried out with the number of MPs quantified in both media (urban and industrial soils) reflected a non-normal distribution ($p < 0.05$) with Saphiro-Wilks test. The concentration of MPs were unevenly distributed within the sampling sites, with particularly high concentrations in some of the study sites. In addition, there were significant differences between the concentration of MPs in urban and industrial soil samples (p 0.05) using Mann-whitney U test..

The spatial distribution map of the number of MPs (Fig. 2) displays greater concentration of MPs in S9 (Alavi Area; 3135 MPs kg^{-1}), followed by S6 (Enghelab street; 1390 MPs kg^{-1}) in the urban sites, and in S13 (1220 MPs kg^{-1}) and S17 (860 MPs kg^{-1}) in the industrial sites. The site is located close to a domestic sewage collection zone in a populated residential area. This site (S9) has insufficient sanitation infrastructure (including sewer systems, solid waste landfills, surface runoff treatment and sewage treatment), based on our field observations, and could lead to increased level of MPs in line with recent reports on the presence of MPs in wastewater effluents (e.g., Talvitie et al., 2017; Prata, 2018; Naji et al., 2021). This site is also located in the vicinity of the Grand Arabic Clothing Bazar that can be a potential source for plastic microfibres from clothing. The S6 site is close to a high-traffic loading street in a commercial zone. The presence of MPs in this area is likely affected by intense commercial activity and also crowded sidewalks. Hence, MPs may originate from people's clothings and fragments of plastic released from discarded and/or weathered plastic bags used in commercial activity. Both S9 and S6 are in the center-west of Ahvaz where the city has the highest population density. The westerly wind dominates the area. Population density and wind direction will both have an effect on MPs transport through the air (Dris et al., 2016; Gasperi et al., 2018; Gaston et al., 2020) and it is consistent with the findings of levels of MPs in the center towards the west of Ahvaz as shown in Figure 2. The lowest MPs contamination in urban soil samples belongs to the S10 (Aban street) with relatively low population density and traffic loading. The S13 and S17 sites are close to the waste depot of the National Iranian Steel Company's factory and the National Iranian Oil Company's pipe factory, respectively. In the aforementioned sites, various types of waste accumulate in open piles. Therefore, plastic particles can potentially be released and distributed in the environment, resulting in elevated concentrations of MPs in nearby soils. The lowest MP contamination in industrial soil samples belongs to S16, this corresponds to the location where the Zargan power plant generates electricity. This industrial unit has been out of service since 2019 due to the repair of its facilities.

Previous studies indicated that atmospheric deposition is an important vector introducing MPs to soil (Dris et al., 2018; Wang et al., 2020). For instance, Dris et al. (2018) estimated that atmospheric fallout was responsible for an annual input of nearly 10 tonnes of microfibres in some areas of Paris. This can be crucial for Ahvaz that is a city with a sustained record of air pollution. The air in Ahvaz is almost dusty. Previous studies indicated that atmospheric deposition can play an important role in introducing contaminants including toxic elements and polyaromatic hydrocarbons to the urban soils of Ahvaz (e.g., Najmeddin, 2018; Ghanavati et al., 2019; Nazarpour et al., 2019; Najmeddin and Keshavarzi, 2019; Goudarzi et al., 2019). Hence, atmospheric deposition may also have played a significant role in introducing MPs arisen from various urban and industrial sources to the surrounding soils and can be responsible for elevated concentrations of MPs in some sites. MPs-bearing dust particles can also come from remote areas and be settled on the soil, resulting in integrated sources of MPs.

3.2. MPs properties

The key properties used to screen MPs were shape, colour, size and the surface chemistry of the objects (potential MPs) extracted from the soil samples. As an example, Fig. 3 shows representative MPs identified in the study sites with optical microscopy. Table 2 shows the classification of MPs found in the study contrasting soils in Ahvaz, and the cumulative percentage of the MP physical characteristics is illustrated in Fig. 4. MPs presented a variety of shapes (fibres, fragments, sheets, spherules or beads), colours (red, blue, green, black, grey, yellow or white) and sizes (50 μm < L < 5000 μm).

3.2.1. MPs shape

In the urban soil samples and also in the samples from the industrial soil sites S13, S16, S18, S20, and S21, microfibres were the dominant type of MPs (Figure 4 and Table 2). In contrast, sheets were dominant in industrial soil sites S15, S17 and S19, and beads, in S14. Previous studies also indicated that fibres were the dominant shape of MPs in urban areas (e.g., Liu et al., 2018; Zhang and Liu, 2018; Kooi and Koelmans, 2019; Ding et al., 2020, Corradini et al., 2021; Ding et al. 2021; Yu et al., 2021). This is because fibres are easily released from textiles, carpets, and other soft furnishings (Rodrigues et al., 2018; Yang et al., 2019). Washing textiles made of synthetic fibres is thus an important process releasing MP debris into the environment. Rodrigues et al. (2018) estimated that about 6 million fibres per 5 kg wash can be released by laundries into municipal sewage. In industrial areas, wastewater treatment plants are potential pathways of MP fibres to the environment (Bitter and Lackner, 2020). For instance, in a study carried out by Wolf et al. (2021), the elimination of MPs was assessed in wastewater treatment. They identified a range of MPs with different polymer types and shapes in wastewater effluents, though microfibres were a notable portion of MPs. Polyethylene terephthalate (PET) MPs were the major component of MPs in the effluent (Wolf et al. 2021). The area of study of our work in Ahvaz included wastewater treatment plants, and they could be an important source/pathway of MPs for the investigated industrial soils. Indeed microfibres constituted a large proportion of the MPs detected in Ahvaz (Table 2 Figure 4).

The shape of MPs appears to be a key factor in inducing toxic effects in organisms. Thereby, microfibres have prolonged retention in the gut of organisms and pose toxicity (Forster et al., 2020). For instance, a very small percentage (0.07 %) of PET-MP fibres fed to snails led to a decreased feeding, injured gut tissues and oxidative stress (Song et al., 2019). The size and shape of MPs affected the plant root system and biomass and caused phytotoxicity (Qi et al., 2018; de Souza Machado et al., 2019). However, research in this area is only starting and the role of shape on toxicity will become clearer progressively. Also, some toxic chemicals adsorbed to the surface of microplastic particles may leach to the soil and be exposed to the plant root (Forster et al., 2020). For instance, de Souza Machado et al. (2019) indicated that microfibres, compared to microbeads and fragments, had a severe impact on plant growth and changed root traits. Therefore, since there is a relatively high percentage of MPs comprised by microfibres in the study area, the toxic effects of MPs for the soil-plant system in Ahvaz can be considerable.

3.2.2. MPs colour

MPs were of variety of colours in the study samples, though white-transparent MPs were dominant in both the urban (52%) and industrial (46%) soil samples (Figure 4). This predominance of light colours was not found in coastal sediments and bivalves in the Hormozgan and Mazandaran provinces in Iran (Nematollahi et al., 2020; Jahromi et al., 2021). The dominance of white-transparent MPs in soil may suggest their origin from disposable plastic products such as plastic bags and other disposable plastic containers. The abundance of clear colours can also signal that MPs have been exposed to the sun for a prolonged period of time (Weber and Opp, 2020) and that the soils constitute a sink for MPs.

Black-grey MPs had greater presence in the industrial soil samples than in the urban soil samples and were among the most common MPs in coastal sediments found elsewhere in Iran (Nematollahi et al., 2020; Jahromi et al., 2021). Possible origins of MPs could be inferred from their colour (Fahrenfeld et al., 2019; Zhang et al., 2020a). However, since it is not permanent and may be affected by photobleaching (Wagner and Lambert, 2018), the determination of MP sources with respect to their colour may be somewhat inaccurate (Yuan et al., 2019; Li et al., 2020; Zhang et al., 2020a). Black MPs could be derived from agricultural activity (Campanale et al., 2019), and indeed agricultural sites in Ahvaz use dark plastics. For instance, black plastic covers are used to protect some plants from the sun, and also black plastic pipes are largely used for drip irrigation in agricultural lands of Ahvaz. Hence, remediation measures and reducing the use of such plastics are proposed. The colourful MPs found, constituting 32 and 39% of the MPs found in urban and industrial soil, respectively (Table 2), could originate from a variety of consumable plastic products with higher durability as suggested elsewhere (Andrady, 2017; Eo et al., 2019), including worn urban and industrial constructive materials. The presence of colour could also indicate that the MPs were relatively new in the environment and had not been photobleached. Remarkably, colorful MPs were among the most abundant in coastal sediments in Iran (Nematollahi et al., 2020; Jahromi et al., 2021).

3.2.3. MPs size

Although MPs were found in different sizes (see Figure 4), both urban and industrial soils presented a greater abundance of MPs within the lowest size range (50 µm - 250 µm) and there was no trend observed with respect to bigger MPs. Large MPs (L > 1000 µm) had the least contribution. The prevalence of the smaller range of MPs is in agreement with studies in coastal sediments in the Nothern Persian Gulf (Jahromi et al., 2021). Recent studies indicated that small MPs, especially those with length 50-200 µm, may originate from small plastic constituents in our various daily life products, such as those used in detergents and cosmetics (Zhang et al., 2018; Mendoza and Balcer, 2019). However, the dominance of small MPs in the Ahvaz soil samples is likely a consequence of the break-down and degradation of large microplastic particles to smaller range during their weathering.

The MP size has a great effect in inducing adverse impact and toxicity on soil organisms (Aliabad et al., 2019; Wu et al., 2019; Forster et al., 2020). Small MPs can easily be bioavailable to soil organisms and pose unfavorable effects (Waring et al.,2018). Also, smaller particles can be digested more comfortably than larger ones (Akhbarizadeh et al., 2018; Li et al., 2020; Zhang et al., 2020b). Recent studies indicated that small MPs ingested by organisms pose both biological and physical harm after nearly one month (Rillig et al., 2017; Lwanga et al., 2017; Maaß et al., 2017). Jiang et al. (2019) indicated that polystyrene (PS) MPs < 5 µm, and also nanoplastics, posed oxidative stress, genotoxicity and a decrease in root biomass in broad beans. Rhodes et al. (2012) demonstrated that a decrease in the size of MPs from rubber used in tyres leads to an increase in the leachability of zinc and it hinders the development of plants. Furthermore, the nitrification and pH of the soil can be changed by the presence of micro rubber particles in the soil (Smolders and Degryse, 2002), severely influencing the soil microbial community and the bioavailability of plant nutrients . Thus, given the dominance of small MPs in both urban and industrial soil samples of Ahvaz, adverse impacts induced by MPs are likely.

3.3. MPs morphology and chemical composition

Weathering evidence on MPs recovered from the study sites was investigated with surface morphology analysis. Fig. 5 shows the morphology and SEM-EDX spectra (with the elemental composition) of representative samples with different MP shapes. MPs had signs of physical and chemical weathering. The weathering fingerprints in fibre MPs were mainly grooves while weathering signs in fragments and pellets were cracks and irregular edges. Spherules showed the weathering signs mainly as pits. Adsorption of organic and inorganic contaminants is favored onto weathered MPs surfaces (Kowalski et al., 2016) and these adsorbed contaminants could cause adverse effects.

Previous studies have reflected that the angular MPs with sharp edges indicate recent entrance into the ecosystem, whereas those with smooth edges reflect long residence time (Hidalgo-Ruiz et al., 2012; Rocha-Santos, 2017). In the investigated samples, most MPs displayed fingerprints of weathering which were influencing the shape of the MPs and reflected a relatively prolonged time in the environment. This supports that the MPs found in the study soils were likely secondary MPs, though a number of particles were also found without any weathering signs, which suggests that some were primary MPs.

The elemental composition of the analyzed MPs confirmed the plastic nature of all particles as they had a high percentage of carbon and oxygen. In addition, MPs with some proportion of major and trace elements, got part of their inorganic fraction from adsorbed minerals such as clays that contain Si, Al, Ca, and Mg, salt (e.g., Na and Cl), sample treatment chemicals (e.g., $ZnCl_2$), and metals used in sample analysis (e.g., Au due to residues from the thin layer of gold coating used in SEM-EDS analysis), as well as additives used in the matrix of plastics to achieve exclusive properties (e.g., different pigments using Ti, Cu, Fe, and Cr) (Nematollahi et al., 2021a, b).

The polymer type of some investigated MPs is illustrated in Fig. 6. The main polymer type of MPs including PET, nylon (NY), polypropylene (PP) and PS, with different shapes and colours, are listed in Table S2. In terms of abundancy, the abundance of the polymers was PET (38.8 %) > NY (27.7 %) > PP (22.2 %) > PS (11.1 %). Importantly, the same colours of MPs were found to be present with different compositions.PET is the most broadly used polymer for synthetic fibres in the textile industry, in packaging materials and beverage bottles (Gong et al., 2018). NY is widely used in daily life products such as clothing, fishnet, rope, carpet, tyre, seat belt, and industrial cords (Hu and Yang, 2000). Both PP and PS are largely applied as packaging materials, reusable bags, and disposable plastic materials (Barrows et al., 2018; Zhang et al., 2020a). It is worth noting that, based on the spectra obtained from Raman spectroscopy, most MPs were not not made of a single polymer, and compositions with more than one polymer (copolymers) such as PET-NY, PET-PS, and PP-PS were abundant, though this work reports on the dominant polymers.

3.4. MPs overview in the study area and other locations

Table 3 compiles a number of studies conducted on the occurrence of MPs in different soil types and some local outdoor dust. The MP concentrations in these locations were compared with the levels of MPs reported in this study. Concentrations of MPs in the soil samples from the study area were lower than in the studies measuring MPs in outdoor and indoor dust in Iran. Microfibres were the dominant type of MP in most studies dealing with soil.. Two polymers, PE and PP, were dominant in most investigated soils. In contrast, PET and NY were the main polymers in the MPs in the Ahvaz metropolis. This can be due to the different chemical compositions of plastic products consumed in our study area compared to those in other studies outside Iran. The concentration of MPs identified in all studies was somewhat different (e.g., Corradini et al., 2021; Scheurer & Bigalke, 2018) that can mainly be attributed to various land uses, waste management practices, sources dispersing MPs to the environment, the effect of wind, density of population, as well as analytical factors such as the number and representativity of the samples investigated or the working range of the microscopes used for the screening of MPs.

This study gives an insight into the status of MPs in the urban and industrial soils of Ahvaz. It has, however, some limitations. A comprehensive study to holistically assess the contamination of MPs in different environmental compartments of Ahvaz including soil, dust, air, water, sediment and organisms should follow to understand MPs pathways. Such a study would require a greater number of soil samples and analysis of MPs' composition than in the present investigation. To diagnose risk points, a systematic sampling of soil in Ahvaz, including samples from all types of land uses, including those with low level of MPs, is needed. Soil sampling could be extended through seasons to investigate the effect of weather conditions on the concentration and dispersion of MPs. In the prospective studies, the toxicity of MPs in each medium could be evaluated, thus the adverse effects of MPs (MPs per se and adsorbed contaminants) could be determined. The status of MPs in urban and industrial soils of Ahvaz should periodically be evaluated to monitor contamination trends, which have not been assessed in this research.

5. Conclusion

Overall, urban soils showed to be more contaminated with MPs than industrial soils. MP contamination of soil in Ahvaz originates from various anthropogenic activities such as inappropriate landfilling, use of synthetic clothing and commercial activity using plastic bags. These potential sources have led urban and industrial soils of the city to contain a variety of MPs with different shapes, colours and sizes. Among them, microfibres being, MPs < 250 μm and white MPs were dominant. Debris from plastic products made of PET and NY (66.5 %) had a greater presence in the soil samples. A possible source of these MPs could be PET-NY textiles and tyres. Indeed, most MPs found in the soils were constituted by more than one polymer. Based on the morphology of MPs surfaces, both primary and secondary plastic sources contribute to the pollution found. The results of this study can be considered as a baseline for future studies that would include all environmental compartments, biota and sampling seasons to establish main MPs sources, pathways and risk points in Ahvaz. Specifically, studying the atmospheric transport and deposition of MPs in the urban areas of Ahvaz is highly recommended.

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Table 1. Comparison of the occurrence of MPs in urban and industrial soil samples in Ahvaz.

Soil type	Unit	Total number of MPs	Range	Mean	Median	S.D.	S-W p. value
Urban (12 sites)	N/kg.	7430	100-3135	619	335	822	1×10^{-4}
Industrial (9 sites)	N/kg.	3510	80-1220	390	240	368	9×10^{-3}

N: number, S.D: standard deviation, S-W: Shapiro-Wilks test

Table 2. Comparison of MPs characteristics found in urban and industrial soils of Ahvaz. Standard deviation (SD) is calculated based on concentrations of MPs kg^{-1} of soil in each category.

MPs properties	**Soil type**	
	Urban	**Industrial**
Shape	(% of MPs found ± SD)	
Fibre	70.3 ± 484.4	54.7 ± 256.7
Spherule	0.4 ± 330.1	31.6 ± 149.3
Fragment	4.6 ± 31.9	3.4 ± 11.5
Sheet	24.6 ± 3.2	10.3 ± 73.2
Colour		
White-Transparent	52.1 ± 352.3	45.6 ± 202.9
Yellow-Orange	10.4 ± 75.4	10.8 ± 55.5
Red-Pink	12.4 ± 149.1	9.4 ± 60.4
Blue-Green	15.7 ± 161.4	11.4 ± 32.4
Black-Gray	9.4 ± 103.5	22.8 ± 82.8
Size		
50 μm ≤L<100 μm	23.1 ± 168.1	31.3 ± 142.5
100 μm ≤L<250 μm	33.0 ± 258.5	25.1 ± 71.6
250 μm ≤L<500 μm	19.8 ± 232.8	13.7 ± 71.2
500 μm ≤L<1000 μm	14.8 ± 124.2	19.9 ± 151.3
1000 μm ≤L≤5000 μm	9.4 ± 74.1	10.0 ± 47.5

Table 3. Characteristics and concentration of MPs in urban and industrial soils of Ahvaz relative to those of other locations. The MP abundance has been expressed in MP units/ soil (Kg), unless specified.

Region	**Sample type**	**MPs frequency**	**Major Polymers**	**Main shapes**	**Reference**
Ahwaz metropolis, Iran	Urban soil	7430[a], 619[b], 100-3135[c]	PET, NY	Fibre	This study
	Industrial soil	3510[a], 390[b], 80-1220[c]	PET, NY	Fibre	
Tehran, Iran	Urban outdoor dust	2649[a], 83±10 - 20116±333[c]	NI	Fragment	Dehghani et al., 2017
Bushehr City, Iran	Urban outdoor dust	74480[b], 21000-165800[c]	NI	Fibre	Abbasi et al., 2017
Asaluyeh county, Iran	Urban outdoor dust	875466[a], 60000[b]	NI	Bead	Abbasi et al., 2019
Shiraz metropolis, Iran	School indoor dust	5464000[a], 195000[b], 10000-635000[c]	PET, PP	Fibre	Nematollahi et al., 2021b
Chile's Región Metropolitana	Crop lands	1600[a]	PE, PP	Fibre	Corradini et al., 2021
	Pastures	1200[a]	PE, PP	Fibre	
	Rangelands	≤200[a]	PE, PP	Fibre	
	Natural grasslands	≤200[a]	PE, PP	Fibre	
Mu Us Sand Land, northwest China	Sand, woodland, and Grassland soils	2697[a], 1360-4960[c]	PP, PE	Fibre, Fragment	Ding et al., 2021
Shouguang City	Agricultural soil	1444[b], 310-5698[c]	PP, PE	Fibre	Yu et al., 2021
Hangzhou Bay coastal plain	Agricultural soil	503[a], 0-2760[b]	PE, PP, PS, Rayon	Fragment, Fibre	Zhou et al., 2020
Chinese farmlands	Farmlands	2783-6366[c]	PE, PA	Fragment	Wang et al., 2021
Northern Germany	Agricultural soil	4±12[b], 0-218[c]	PE	Foil	Harms et al., 2020
Yunnan, China	Tree planted soils	7100-42960[c]	NI	Fibre	Zhang and Liu (2018)
Switzerland	Floodplain soil	593[a]	PE, PS, PVC	NI	Scheurer & Bigalke (2018)
Shandong, China	Coastline soil	1-14713[c]	PP, PE, PES	Foams, Fibres, Pellets	Zhou et al. (2018)
Shanghai, China	Vegetable fields	63±13[b]	PES	Fibre, Film, Fragment	Liu et al. (2018)
	Vegetable fields	78±13[b]	PE, PP	Fibre, Film, Fragment	
Sydney, Australia	Industrial soil	300-67500[c] $mg\ kg^{-1}$	PVC	NI	Fuller and Gautam (2016)

a = total abundance, b = mean, c = range, NI = Not-Identified

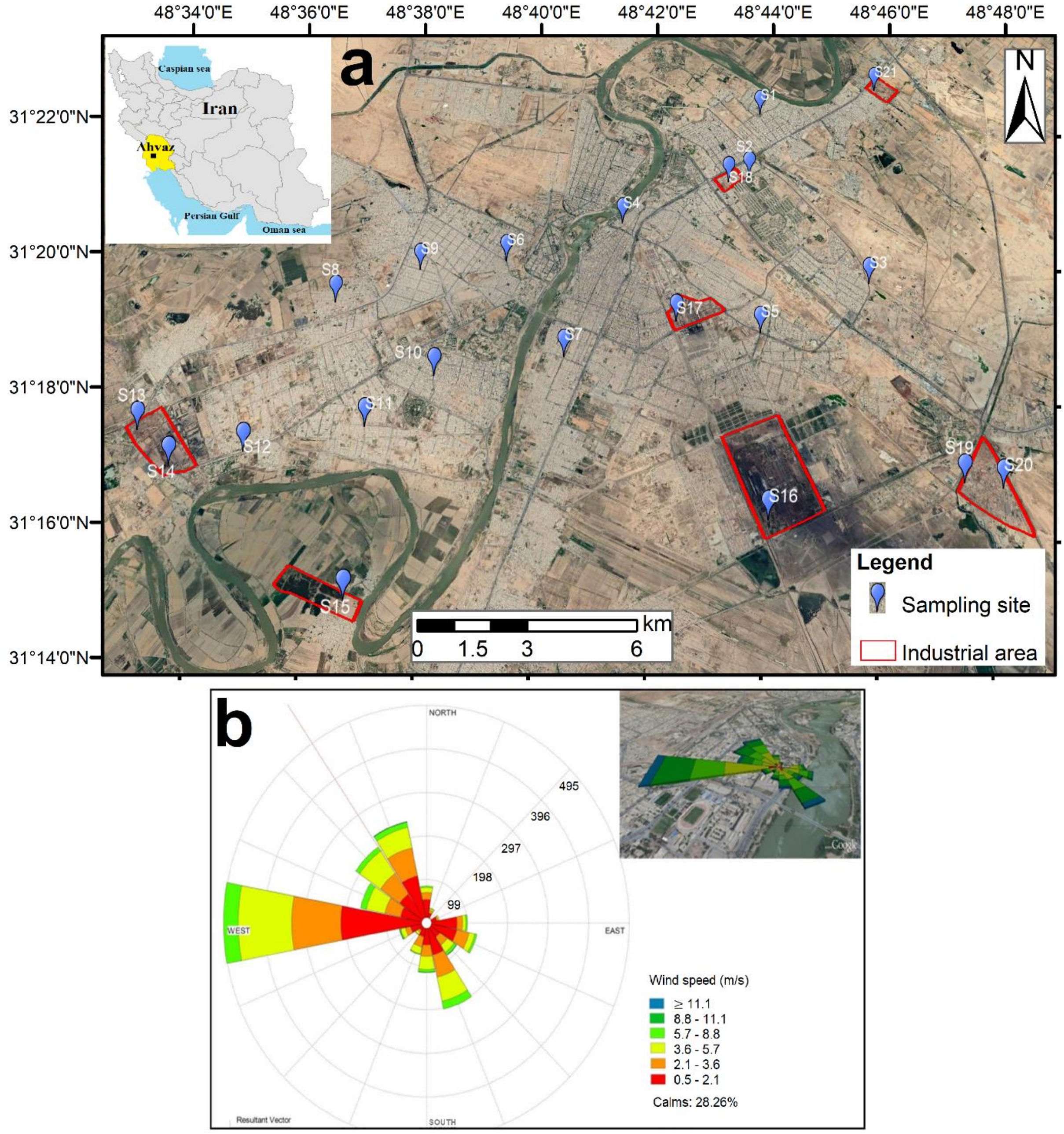


Fig. 1 a) Geographic location of Ahvaz metropolis in Iran, and location of the soil sampling sites: S1-S12: urban soil samples, S13-S21: industrial soil samples, and **b)** rose diagram showing dominant wind direction in Ahvaz (MOKP, 2017)

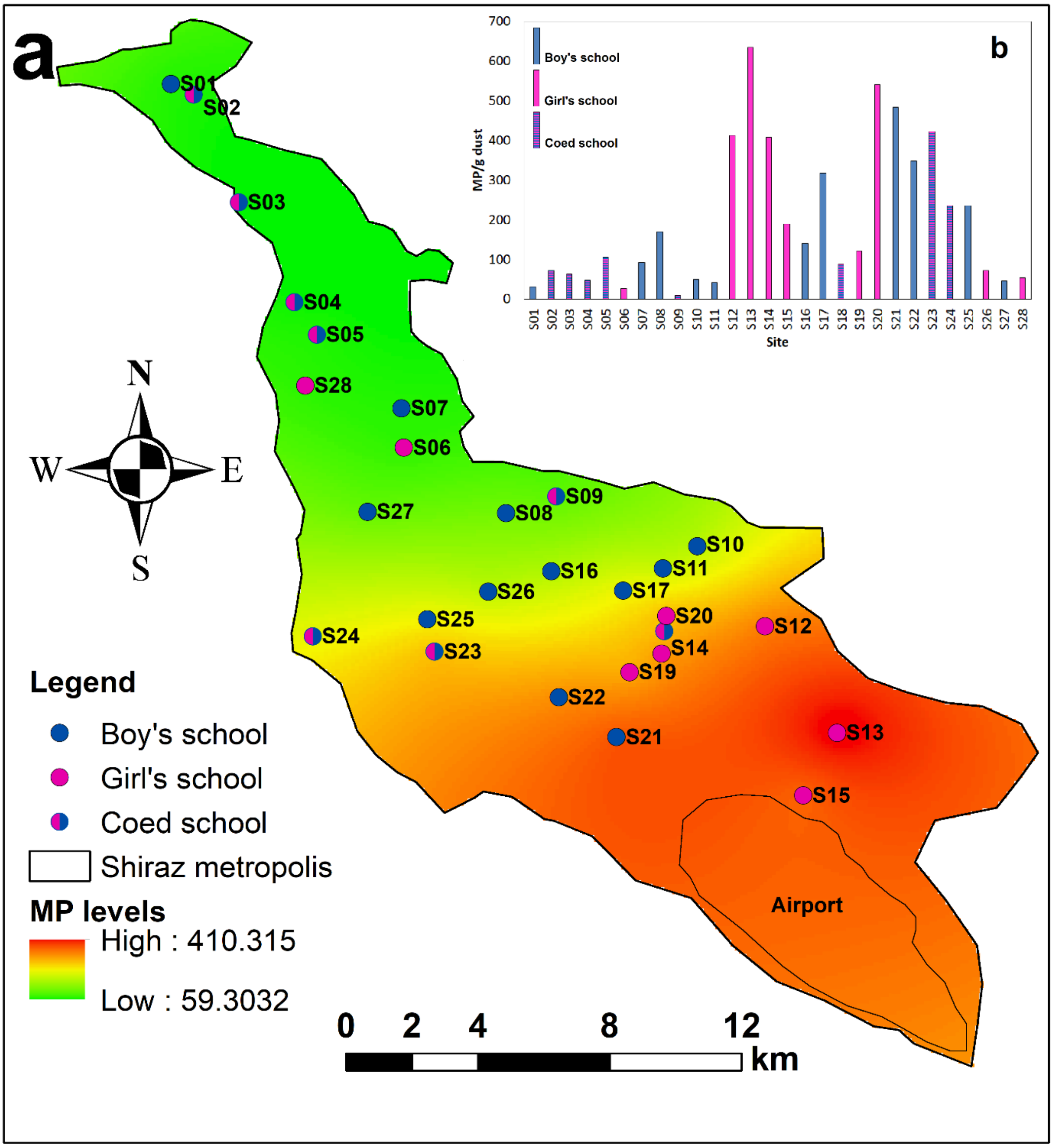


Fig. 2 a) Heat map of Shiraz including spatial distribution of MP levels in indoor dust of school in Shiraz and **b)** Detail of MP concentration at each sampling site.

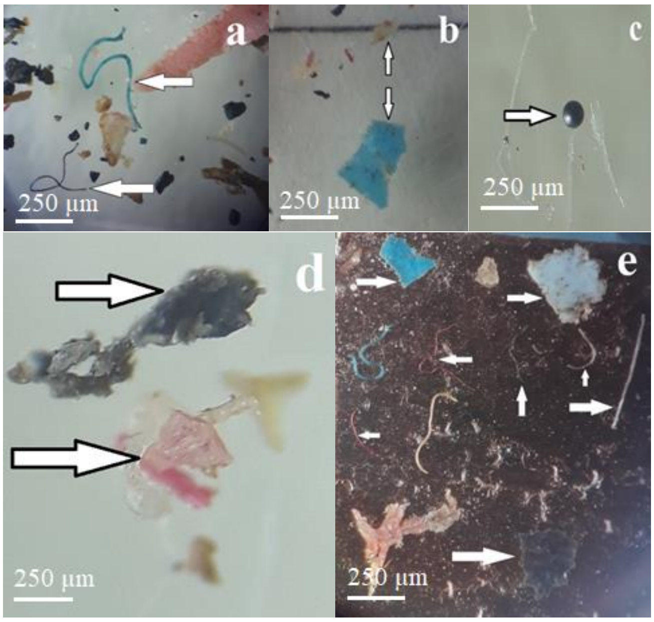
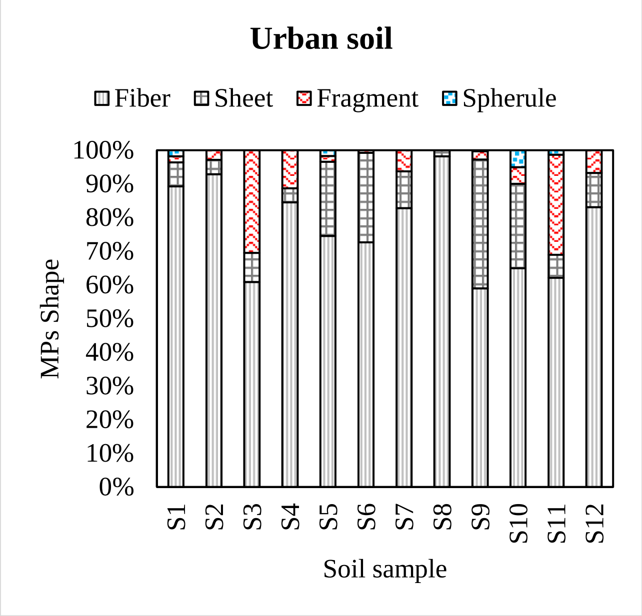
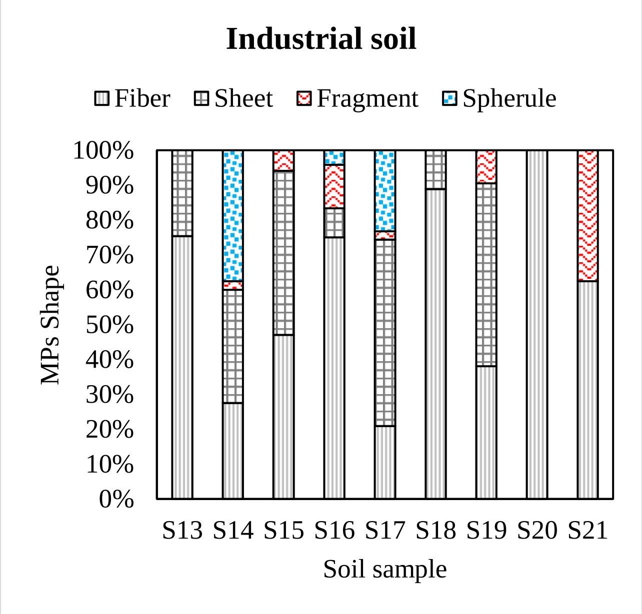
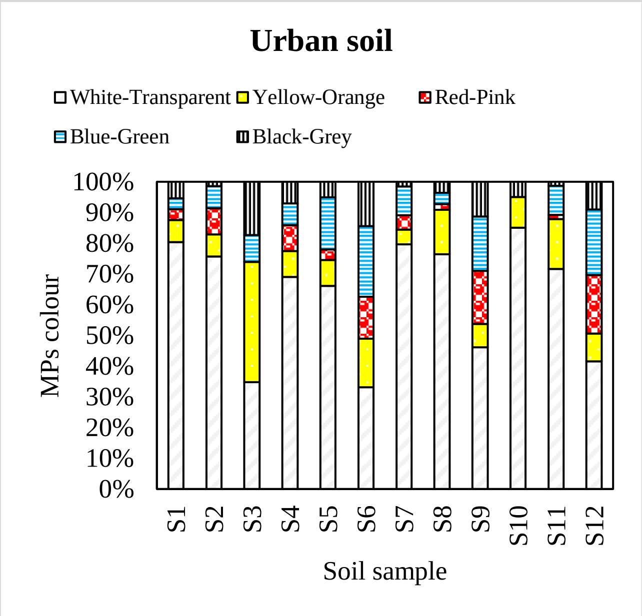
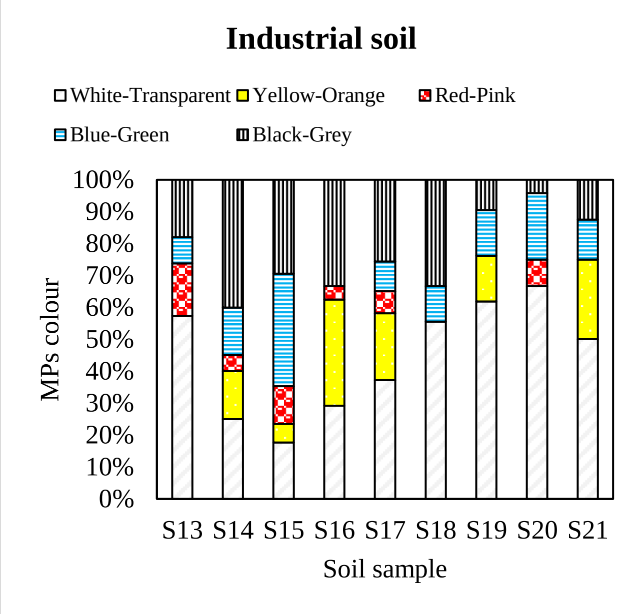


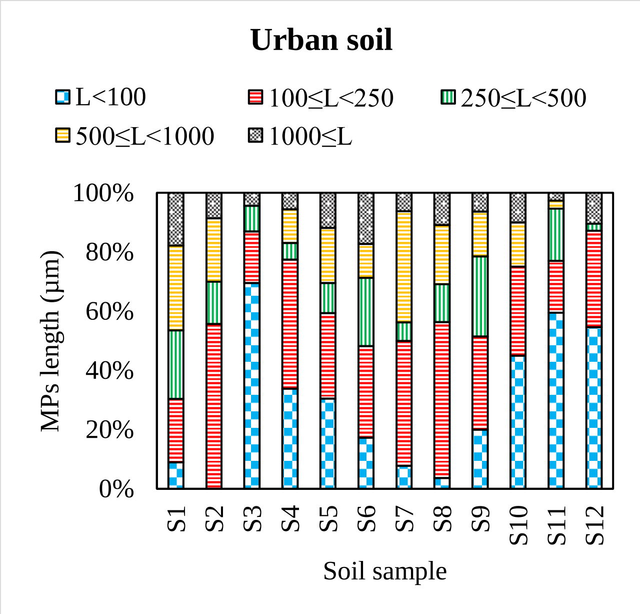
Fig. 3. Examples of representative microplastics detected with optical microscopy with optical zoom of 10X; **a)** blue and black microfibres, **b)** blue and white sheets, **c)** a black spherule or bead, **d)** black and red fragments, and **e)** different type of MPs on the copper adhesive.


Urban soil
Fiber
Sheet
Fragment
Spherule
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MPs Shape
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
Soil sample


Industrial soil
Fiber
Sheet
Fragment
Spherule
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MPs Shape
S13
S14
S15
S16
S17
S18
S19
S20
S21
Soil sample


Urban soil
White-Transparent
Yellow-Orange
Red-Pink
Blue-Green
Black-Grey
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
MPs colour
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
Soil sample


Industrial soil
White-Transparent
Yellow-Orange
Red-Pink
Blue-Green
Black-Grey
MPs colour
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
S13 S14 S15 S16 S17 S18 S19 S20 S21
Soil sample


Urban soil
L<100
100≤L<250
250≤L<500
500≤L<1000
1000≤L
MPs length (µm)
100%
80%
60%
40%
20%
0%
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12
Soil sample

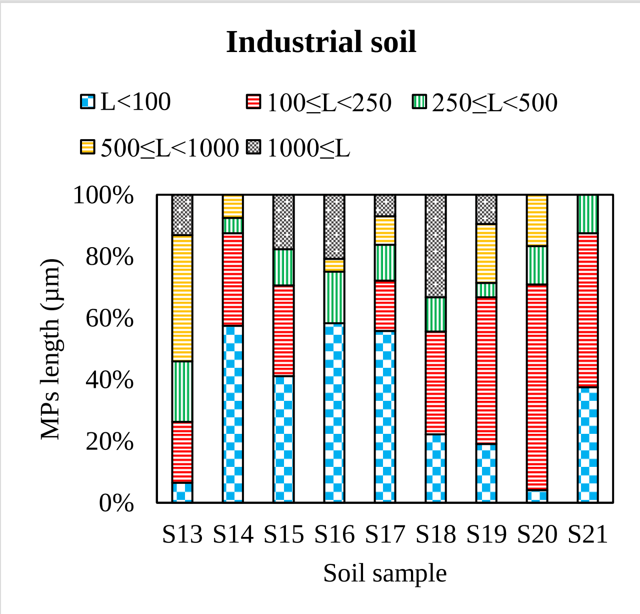

Industrial soil
L<100
100≤L<250
250≤L<500
500≤L<1000
1000≤L
MPs length (µm)
100%
80%
60%
40%
20%
0%
S13 S14 S15 S16 S17 S18 S19 S20 S21
Soil sample

Fig. 4. Abundance of MPs classified by their shapes, colours, and sizes (μm) within urban and industrial soil samples

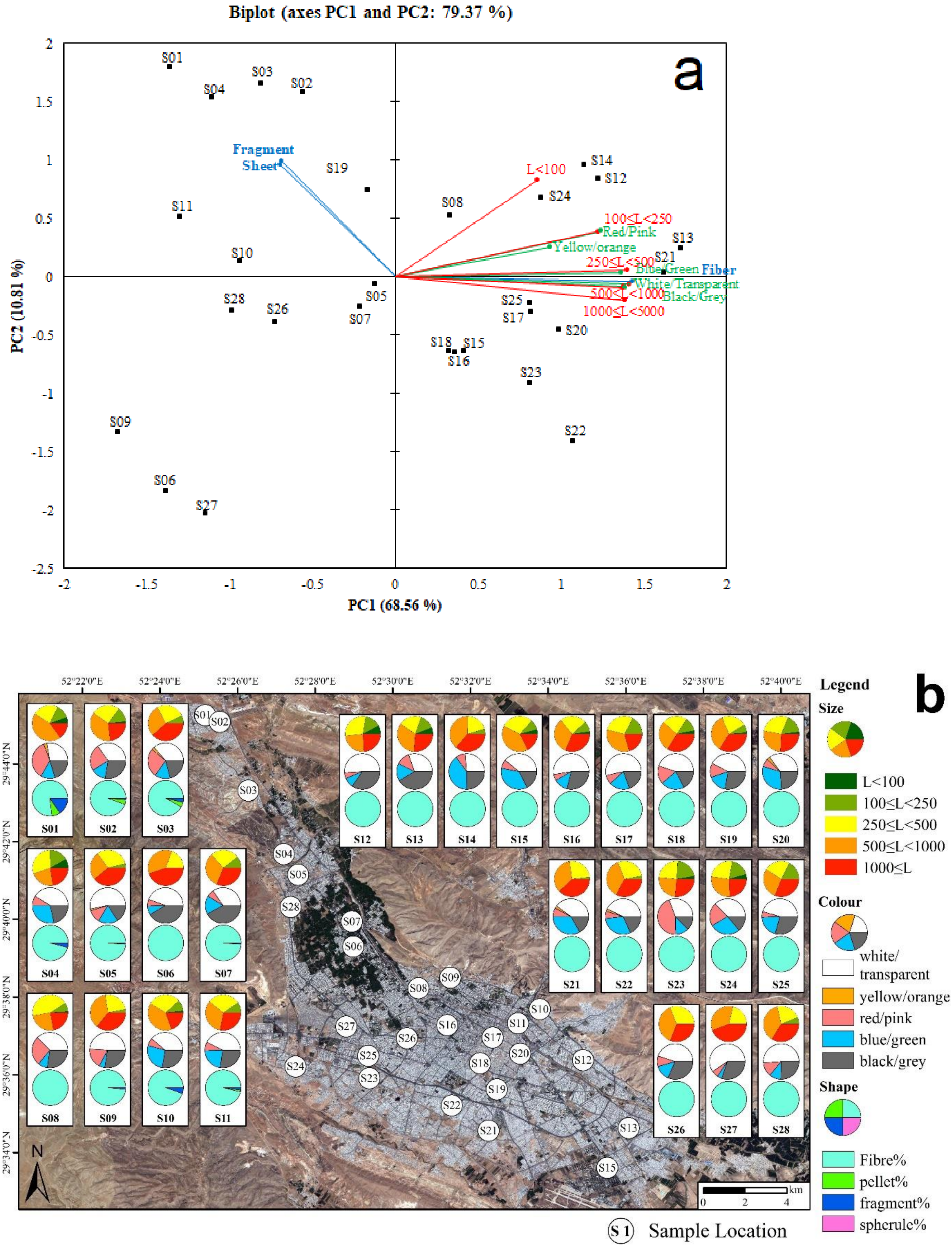


Fig. 6 PCA biplot showing interrelations of MP characteristics **(a)**, and spatial distribution of MP characteristics within indoor dust in the Shiraz's schools (sampling sites S1-28) **(b)**

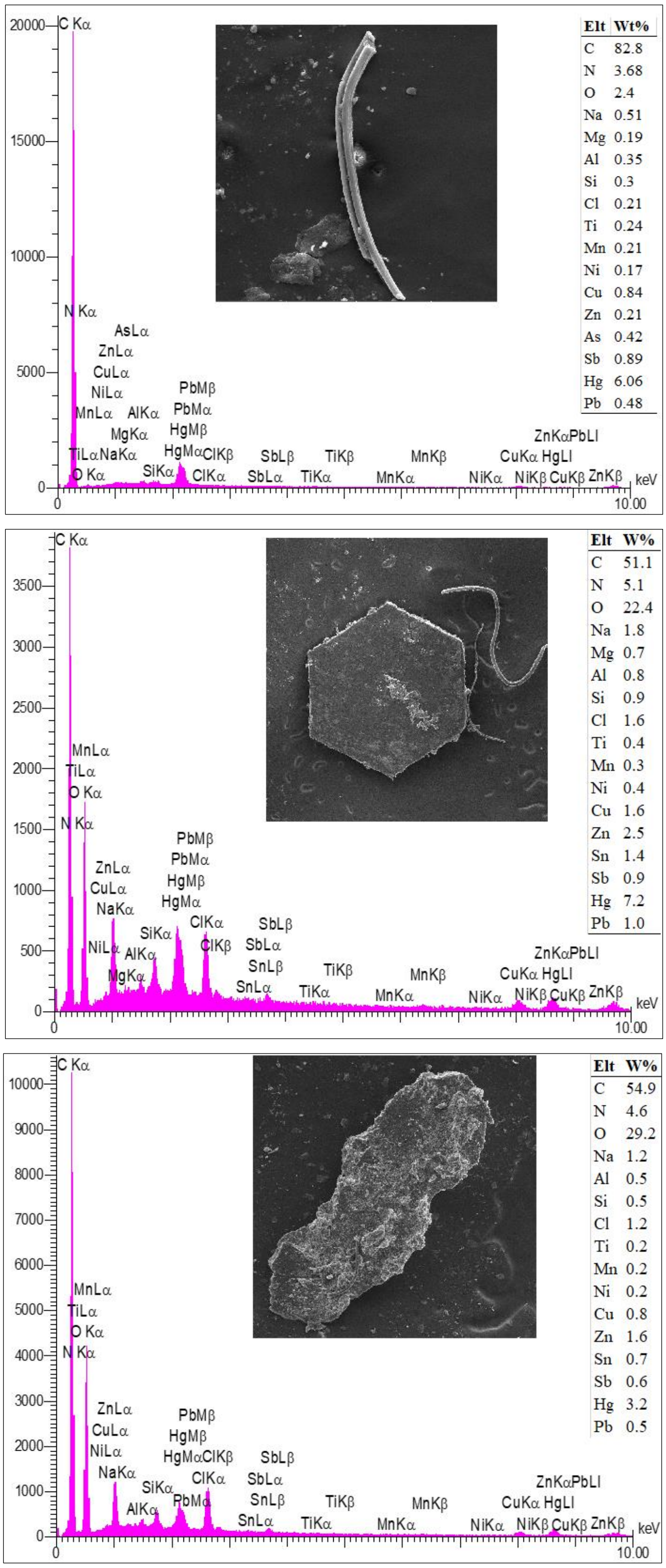


Fig. 5 SEM micrographs and their corresponding EDS spectra showing the elemental composition of representative MPs (with different shapes) in indoor dust of Shiraz's schools.

Science of the Total Environment Microplastic occurrence in urban and industrial soils of Ahvaz metropolis: a city with a sustained record of air pollution

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Table S1. Position of sampling sites along with number of MPs found at each site

Site	Number of MPs	Location
S1	56	Imamzadeh Seyed Abdullah- Health Complex #7
S2	70	Oil town-Oil Hospital
S3	23	Aghajari town-Oil Boulevard
S4	71	Azadegan Street
S5	59	Bahonar triple ways
S6	278	15 Khordad Square
S7	64	Shari'ati Boulevard
S8	55	Goldasht Area
S9	627	Alavi Area
S10	20	Aban Street
S11	74	Baharestan Area
S12	89	Khouzestan Steel facturies
S13	244	National Iranian Steel Company’s factory
S14	80	Iran National Steel Industrial Group
S15	34	Jangiyeh and Jil Brick making Area
S16	48	Khouzestan Steel Complex
S17	172	National Iranian Oil Company’s pipe factory
S18	18	Industrial town #1
S19	42	Karoun River #2
S20	48	Industrial town #3
S21	16	Zargan power plant

Table S2 Polymer type of the analyzed MP items with different shape and colour

MP Shape	MP Color	Polymer type
Fiber	White-Transparent	PET
Fiber	White-Transparent	PET
Fiber	Yellow-Orange	PP
Fiber	Red-Pink	PP
Fiber	Red-Pink	PET
Fiber	Blue-Green	PS
Fiber	Blue-Green	PP
Fiber	Black-Grey	PS
Fiber	Red-Pink	PET
Pellet	White-Transparent	Nylon
Pellet	Yellow-Orange	PET
Pellet	Blue-Green	PP
Pellet	White-Transparent	Nylon
Pellet	Black-Grey	PET
Fragment	White-Transparent	Nylon
Fragment	Yellow-Orange	Nylon
Fragment	Red-Pink	Nylon
Spherule	Black-Grey	PET