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RESEARCH ARTICLE

Evidences of microplastics in aerosols and street dust: a case study of Varanasi City, India

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Abstract
Microplastics (MPs) are ubiquitous in our environment. Its presence in air, water, and soil makes it a serious threat to living organisms and has become a critical challenge across ecosystems. Present study aimed to assess the abundance of MPs in aerosols and street dust in Varanasi, a typical urban city in Northern India. Airborne particulates and street dust samples were collected from various sampling sites around Varanasi City. The physical identification of MPs was conducted by binocular microscopy, fluorescence microscopy, and scanning electron microscopy (SEM), while elemental analysis was made by energy-dispersive X-ray (EDX). Finally, Fourier-transform infrared spectroscopy (FTIR) was used for chemical characterization of MPs. Presence of MPs in both aerosols and street dust from all selected sampling sites was confirmed, however with varying magnitude. MPs of different colors having the shape of fragments, films, spherules, and fibers were recorded in the study while fragments (42%) in street dust and fibers (44%) dominated in aerosols. Majority of the MPs were < 1 mm in size and were primarily polypropylene, polystyrene, polyethylene, polyethylene terephthalate, polyester, and polyvinyl chloride types. The EDX spectra showed the presence of toxic inorganic contaminants like metallic elements on MPs, especially elements like aluminum, cadmium, magnesium, sodium, and silicon found to adsorb on the MPs. Presence of MPs in the airborne particulates and street dust in Varanasi is reported for the first time, thus initiating further research and call for a source-specific management plan to reduce its impact on human health and environment.

Keywords Aerosols · FTIR · Microplastics · Particulate matter · Polymer · Street dust

Introduction

Microplastics (MPs) are the emerging contaminant of the environment, ubiquitous in air, water, and soil. Since last decade, the research in the field of MPs has gained momentum. Mostly the studies are conducted for the availability of MPs in the water and rarely for the air medium (Dris et al. 2016). Few studies have documented the existence of MPs in both the indoor and outdoor air (Abbasi et al. 2019; Akhbarizadeh et al. 2021; Cai et al. 2017; Dris et al. 2016; Enyoh et al. 2019; Liu et al. 2019). Synthetic fabrics, abrasion from synthetic rubber tires, erosion, and dust from city and household areas are the most common sources of MPs in the air (Prata 2018; Sol et al. 2022). According to estimates, a single item of clothing might release up to 2000 fibers per wash (Browne et al. 2011). Other major sources of airborne MPs may include construction and waste incineration site, road dust, landfilling area and industrial outflow, particle re-suspension, synthetic particles such as polystyrene (PS) peat (used in horticultural soils), sewage sludge (used as a fertilizer), and exhaust from tumble dryer (Dris et al. 2016; Prata 2018). Anthropogenic activities always influence the abundance of MPs in air (Abbasi et al. 2019). The study conducted by Dris et al. (2016) at urban and suburban sites in Paris observed fibers in most of the atmospheric fallout. Another study by Zhou et al. (2017) detected airborne MPs including fibers, fragments, films, and foams of different colors in a coastal city Yantai, of Shandong Province. Similarly, Liu et al. (2019) studied the airborne MPs in Shanghai City and

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the analysis showed fibers (67%) as the dominating shape, followed by fragments (30%) and granules (3%), respectively. Catarino et al. (2018) studied household fiber fallout during a meal in Edinburg, UK. They found fiber sizes of < 500 µm made of polyethylene terephthalate (PET) and polyurethane (PUR). MPs in air are also undefined source for aquatic pollution. The suspended particles in air wet-scavenge by rainfall and reach to the aquatic bodies via sewage system as runoff water. Hence, MP concentration is noticed to accelerate in aquatic system after rainfall and due to urban runoff (Masiá et al. 2020). In the waste water treatment plant, microplastics gradually settled in the sludge. The sludge when used as organic fertilizer in agriculture can impair the quality of soil with MPs (Sol et al. 2020). As MPs are commonly reported in quite diverse media, from soil, aquatic environment, aerosols, aquatic animals and in human blood, and considering its stability to complete biodegradation, there is every possibility that it can enter into the food chain and cause many health complications (Chauhan et al 2021).

Many researches also tried to quantify the reach and impacts of MPs. Fine MPs present in air can easily pass through respiratory defense system and reach deep in the bronchioles. Pauly et al. (1998) got fibers of up to 250 µm in the deep part of the lung in their study. Until date, the potential risk of ingested airborne MPs to the human body is not known completely but it is assumed that the risk associated with it depends on many factors like particle size, adsorbed chemical, concentration, deposition, and clearance rate (Teuten et al. 2007, 2009). The ability of MPs to adsorb toxic chemicals on their surface because of their large surface area and hydrophobic property makes the impact worse (Prata et al. 2020; Sol et al. 2021). Pollutants like heavy metals (Kumari et al. 2021; Li et al. 2013; Mohanraj et al. 2004) and polycyclic aromatic hydrocarbons (Akhbarizadeh et al. 2021) are detected in atmospheric particulate matters adsorbed on surface. MPs can also act as a medium to carry pathogens or microorganisms to the lungs and possibly result in an infection to humans (Prata 2018). Adsorbed microbial biofilm on MPs could also be responsible to adsorb and transport heavy metals with it as it is a potential chelating agents for metals (Verla et al. 2019). Till date, there is no published report on the abundance and type of MPs that are present in the ambient air and roadside dust in Varanasi. Present study was therefore, designed to find evidences of MPs in air and street dust in Varanasi. Two objectives were specifically explored: (1) to quantify and characterize MPs present in air and dust of Varanasi and (2) to identify and estimate the metals adsorbed with the MPs.

Material and methods

Study area

Atmospheric suspended particulate matter and street dust samples were collected from some selected sites of Varanasi, India (Fig. 1). Varanasi is situated on the Indo-Gangetic plains of North India and has a population of 1,198,491 and an area of 112.26 km^2. Samples were collected during April to June, 2019 and were analyzed subsequently.

For suspended dust samples, site (S1), Banaras Hindu University (Institute of Environment and Sustainable Development), was chosen. It is an institutional area surrounded by a typical mixed urban environment characterized by congested roads and a variety of commercial and residential activities. For street dust samples, six specific sites (S2, S3, S4, S5, S6, and S7) were selected representing the urban environment within Varanasi. The map of the sampling sites is cited as Fig. 1 and the details of the sampling locations are included in supplementary file 1.

Sampling

All the samples were collected during the April to June month of the dry season of year 2019 from the selected sites. Different methodology was opted to conduct sampling for street dust and suspended particles/ aerosols.

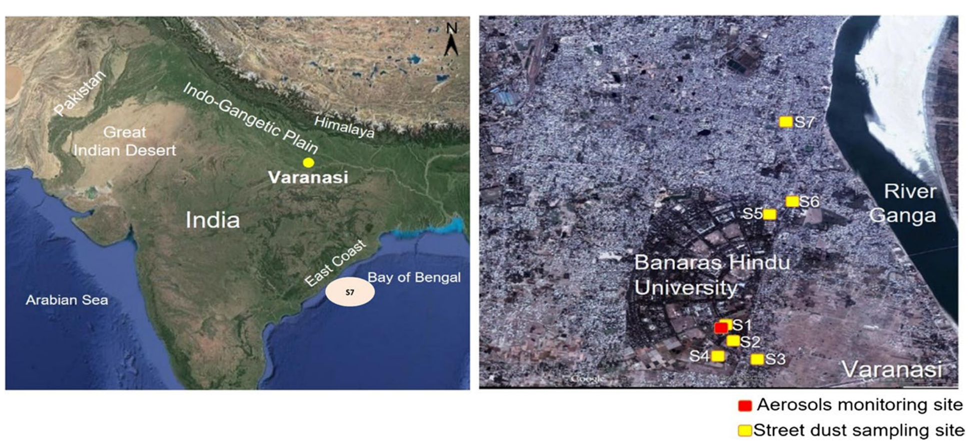

Fig. 1 Geographic map of the study area and respective sampling sites

Street dust samples

Approximately 50 g of street dust composite sample was collected from all the six selected urban sites (S2 to S7) within Varanasi from the road surface neighboring to the kerb of the two sides of the road. To minimize plastic contamination during sample collection, an anti-static wooden brush and a metal pan were used to gently sweep the material straight into an airtight glass vial which was rinsed with Milli-Q water and dried between subsequent samplings. All collected samples of street dust were then brought to the laboratory and materials such as gravels, leaves, small pieces of bricks, and concrete were removed from the samples. Then, each sample was sieved using a 5-mm sieve and all particles collected on 5-mm sieve also discarded. To reduce the uncertainty caused by lingering particles on the road surface and particle disruption in the ambient air during the sweeping process, the resultant MP concentration was given as the number of MP per 15 g mass of dust rather than the number of MPs per sq. meter of street dust (Dehghani et al. 2017).

Atmospheric suspended dust samples

Over the roof of IESD-BHU, particulate matter samples were collected on 10 × 8 inch glass fiber filters (GF/A Whatman) with the help of dust sampler (APM-BL 460, Envirotech) that isolates dust particles of desired aerodynamic diameters (<10µm) at an average flow rate of 1.2 m^3/min. Particulate of greater diameter (>10µm) was also simultaneously collected and kept for further analysis with coarse particles (<10µm). To avoid local disturbances like from automobiles, the high-volume air sampler was installed at a height of 7.5 m. Particulates of both the sizes were carefully removed from the sampler and quickly transferred to clean glass Petri dishes with the help of tweezers and were brought to the laboratory for MPs extraction. Before and after sampling, all filters were desiccated for 24 h. The desiccated filter papers were weighted using electronic microbalance with 0.01 mg resolution. The difference among the initial weight and final weight of the filters was used to compute the aerosol mass (µg), and then the concentration was estimated by dividing the aerosol mass by the total volume of air (m^3).

Sample processing

Street dust samples

Each street dust sample taken from different sites was air-dried for 7 days. To eliminate organic matter, 15 g sample of street dust was treated with 35 ml of hydrogen peroxide (30%) for 8–10 days (until no bubbles were formed) in a 500-ml glass beaker (Abbasi et al. 2017, 2019).

Atmospheric suspended dust samples

Each sample collected on the filter paper was carefully removed and kept in the glass vial and brought to the laboratory for further experiment. The contents of the filter paper were washed with filtered de-ionized water and afterwards cautiously transferred to a clean beaker as much as possible using a clean metal spatula. Then, the content was kept in the oven at 70–80 °C for drying completely. After the content was completely dried, it was transferred to another beaker and then 35 ml of H_2O_2 was added and is kept for approximately 8–10 days until the air bubbles coming out from the beaker stop (Abbasi et al. 2017, 2019). This was done to remove all the organic matter or biogenic matter present in the samples.

The reagents used for this study were 30% hydrogen peroxide and $ZnCl_2$ provided from Thermo Fisher Scientific India Pvt. Ltd., and de-ionized water (Milli-Q) was used throughout all the experiments.

Microplastic separation

A zinc chloride ($ZnCl_2$) solution of 1.6 g/cm^3 density was prepared and 100 ml of this solution was mixed with each sample and the content was shaken at 350 rpm for 5 min and left 1–2 h to settle. The supernatant was then centrifuged at 4000 rpm for 4 min and then vacuum filtered through a cellulose nitrate filter (Axiva Sichem Pvt. Ltd., pore size 0.45 µm). The filtered contents were then washed with Milli-Q water to restrict the formation of $ZnCl_2$ crystals. Density separation, centrifugation, and filtration processes were repeated three times on the same filter paper to capture all MPs. The samples were further dried for 24 h in an oven at 50° (Dehghani et al. 2017).

Microplastic identification

For identification of MPs on the filters from the street dust samples and suspended particulate matter, fluorescence microscopy, binocular microscopy, SEM, EDX, and FTIR analysis were performed.

Microscopic analysis

MPs were observed and identified on the basis of visual characteristics mainly shape, color, and size using binocular microscope. Apart from this, particles were identified as MPs considering certain criteria described by Chubarenko et al. (2018) like the following:

1. There should be no evidence of cellular or biological structure.
2. Fibers should be uniformly thick along their length and not tapering at the end.
3. Colored particles must be uniform in color.
4. Fibers should not be segmented and should not look as twisted flat ribbons.

In this study, a binocular microscope (Catscope) was used to identify and separate MPs on a filter paper from road and aerial dust samples, and images were taken with a digital camera (Catymage) equipped with a microscope.

Fluorescence microscopy was also conducted to verify different MPs that has potential of fluorescence. During the different process of synthetic textile and plastic industries, a wide range of dyes, fluorescent pigments, optical brightening, and whitening chemicals are used (Christie 1994). Hence, fluorescence microscopy was used for identification of the extracted MPs using fluorescence microscope (Nikon eclipse 90i) with × 100 magnification under ultra violet filter. The corresponding images were taken with the Nikon digital camera which was equipped with the fluorescence microscopy (Dehghani et al. 2017).

SEM–EDX analysis

The morphological characteristics and elemental content of MPs were investigated using SEM–EDX. Selected samples were prepared on double-sided carbon conductive tape and were fixed on a 10-mm diameter SEM stub and analyzed under an accelerating voltage (Dehghani et al. 2017). These samples were also examined for their compositional characteristics using an EDX detector. In this study, ZEISS EVO 18 scanning electron microscope was used for morphological characteristics.

FTIR analysis

FTIR is a widely used as analytical approach to identify MP in samples. We have also used FTIR for the analysis of our desired samples. FTIR spectroscopy method has a long history of use in the investigation and characterization of synthetic polymers and their products. The vibrations of a sample's molecules are stimulated and detected by vibrational spectroscopy, resulting in unique spectrum fingerprints in the FTIR, which helps in characterization on the basis of comparison of polymeric chemical structure with known reference spectra. Here, in our study, PerkinElmer Spectrum version 10.4.3 was used for sample analysis and essential FTIR software was used for comparison of the unknown FTIR spectra. During FTIR spectroscopy, the sample was treated with infrared light (wavenumber range 400–4000 cm^{-1} for Mid-IR). A part of this infrared radiation is absorbed by the sample and finally measured in transmission or reflection mode.

Quality control and assurance of experiment

All equipment and glassware were pre-cleaned with Milli-Q and distilled water to prevent the contamination of external plastic/fiber with the required test setup throughout the test. All the chemicals and the reagents used were also filtered through the Whatman 42 filter paper. Working areas were carefully wiped with ethanol, and closed environment was maintained. Single use non-latex nitrile gloves were used and samples or the containers were also covered with aluminum foil to avoid any contamination. Also, blank was run throughout the experimental period to observe any contamination of MP presence from the surrounding environment or from the apparatus used, and the same procedure of double filtration was followed as for the samples analyzed. The resulting filter paper obtained after it was also observed under the microscope revealed that there was no detectable MP contamination during the analysis.

Result and discussion

Presence of microplastics in the studied area

MPs were found in the samples of street dust at all the sites of Varanasi and also in all the replicates of suspended dust samples at IESD-BHU. These MPs were of different size, shape, and color. The observed color of the MPs was pink, yellow, green, and red and few were transparent. The probability is high that transparent particles go undetected as transparent MPs are not easily visible or identified. At all sites, the presence of MPs was observed indicating the contamination of lower atmospheric environment with MPs.

Visual identification of microplastics

For visual identification, binocular and fluorescence microscopy was used and from the experimental analysis, varieties of MPs in the sample were observed. Fibrous, fragmented, and film-like MPs were commonly observed particles in both suspended dust and samples collected from the street dust. The fragmented MPs were 42% followed by fibers (33%), films (18%), and spherules (7%) in street dust sample (Fig. 2). Figure 3 and Fig. 4 exemplify the types of few MPs that were commonly observed in the present study by binocular microscopy. In a study from Chennai, India, mostly fragments and fibers were resulted from the street dust samples (Patchaiyappan et al. 2021). Similarly in Iran the street dust samples of city and county of Asaluyeh, MPs of fibers,

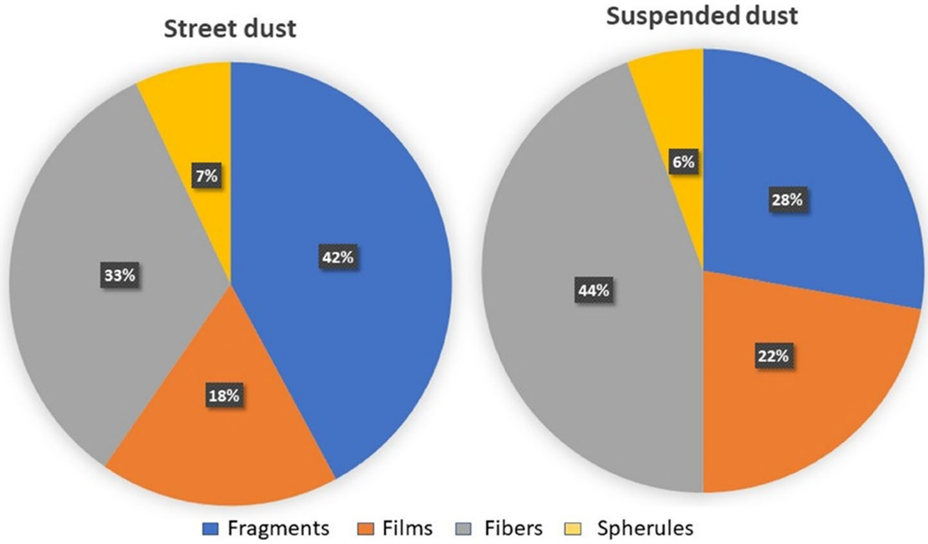

Fig. 2 Contribution of different types of MPs in pollution load

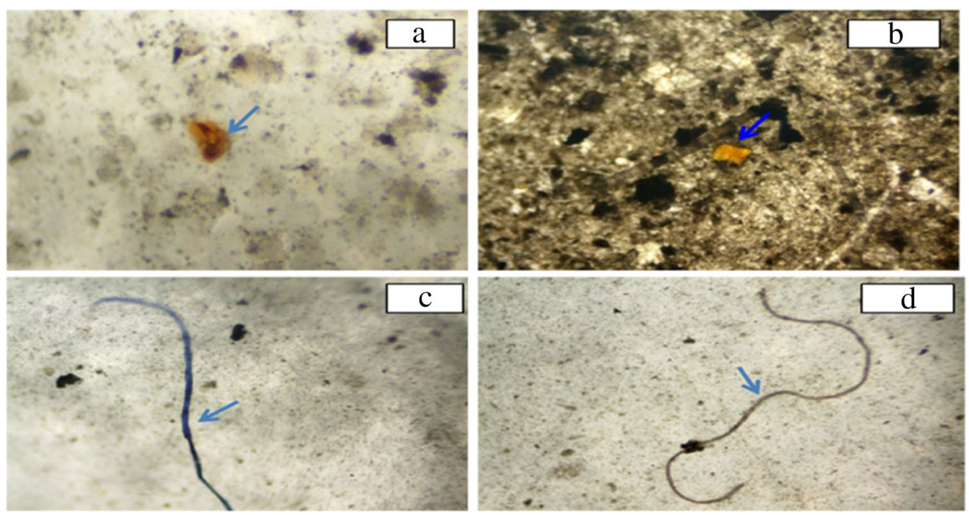

Fig. 3 Binocular microscopic images (at 20×) of different types of MPs in suspended air samples at IESD-BHU. **a** Fragmented. **b** Film-like. **c** and **d** Fibers

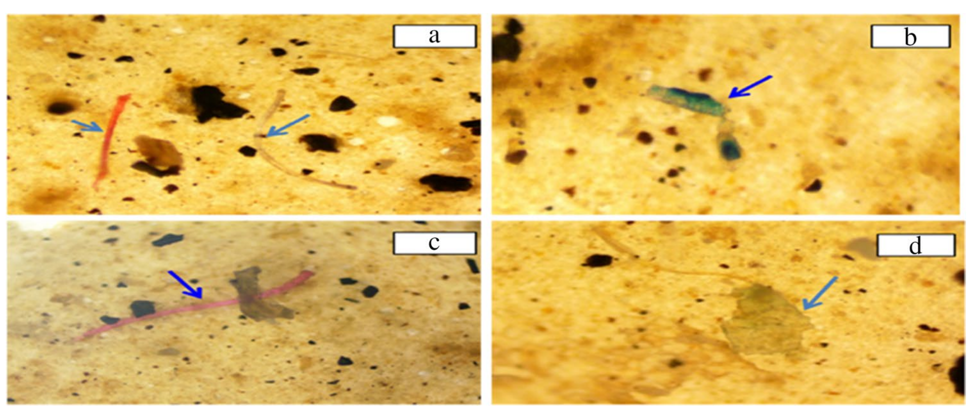

Fig. 4 Binocular microscopic images of different types of MPs (at 20×) in street dust at certain locations of Varanasi. **a** and **c** Fibers of different colors and different shapes. **b** Fragmented MP. **d** Film-like MP

fragments, spherules, and films were noticed (Abbasi et al. 2019). Dris et al. (2016) reported fibers as the major component of atmospheric fallout in Paris metropolis at two different urban and suburban sites. Similar observation was also noticed by Cai et al. (2017) while analyzing MPs in the atmospheric fallout from Dongguan City.

The suspended dust samples collected from the study area show presence of fibers (44%), fragments (28%), films

(22%), and spherules (6%) (Fig. 2). Identical results were also obtained from the other studies in India. Most common form of MPs in roadside suspended dust from Nagpur's urban and rural environments follow similar trend (Narmadha et al. 2020).

Such results were also noticed by Akhbarizadeh et al. (2021), while analyzing the dust of an urban area of Bushehr port, in the northern part of the Persian Gulf. Similarly, Liu et al. (2019) found microfiber, fragment, and granule types of MPs in the suspended atmospheric air of Shanghai.

The source of MPs in the atmosphere and street dust maybe indicated based on the morphological characteristics of MPs. The major source of fibers is clothes and textiles, while films/fragments result from disposable plastic bags and thicker plastic products (Browne et al. 2011). Dust emission from the land surface might be the probable source of MPs in the suspended atmosphere. Thus, dust emission and deposition between land surface, atmosphere, and aquatic environment were related with the transportation of MPs (Cai et al. 2017).

Fluorescence microscopy was also conducted to improve the quantification. Each sample was first counted by binocular and then by florescence so that maximum particles can be counted. In fluorescence, the MPs mainly absorb UV light at 300–400 nm and radiate blue (450–480 nm) or purple (400–450 nm) fluorescence (Lei et al. 2006). Abbasi et al. (2017) also used technique of fluorescence microscopy to identify the presence of MPs in the street dust samples of Bushehr City, Iran. Most of the visible particles include fragments and fibers which give fluorescence, followed by rare films, spherules, and pellets**.** Fluorescence particles were detected in most of samples but proper quantification was not achieved as not all MPs showed fluorescence property. Binocular microscopy technique was majorly considered for MP quantification. Data is given in supplementary file 2.

Morphology and elemental analysis

SEM–EDS is considered for assessment of the surface morphology and composition of MPs (Rocha-Santos and Duarte 2015). Many researchers have used SEM-EDS to obtain high-resolution image of the surface properties of the MP, with qualitative information. The results of the elemental composition recorded through SEM are recorded as Fig. 5. The SEM images of MPs were different for samples; few images showed a fairly smooth surface while others reflected rough surface indicating the marks of mechanical and chemical weathering, such as flaking, pits, grooves, and jagged edges. The elemental composition recorded through EDS marked presence of carbon and oxygen primarily. Other elements traced were Si, Ca, Mg, Al, Na, Fe, and Zn, possibly an indication of foreign solids, chemicals, dust and soil, or materials used for sample preparation. These elements maybe due to additives used in plastic polymers or adsorbed content on the MP surface. Various types of complex combinations of elements are used to provide special feature to polymers. For example, like Ca, Al, Mg, Na, and Si are used in most of the hydrocarbon polymers (e.g., PE, PP, and PS) to weigh down the oxidation cycle.

Chemical composition

The chemical composition of selected MPs from suspended and street dust was analyzed through FTIR. The polymers reported from FTIR were dominated by Polyethylene (PE). Other plastic types identified were polypropylene (PP) and polyethylene terephthalatete (PET). The spectrum range for these polymers of MPs ranges from 400 to 4000 cm^{-1}. Narmadha et al. (2020) investigated roadside suspended dust from urban and rural areas in Nagpur, India, and found low-density polyethylene (LDPE), rubber fiber, rayon, PS, polyolefin, polyaniline, and chlorinated PVC in the region. Likewise, PP, PS, and PE were the major MPs analyzed in Dongguan City air fallout (Cai et al. 2017). Liu et al. (2019) reported that in Shanghai, suspended atmospheric MPs included PET, PE, PS, rayon, polyacrylonitrile, ethylene vinyl acetate, poly(N-methylacrylamide), alkyd, and epoxy resin.

The commonly traced plastic by FTIR was PE. The function PE absorbance bands are positioned at 2914, 2847, 1470, and 718 cm^{-1}. The wide band around 1000 cm^{-1} was possibly detected because of inorganic impurity (presumably a silicate) on the particle surface. The typical PE bands at 1034, 1100, 1449, 2852, and 2920 cm^{-1} were noted. Further bands especially at 530, 690, 1385, and 1460 cm^{-1}, not existing in pure PE, were also visible. Also, in the atmospheric suspended dust, spectra of the sample show almost the same trend and peaks; thus, it is also classified as PE. Data is given in supplementary file 3 and 4. Majorly detected PE could be due to the widespread use of various PE-made items such as toys, milk and shampoo bottles, pipes, packaging films, grocery bags, and other bags in our day-to-day life.

Conclusion and future insight

In the current study, presence of MPs was investigated in the street and airborne suspended dust particles in Varanasi, India. This study shows that road dust and airborne dust from all sampling points contain MPs of different shapes and colors, and most of them were less than 1 mm in size. Particles detected were classified as fibers, spherules, fragments, and films, probably having sources like domestic, vehicular, and other commercial areas. The MPs found were dominated by fragments (42%) in street dust sample and fibers (44%) in suspended dust of the study area. In overall study, vivid colors of MPs were observed and a few were transparent in

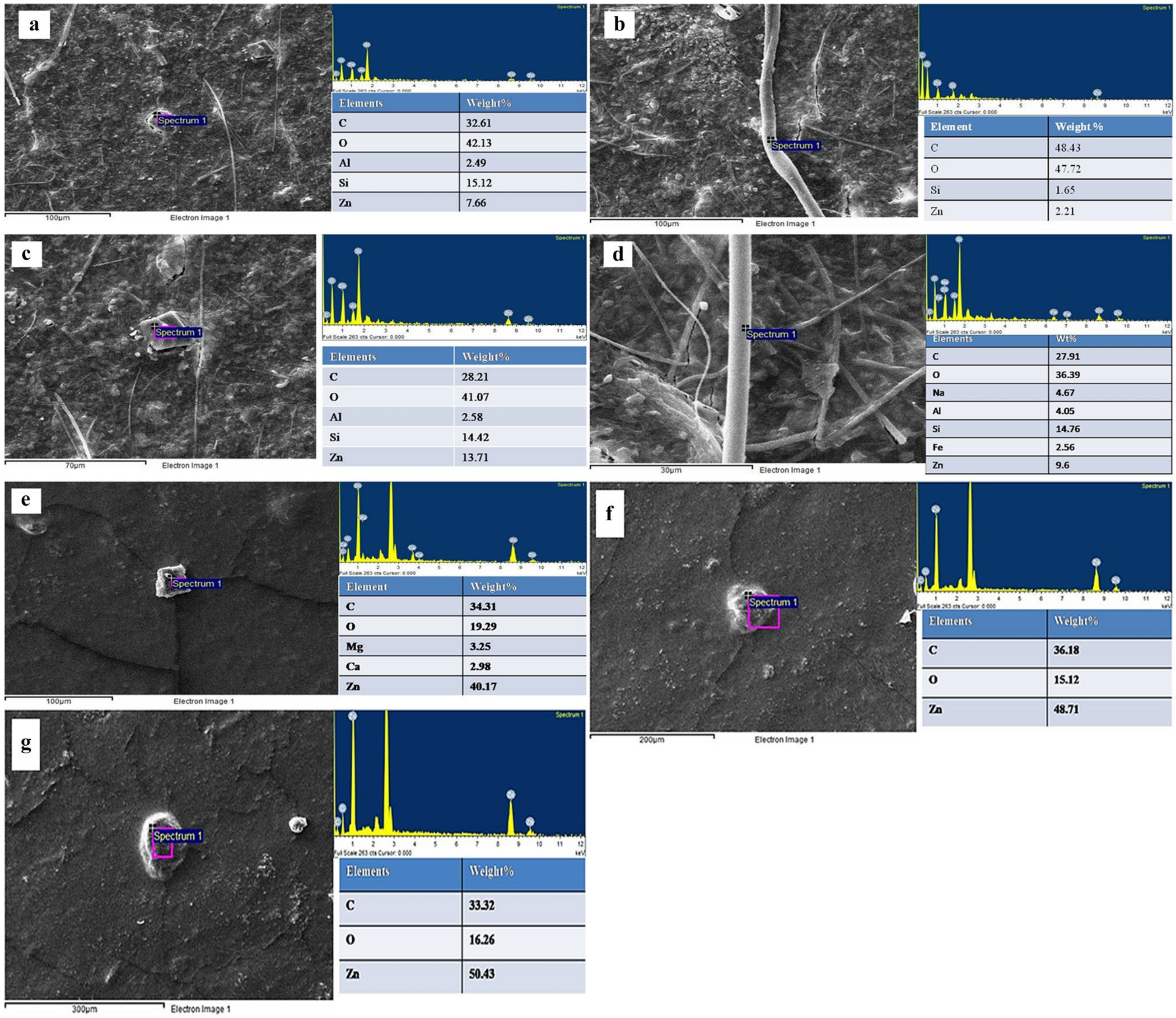

Fig. 5 SEM images and EDX analysis result of selected MPs. **a** and **e** Fragments. **b** and **d** Fibers. **c** Film-like. **f** and **g** Spherule

nature. Few MPs were also detected to show fluorescence under the blue filter, indicating the use of fluorescent dye in manufacturing. The probability of adsorption of different elements (Si, Ca, Mg, Al, Na, Fe, and Zn) on the rough surface of MPs was indicated by SEM–EDS. These elements may also be due to the presence of additives, plasticizer, stabilizers, pigments, and dye used in plastic manufacturing.

Our study gives first evidence on the presence of microplastic particles in both suspended and settled dust in a typical urban city of northern India. Presence of such MPs can have many detrimental effects on various ecosystems, which calls for systematic research to associate their presence and chemical nature with human exposure and possible health complications. We therefore, recommend, more detailed research considering their sizes and chemical nature with emphasis to identify individual particles so that source-specific management plan can be developed.

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Author contribution Tirthankar Banerjee and Jaspal Singh Chauhan designed the work. Dipika Pandey conducted the research and analysis. Dipika Pandey and Neha Badola wrote the manuscript. Tirthankar Banerjee, Jaspal Singh Chauhan, Dipika Pandey, and Neha Badola participated in the interpretation of results, review, and editing of the paper.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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