EXPLORATION OF MICROPLASTICS CONCENTRATION AND ATTRIBUTABLE HEALTH RISKS IN THE INDOOR AND OUTDOOR AIR SAMPLES.

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National University of Sciences & Technology
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A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Environmental Science

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2023

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"Exploration of microplastics concentration and attributable health risks in the indoor and outdoor air samples"

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DEDICATION

I dedicate this research work to my unwavering source of inspiration, my family, whose boundless support, and encouragement have been the driving force behind this academic journey. To my parents, whose sacrifices and belief in my potential have fueled my determination to pursue knowledge relentlessly. This work is also dedicated to my mentor, whose guidance and expertise have shaped my intellectual growth. Lastly, I dedicate this research to all those individuals who strive for excellence in the pursuit of knowledge; may this work contribute in some small way to the collective advancement of our fields of study.

ACKNOWLEDGEMENTS

My deepest gratitude to Allah Almighty, the most compassionate, the most merciful, for bestowing upon me wisdom, guidance, and strength during my academic journey. His mercy has been a constant source of motivation and inspiration for me. His blessings have been a constant driving force behind every step that I have taken in my quest for knowledge.

I express my sincere gratitude to my esteemed supervisor Dr. Muhammad Fahim Khokhar for his unwavering support, invaluable guidance, and expert mentorship throughout the entirety of my research work. His insightful feedback and encouragement have been instrumental in shaping the outcome of this research work.

I extend my heartfelt thanks to all guidance examination committee members, Dr. Muhammad Bilal Khan Niazi from Chemical Engineering Department (SCME, NUST) and Dr. Muhammad Ansar Farooq from IESE department for their time, expertise and constructive feedback which has significantly contributed to the refinement of this research work.

My heartfelt thanks go to my family for their boundless love, understanding, and encouragement. Their unwavering support has been a pillar of strength, and I am grateful for the sacrifices they made to facilitate my academic endeavors. Without my parents’ guidance and support I would not be here.

I acknowledge the lab facilities I availed at Institute of Environmental Science and Engineering, School of Natural Sciences (SNS) and Department of design and manufacturing engineering (DME) at NUST. I am also grateful for NUST research and development fund that has played a significant role in completion of research work.

Thanks to all for being an integral part of this significant milestone in my academic journey.

KHADIJA SHARAF DIN

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List of abbreviations

ABS	Acrylonitrile butadiene styrene
AMPs	Airborne microplastics
ATR-FTIR	Attenuated total reflection-Fourier Transform Infrared
HDPE	High density polyethylene
LDPE	Low density polyethylene
MPs	Microplastics
OECD	Organization for Economic Co-operation and Development
PC	Polycarbonates
PE	Polyethylene
PET	Polyethylene terephthalate
PM	Particulate matter
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene

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Abstract

Microplastics are ubiquitously pervasive throughout the environment, but unlike aquatic and terrestrial microplastics, airborne microplastics have received less scientific attention. This study is the first of its kind to explicitly examine microplastics in the indoor and outdoor air ($PM_{2.5}$) samples collected using active air samplers in Islamabad, Pakistan. The suspected synthetic particles were analyzed using ATR-FTIR, µ-Raman and SEM-EDX to categorize them based on their morphological characteristics, polymeric composition, and elemental makeup. Microplastics were found in all indoor and outdoor air samples, with indoor air samples (4.34 ± 1.93 items/m^3) being significantly more contaminated than outdoor air samples (0.93 ± 0.32 items/m^3) ($P<0.001$). Among all the indoor air samples, samples taken from classroom (6.12 ± 0.51 items/m^3) were more contaminated than samples taken from hallway (4.94 ± 0.78 items/m^3) and laboratory (1.96 ± 0.44 items/m^3). Fibers were found to be the prevalent shape type in indoor and outdoor airborne microplastics followed by fragments. Transparent- and black colored microplastic particles were predominant in both indoor and outdoor air samples. According to ATR-FTIR analysis, polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), and polystyrene (PS) were the most prevalent polymer types in both indoor and outdoor environments. Results from µ-Raman analysis corroborated the presence of the polymers identified by ATR-FTIR. Morphological analysis of particles by SEM indicated signs of weathering on particles' surface i.e., grooves, breaks, shredded edges, pits etc. SEM-EDX of randomly chosen particles unraveled the presence of C and O as core elements, along with the presence of heavy metals at some spots due to foreign material adhering to their surface. Correlation analysis of environmental factors i.e., $PM_{2.5}$, relative humidity, temperature, and wind speed with MPs abundance revealed non-significant relationships. The findings of this study call for further research on airborne MPs to better comprehend their dispersion, toxicity, interactions with other air pollutants, and attributable health risks.

Chapter 1

1. Introduction

1.1. Background

Global plastic production, driven by growing population, improving lifestyle and economic expansion, has steadily increased since the middle of the nineteenth century reaching 460 Mt in 2019. Likewise, plastic waste generation reached 353 Mt in 2019 with only 9% of this waste being recycled and the rest ending up in environment due to improper waste management practices i.e., dumping in landfills, incineration etc. (Organisation for Economic Co-operation and Development, 2021). Plastics are omnipresent and persistent in all environmental compartments, including water, soil, and air, and they have detrimental effects on the ecosystem (Choi et al., 2022).

Plastic waste, disposed into the environment, undergoes breakdown by manual (cutting, grinding) or natural ways (i.e., weathering) resulting in tiny plastic particles which can be classed as per their size range into different categories i.e., microplastics (less than 5 mm) and nano plastics (less than 100 nm) (Hartmann et al., 2019). According to a recent OECD (Organization for Economic Co-operation and Development) report, plastic waste generation is projected to increase thrice the amount of plastic waste generated in 2019 with environmental leakage of these plastics doubled reaching 44 Mt by 2060 (Organisation for Economic Co-operation and Development, 2021).

Depending on the fashion of being introduced into the environment these plastics can be categorized as primary plastics (directly released from a source i.e., textile industry) and secondary plastics (recycled plastics, or plastics resulting from breakdown of primary plastics) (Plastics Europe, 2021). Plastic waste that is released into the environment comes from a variety of sources, such as landfills, the burning of solid waste, the paint and textile industries, etc. Plastic waste is subject to degradation that can be either natural or artificial, producing minuscule invisible particles. Plastic particles of less than 5 mm in size are classed as microplastics which are pervasive in all aspects of the environment i.e., aquatic bodies, terrestrial ecosystem, and atmosphere (Kirchsteiger & Kasper-giebl, 2023).

1.2. Categorization of microplastics

Microplastics have been categorized as fibers, pieces (fragments), films, sheets, beads, flakes, etc. based on their morphology (Hartmann et al., 2019; Liao et al., 2021; Yadav et al., 2021; Yao et al., 2022). Plastic particles have also been classified based on their color i.e., black, white, grey, red, blue, pink, purple, yellow, and green (Hartmann et al., 2019). Furthermore, numerous synthetic polymer types residing in various parts of the environment have been identified in the literature i.e., polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyethylene (PE), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), low-density polyethylene (LDPA), high-density polyethylene (HDPA), and the list goes on (Hartmann et al., 2019; Konechnaya et al., 2020). Based on polymeric makeup of microplastics they are broadly classified into seven major groups i.e., Acrylics, polyethylene terephthalate, polypropylene, polyethylene, polyvinyl chloride, and acrylonitrile butadiene styrene (ABS). Major sources of primary microplastics in the atmosphere reported in the previous studies include the textile industry, paint, agriculture, plastic pallets, solid waste containing plastic, tire wear, landfill sites (Ahmad et al., 2023; An et al., 2020; Hale et al., 2020; Liu, Wang, Fang, et al., 2019) and oceans (via bubble burst) (Ding et al., 2022).

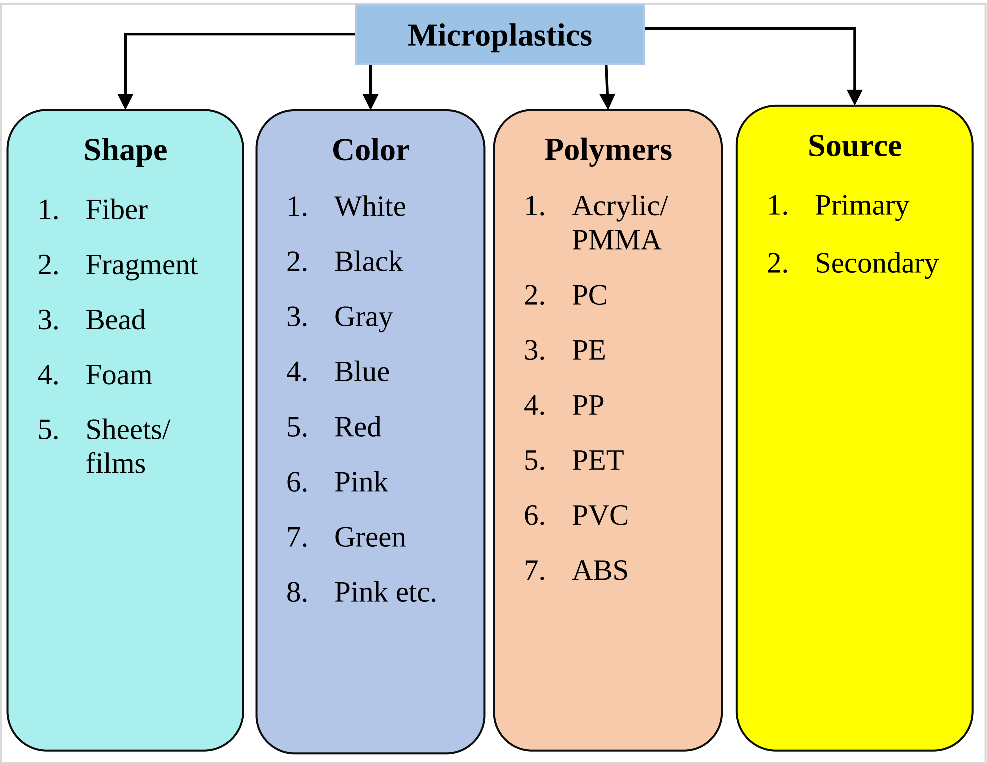


Figure 1.1. Categorization of microplastics

1.3. Atmoshere as a disregarded source and sink of MPs in Environment

Microplastics are ubiquitously present in all the environmental compartments and keep moving from one matrix to another through various routes. Recent studies have demonstrated atmosphere as a major source of microplastics in soil, water and far off remote areas (Allen et al., 2019; Su et al., 2019; Tian et al., 2022; Vitali et al., 2023; Zhou et al., 2020). In the past two decades, a plethora of research work has been published on aquatic and terrestrial microplastics in contrast to airborne microplastics (Amato-Lourenço et al., 2020; Dobaradaran et al., 2018). Microplastics residing in the air for the very first time were explored in Paris (Dris et al., 2015) and since then, this topic has drawn increasing attention, and the number of publications is progressively rising along with the level of awareness. Thus far, studies on airborne microplastics have been conducted in Paris (Dris et al., 2015, 2016, 2017), Germany (Enyoh et al., 2019), China (Cai et al., 2017; Li et al., 2020; Liao et al., 2021; Liu, Wang, Fang, et al., 2019; Zhu et al., 2021), Portugal (Xumiao et al., 2021), south Korea (Choi et al., 2022), India (Pandey et al., 2022), Sri Lanka (Perera et al., 2022), Iran (Abbasi et al., 2023), Spain (Torres-Agullo et al., 2022), Mexico (Shruti et al., 2022), New Jersey (Yao et al., 2022), and central London (Kacprzak & Tijing, 2022). It is challenging to compare the findings of previous studies on airborne microplastics published since 2015 since different techniques have been used for sampling, sample handling, and analysis (Zhu et al., 2021). Various studies have used passive air sampling while others have employed active air sampling to collect samples of suspended airborne particulate matter (Abbasi et al., 2023; Chandrakanthan et al., 2023; Choi et al., 2022; Klein & Fischer, 2019; Zhu et al., 2021). Analytical approaches to investigate airborne MPs have evolved over time and developed into more reliable methodologies, therefore it is imperative to stringently adhere to one standard methodology to get more accurate, reliable, reproducible, and comparable results.

1.4. Transport of microplastics

Microplastics, owing to their light weight and low densities can be transported with winds over long distances, thereby contaminating far off sparingly inhabited areas. Allen et al. reported ubiquitous presence of synthetic particles (e.g., fibers, fragments) in all samples taken from wet and dry atmospheric deposition in remote Pyrenean mountain catchment area (Allen et al., 2019) suggesting atmospheric transport of MPs from nearby urban areas. Allen et al. further demonstrated MPs transport via atmosphere over ~95 km employing air mass trajectory, implying potential of airborne MPs to contaminate remote areas (Allen et al., 2019). Additionally, there is a dearth of knowledge on transport dynamics, distribution, source apportionment, fate, interactions with other pollutants and health implications of airborne MPs, which require further study.

Microplastics have been widely reported in agricultural soil (Tian et al., 2022), dust (e.g., Aslam et al., 2022; Dehghani et al., 2017; Pandey et al., 2022), personal care products (Deng et al., 2022), cosmetics (Cheung & Fok, 2016; Napper et al., 2015), wastewater treatment plants (Acarer, 2023), food items (Vitali et al., 2023) and water systems. Given the widespread presence of microplastics in the environment, concerns about ongoing human exposure to these synthetic particles and the ensuing harmful effects are growing. Microplastics can enter the human body via various routes i.e., ingestion, breathing (Dris et al., 2017; Vianello et al., 2019; Wright & Kelly, 2017), and can have serious lacerating, cognitive, and numerous other unknown impacts on human health (Vianello et al., 2019). Recently microplastics have been found in human lung tissues (Amato-Lourenço et al., 2021; Vianello et al., 2019), placental tissue, lymph nodes, and blood (Boakes et al., 2023; Jenner et al., 2022) implying serious health risks. Microplastics suspended in air have been reported to adsorb toxic chemicals i.e., heavy metals, persistent organic pollutants and serve as a vector for transport of these hazardous chemicals in environment (Abbasi et al., 2020; Ortega & Cortés-Arriagada, 2023). The growing human and environmental health concerns call for further investigation of airborne MPs to help form effective policies and regulations to curb emissions of these particles in the environment.

1.5. Rationale of study

Despite the worst air quality challenges in Pakistan (Anjum et al., 2021; Anwar et al., 2021; Rasheed et al., 2015), there is no study on airborne microplastics, leaving the public health sector and policymakers without any baseline information for policymaking and abatement strategies. Albeit (Aslam et al., 2022) studied MPs in deposited dust samples taken from residential indoor environments in Lahore and Sahiwal and reported 241.4 items/m^2 in Lahore and 162.1 items/m^2 in Sahiwal, but it lacks direct analysis of microplastics residing in indoor and outdoor air (Aslam et al., 2022). This research has been designed to fill this gap by exploring the existence, physical, and chemical properties of airborne microplastics and developing a complete methodology for future research. According to our knowledge, no previous research has been published on airborne microplastics in Pakistan; nevertheless, limited research has been available on microplastics residing in dust, soil, sediments, and wastewater.

1.6. Research questions

Listed below are the study's research questions.

- “Are there microplastics in indoor air and outdoor air samples of study area?”
- “If there are microplastics in collected air samples of study area, what are their physical and chemical characteristics?”

1.7. Objectives of study

Keeping in view the research gaps study objectives were designed as listed below:

1. To Visually sort and quantify microplastic particles extracted from $PM_{2.5}$ samples. This objective also encompasses classifying MPs based on their physical characteristics i.e., color, size, and shape.
2. To analyze polymeric composition of identified microplastic particles using µ-Raman and ATR-FTIR.
3. To unravel surface details of particles and unravel their elemental composition using scanning electron microscope coupled with energy dispersive X-ray analysis.
4. To suggest a simplest and efficient methodology for exploration of airborne microplastics

Furthermore, this study also emphasizes the existing breadth of knowledge regarding the risks of inhalable microplastics to human health and offers potential directions for this work in the future.

Chapter 2

2. Literature Review

There is a plethora of research work on aquatic and terrestrial microplastics in contrast to research work on airborne microplastics. Microplastics residing in the air for the very first time were explored in Paris and since then this subject has gotten ever-increasing attention and the number of publications is increasing gradually with increasing awareness on the subject. Studies from 2015 to date have used varying approaches for exploring airborne microplastics which make comparison of their findings less likely.

Dris et al., (2015) examined microplastics in atmospheric fallout in Greater Paris and reported that fibers were a common form type of synthetic particle detected in the fallout samples with more than 50% of the fibers having a size greater than 1000 µm. Additionally, their findings suggested that synthetic fibers in the air might be sources of microplastic debris in other environmental matrices, like aquatic ecosystems (Dris et al., 2015). To study microplastics residing in atmosphere as potential source of microplastics in other environmental compartments, Dris et al., (2016a) explored airborne microplastics in urban and suburban areas later in 2016. They reported a large number of synthetic fibers, 2-355 particles/m^2/d, indicating that the atmosphere cannot be disregarded as a source of MPs in the environment (Dris et al., 2016). Following Dris et al., 2015 & 2016, Dris and his team for the very first time studied microplastics in indoor and outdoor air in a parallel fashion and reported indoor air (1.0-60.0 fibers/m^3) being significantly more contaminated then the outdoor air (0.3-1.5 fibers/m^3) with 33 percent of all identified fibers being synthetic in nature (predominately PP) (Dris et al., 2017).

Klein and Fischer (2019) conducted research to examine prevalence of microplastics in atmospheric deposition in urban and suburban areas of varying degree in Hamburg, Germany. Their work reflected the ubiquitous existence of microplastic fibers in all samples with range of shape (fiber and fragment dominated by 95%) and size in identified MPs (Klein & Fischer, 2019). A study in northern New Jersey has characterized airborne microplastics in different indoor (office, classroom, hallway, residential house) and ambient settings (roof area) by employing passive indoor air sampling of total atmospheric deposition and of ambient particulate matter ($PM_{2.5}$ and PM_{10}). It revealed the predominance of fibers in interior settings and suggested 13-57 times higher deposition rate indoors than it was outside (Yao et al., 2022). Microplastics levels in interior environments have been found to be substantially greater than in outdoor settings (Choi et al., 2022; Yao et al., 2022). Choi and his coworkers discovered that indoor air contains longer, heavy synthetic fibers than outdoor air. Furthermore, their findings showed that the size range of 48–96% of the particles discovered in samples is 20–100 µm, with PP and PE being the most prevalent polymers in the atmosphere (Choi et al., 2022).

Cai and his colleagues reported existence of MPs in atmospheric fallout (175-313 particles/m^2/d) and unraveled their morphological and polymeric characteristics in Chinese city of Dongguan using SEM and µ-FTIR techniques (Cai et al., 2017). Later in 2020, *Li* and his colleagues studied airborne fibers to unravel their concentration and categories based on chemical composition and size in Beijing. According to this study most of the fibers had size less than 20 µm with 80 percent of these fibers being synthetic in nature (Li et al., 2020). Owing to change in methodologies opted in earlier studies, another study was conducted simultaneously in five megacities of China with same protocol to acquire comparable results. This study reported MPs in all collected air samples from northern (358 ±132 particles/m^3) and southeast urban areas (230 ± 94 particles/m^3) (Zhu et al., 2021). Likewise in Shanghai (Liu, Wang, Fang, et al., 2019) and coastal city of China (Liao et al., 2021) MPs residing air have been studied to investigate sources and attributable human health risks.

2.1. Airborne microplastics as pollutant carrier

Microplastics can absorb heavy metals, PAHs (polycyclic aromatic hydrocarbons), and other contaminants on their surface (Abbasi et al., 2020; Wright & Kelly, 2017) thereby acting as a pollutant carrier in soil, air and water. Interactions with other pollutants in air may increase its toxicity and alter chemical structure of polymers (Kacprzak & Tijing, 2022). The production of microplastics for various purposes i.e., in the form of microbeads to replace other exfoliating ingredients in personal care products has led to a rise in the amount of microplastics used in daily life (Fendall & Sewell, 2009). These microplastics used in various daily life products after their primary usage enter waste water streams wherefrom they can enter plants or escape into atmosphere due to their extremely small size and ability to persist in environment (Ettore et al., 2008). Microplastics released into atmosphere can pose serious health risks via inhalation to humans which are not completely known thus far (Wright & Kelly, 2017). Due to the inevitability of inhalation exposure to airborne MPs, a study was carried out to determine the abundance of MPs in the interior air of five different residential homes in Aveiro, Portugal, to calculate the risk of inhalation. According to this study, 58.7% of the fibers were natural fibers, while 19.6% of the detected fiber polymers were synthetic.

Nearly 21.7% of the overall percentage of fibers in the samples were unidentified. Average airborne MPs concentration in indoor air of living rooms was reported to be 1.1 particles/m^3 (Xumiao et al., 2021).

Owing to paucity of research work on the human exposure to microplastics in environment and study of these particles reported in human blood and lung tissues (Amato-Lourenço et al., 2021) at molecular level to unravel their health implication, their impacts on human health are not known (Amato-Lourenço et al., 2020). Furthermore, studies that have identified and quantified airborne microplastics to date have been using varying sampling and analyzing approaches which limit their comparison (Zhu et al., 2021). Recently microplastics have been found in human lung tissues (Amato-Lourenço et al., 2021; Vianello et al., 2019), placental tissue, lymph nodes, and blood (Boakes et al., 2023; Jenner et al., 2022) implying serious health risks. The first three studies conducted on atmospheric MPs in Paris (Dris et al., 2015, 2016, 2017) used a passive sampling technique for air sample collection, stereomicroscope for quantifying MPs and FTIR for polymer type analysis. Since then, analytical methods to study microplastics have evolved into more reliable techniques. A number of publications have summarized sample collection, preparation and subsequent analytical methods for analyzing airborne microplastics (Chen, Fu, et al., 2020; Liu, Wang, Wei, et al., 2019; Liu, Zhang, et al., 2019; Prata et al., 2020), nevertheless there is a difference in these methods at some point or other.

2.2. Discrepancies in past methodologies

Various studies have used passive air sampling while others have employed active air sampling to collect samples of airborne particulate matter (Abbasi et al., 2023; Chandrakanthan et al., 2023; Choi et al., 2022; Klein & Fischer, 2019; Zhu et al., 2021). Initial studies i.e., Dris *et al.* 2016, 2017 have used only visual analysis to examine microplastics sampled from atmosphere. Owing to size limitation of FTIR spectroscopy recent studies have used µ-Raman spectroscope to study MPs smaller than 20 µm. Both FTIR and Raman spectroscopy do not require sample preparation for analysis and are non-destructive and effective in identifying airborne MPs (Beaurepaire et al., 2021; Chen, Feng, et al., 2020). Likewise different sampling approaches have been adopted in previous studies to collect airborne particles i.e., passive air sampling, active air sampling, use of funnel to collect atmospheric deposition, use of particulate matter sampler and vacuum sampler.

Owing to sampling efficiency and learned benefits of active air sampling from literature this study has opted active air sampler to collect $PM_{2.5}$ samples. Microplastics can enter the human body via various routes i.e., ingestion, breathing (Dris et al., 2017; Vianello et al., 2019; Wright & Kelly, 2017) and can have serious lacerating, cognitive, and numerous other unknown impacts on human organs (Vianello et al., 2019).

Recently microplastics have been found in human lung tissues (Amato-Lourenço et al., 2021; Vianello et al., 2019), placental tissue, lymph nodes, and blood (Boakes et al., 2023; Jenner et al., 2022) implying serious health risks. First three studies conducted on atmospheric MPs in Paris (Dris et al., 2015, 2016, 2017) used a passive sampling technique for air sample collection, stereomicroscope for quantifying MPs and FTIR for polymer type analysis. Since then, analytical methods to study microplastics have evolved into more reliable techniques. A number of publications have summarized sample collection, preparation and subsequent analytical methods for analyzing airborne microplastics (Chen, Fu, et al., 2020; Liu, Wang, Wei, et al., 2019; Liu, Zhang, et al., 2019; Prata et al., 2020), nevertheless there is a difference in these methods at some point or other. This study has opted methods reported with better efficiency, reliability, suitability, and precision for airborne MPs’ analysis in literature to acquire reliable outcome.

Chapter 3

3. Material and methodology

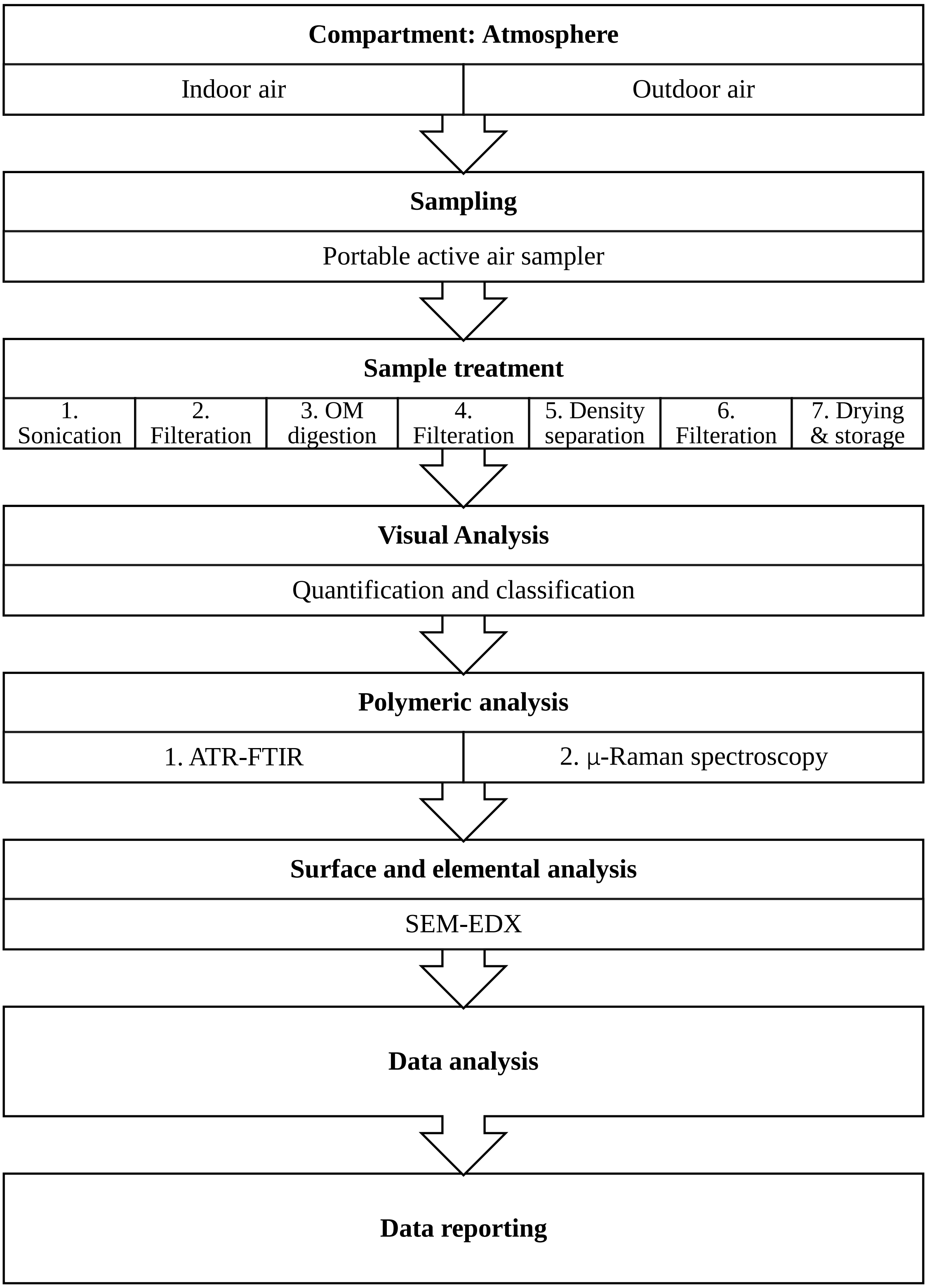


Figure 3.1. Flowsheet diagram of methodology

3.1. Study area

This study was conducted at Institute of Environmental Engineering and Sciences (IESE), the National University of Science and Technology, Islamabad (Lat: 33.645572. Lon: 72.990345). Islamabad, the capital, and ninth-most populated city in Pakistan, is situated on the Potwar plateau and has a population of 12,32,000 people. This city is enriched with eye catching scenery and is home to the affluent population of the country. It is known for it well maintained infrastructure.it receives an annual rainfall of 1143 mm and has a humid subtropical climate. Four places at the IESE department were chosen for sampling, including the laboratory, hallway, classroom, and roof top, considering numerous aspects such as occupancy rate, human activity, and environmental conditions. The two-week sample window for this study is from December 7 to December 22, 2022. In case of precipitation event a three-day gap was taken before resuming sampling. Furthermore, only working days of the week were used for sampling.

Figure 3.2. Study area map (a: Rooftop, b: Laboratory, c: Hallway, d: Classroom)

1. Material required

1. Aluminium foil
2. Metal tweezer
3. Glassware (beakers, petri dishes, pipette)
4. Sterile gloves
Whatman® quartz filter paper
5. Glass fiber filter paper

2. Equipment

1. Active air samplers
2. Laminar flow hood
3. Oven, Incubator
4. Filtration assembly
5. Sonicator
6. Beaker shaker
7. Weighing balance
8. µ-Raman
9. FTIR
10. SEM-EDX
11. Microscope

3. Software

1. ImageJ
2. Origin Lab
3. PerkinElmer Spectrum IR (Version 10.6.2)

4. Solutions

1. 30% Hydrogen per oxide (H_2O_2)
2. Zinc Chloride ($ZnCl_2$), (density: 1.6 g/cm^3)
3. Distilled water
4. Ethanol (70%)

Figure 3.3. Required resources for study.

3.2. Sampling protocol

Before commencing air sampling, a thorough survey of the study area was conducted to select appropriate sampling locations keeping in view various factors i.e., human activity, space, and environmental conditions. All the quartz filter papers, to be used in the sampling, were pre-weighed and stored in labeled packaging. Glassware to be used immediately after the sample collection, for the sample storage and sample preparation, was thoroughly washed with ultrapure water and then dried. Depending on the working efficiency of active air sampling, it was chosen for collecting both indoor and outdoor particulate matter ($PM_{2.5}$) samples. Quality control measures were taken to avoid any sort of sample contamination. Sampling was conducted during weekdays to estimate the influence of human activities on airborne microplastics and for comparison, a sample on weekends was also conducted.

For outdoor air sampling, a gravimetric sampler was installed on the rooftop of the IESE building. Pre-weighed Whatman's quartz filter paper (pore size = 1.2 µm, diameter = 47mm) was placed inside the sampler using a metal tweezer to avoid any sort of contamination, and the sampler was run at the flowrate of 16 l/min for 24 hours. After the 24-hour sampling period filter paper was removed using a metal tweezer and then placed in a labelled petri dish. Labelled petri dishes were covered with aluminum foil to avoid contamination and were opened only when necessary for sample preparation and analysis. For indoor air sampling a similar protocol was followed, except the flow rate for indoor sampling was 6 l/min for 24 hours. Figure 3.3. indicates required resources for exploration of airborne microplastics.

3.3. Sample preparation

After sample collection, labelled petri dishes containing filter papers covered with aluminum foil were sent to a laboratory for sample preparation and analysis. Every filter paper containing particulate matter was first placed in a desiccator for 24 hours and then weighed to calculate the total suspended particulate matter (final weight of filter paper – initial weight of filter paper). Sample treatment includes following steps:

i. Sonication

Each filter paper was placed in a beaker with 15 ml of deionized water and sonicated for 10 minutes to remove sample particle from the surface of the filter paper effectively.

ii. Organic matter digestion

Organic and inorganic impurities may affect the subsequent lab analysis, so removing these impurities can help acquire more precise results. For removing organic impurities, oxidative digestion was employed. After sonication clean filter paper was removed from the beaker and 15 ml of 30% hydrogen peroxide (H_2O_2) was added into the beaker containing particulate matter and 15 ml deionized water for organic matter (OM) digestion. This beaker was then heated at 70ºC for 1 hour to speed up digestion.

iii. Filtration

After the digestion of organic matter, the remaining solution was passed through the filtration assembly using GF/C glass microfiber filter paper (1.2µm, 47 mm) to recover acid digested sample.

iv. Density separation

The sample was next subjected to density separation to remove inorganic mineral contaminants from the sample, for which glass fiber filter paper containing acid digested sample was washed into the beaker with 10 ml of $ZnCl_2$ solution (having density of 1.7 g/cm^3) and this solution was then agitated at 350 rpm for 5 minutes. After agitation, it was left in laminar flow hood for settling of particles under gravity (sedimentation) for 1 hour. Since synthetic particles are less dense than inorganic impurities so they tend to float at surface during sedimentation.

v. Filtration and storage

A supernatant layer of synthetic particles was carefully removed onto another glass fiber filter paper by filtration. Additional deionized water (10 ml) was passed through filtration assembly to remove the remaining salt solution (Prata et al., 2020). After extraction of the desired sample particles, it was dried in an oven at 70ºC for 1 hour and then stored in incubator (37°C) for subsequent lab analysis. Similar procedure was repeated with every sample.

3.4. Visual analysis and quantification

Prepared samples were observed using Olympus Digital microscope (DSX 1000) under 20x magnification Lense. Various physical characteristics were considered to sort microplastics into different categories under microscope i.e., color, shape, elasticity, hardness test (i.e., pressing particles slightly with needle/tweezer to observe if they break or resist, with particles breaking during this test being considered as organic matter) (Hidalgo-Ruz et al., 2012; Liu, Wang, Wei, et al., 2019; Mbachu et al., 2020; Prata et al., 2020). For the purpose of identifying and quantifying MPs, a set of criteria was adopted, including the following: 1. No evident organic structure; 2. Uniform thickness of the particle; 3. Even color; and 4. Remain intact when being applied pressure (Hidalgo-Ruz et al., 2012; Masura et al., 2015).

Samples were strictly opened under microscope to avoid contamination. Based on shape, microplastics were classed as fragments, fibers (length-width ratio >3:1), beads, and sheets. Microplastics were analyzed with respect to size, shape, and color. Based on size, particles were classed in five size groups i.e., < 50 µm, 50-100 µm, 100-250 µm, 250-500 µm, 500-1000 µm.

3.5. ATR-FTIR analysis

For polymeric analysis, 30 particles per each sampling site encompassing each color and shape type were randomly selected. These randomly selected plastic particles were analyzed under ATR-FTIR spectrophotometer (Spectrum Two, PerkinElmer, USA, range = 400-6000 cm^{-1}). FTIR results help to verify the suspected microplastic particles by giving different spectral graphs of different sample particles. These spectral graphs were compared with the reference spectrums of various polymers identified in literature, with more than 70 percent similarity considered as positive match. Following each sample analysis ethanol was used to clean the crystal before a background scan was performed to prevent contamination.

3.6. µ-Raman spectroscopy

Sample particles of <20 µm size were particularly analyzed using µ-Raman spectroscope (Model: 532-TEC-Ci) using Raman shift = 0–4000 cm^{-1} and laser = 532 nm. A subsample of different particles (n = 28) from each sampling site was randomly prepared to consider each color and shape type. The obtained spectral data was analyzed using Origin Lab to make graphs and analyze peaks. By comparing the key distinctive peaks with the reference spectra provided in the literature, different polymer types were identified.

3.7. SEM-EDX analysis

Random particles were chosen from each sample group and examined under a scanning electron microscope (Model: KYKY EM-6900) coupled with energy dispersive X-ray spectroscopy for the purposes of surface examination and elemental composition analysis. SEM employs an intense beam of electrons to scan the surface of sample particles and give output in the form of high-resolution photographs indicating surface details of the particles. Microplastic particles from each sample were picked with the help of metal tweezer under microscope and were carefully placed on stubs. Peaks of elements possibly present in particles are shown by energy dispersive x-ray analysis of particles.

3.8. Quality control

Each stage of analysis, including sample collection, preparation, and analysis, was conducted with the utmost attention to quality. Before usage, every glassware was thoroughly cleaned with ultrapure water. Metal tweezers were used to insert and remove filter papers from the sampler. To prevent contamination, all the obtained samples were put in labelled petri dishes that were wrapped with aluminium foil. When necessary, washing and solution preparation utilized only distilled water. Furthermore, the use of latex gloves and lab coats was assured. Only when a sample was required for analysis was it conscientiously opened to prevent contamination of any type.

3.9. Statistical analysis

For statistical analysis of data, Origin Lab and RStudio (4.2.2) were used. To test the difference between means of two sampling groups i.e., indoor, and outdoor, a paired t-test was performed. Difference determined by this method was statistically significant $p < 0.005$. Shapiro wilk’s test was performed to verify normality of data. All statistical outcomes are represented as (mean ± SD), unless otherwise stated. To evaluate correlation of MPs abundance with selected air quality factors i.e., T (°C), RH (%), $PM_{2.5}$, and wind speed (m/s) correlation coefficient was determined using Pearson's method.

Chapter 4

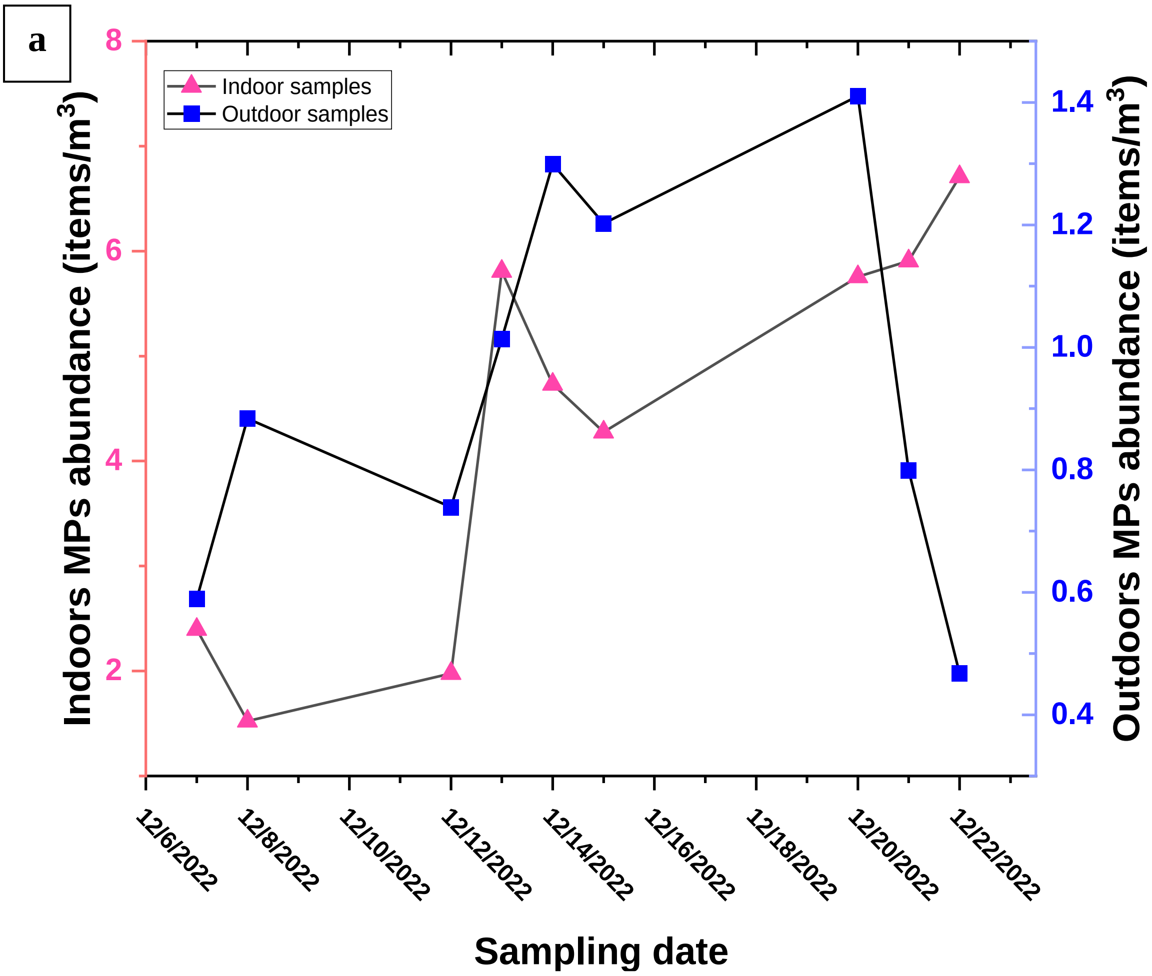
4. Results and Discussion

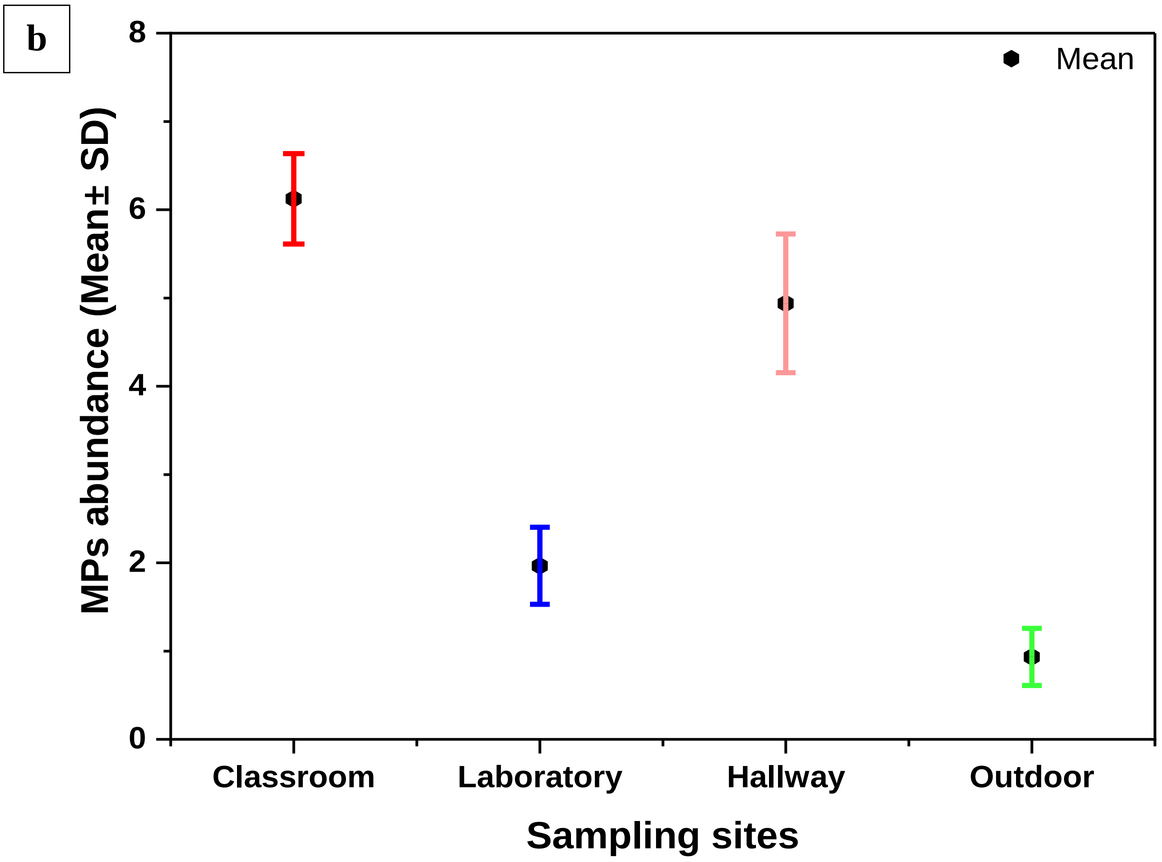
4.1. Microplastics abundance in air samples

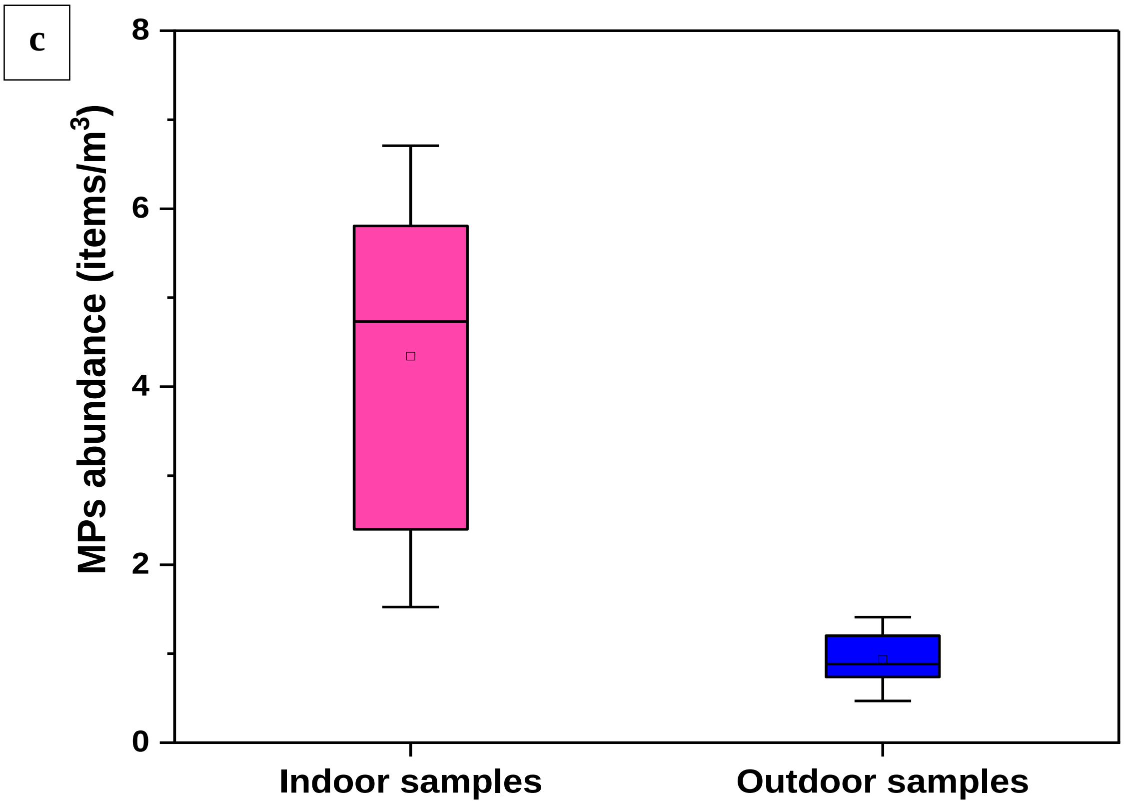
Microplastics were ubiquitously found in all indoor and outdoor samples (n = 18) with varying abundance. Indoor samples (4.34 ± 1.93 items/m^3) were more contaminated than outdoor samples (0.93 ± 0.32 items/m^3). Among indoor air samples, samples taken from class (6.12 ± 0.51 items/m^3) had comparatively higher microplastic abundance (Items/m^3) than those taken from laboratory (1.96 ± 0.44 items/m^3) and hallway (4.94 ± 0.78 items/m^3) (Fig. 2. b). There was a significant difference between the means of both sample groups ($P < 0.001$; Fig. 2. a, b, c). Increased human activity, erosion of plastic products, and inadequate ventilation are the main contributors to higher indoors contamination. The difference in MPs abundance among different indoor locations may be attributed to varying human activities and ventilation level.

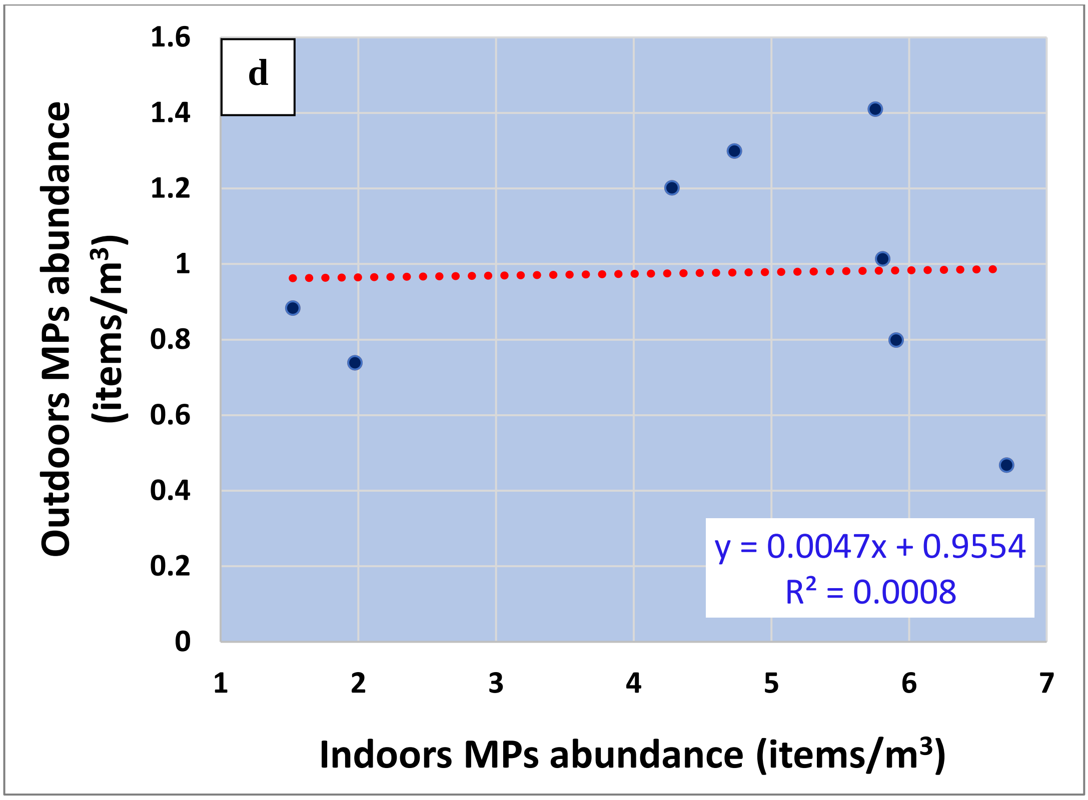
There was non-significant relationship (since correlation value was far <1) between MPs abundance in indoors environment and outdoors environment as shown in Fig. 2. (d). Likewise, relationship between particulate matter concentration ($PM_{2.5}$) was also very weak i. e., correlation value was $0.15 \ll 1$ as indicated in Fig. 2. (e). Both environments have different potential sources, and dispersion dynamics which may also serve as factors leading to the difference found in their MPs' concentration levels and varying characteristics. Both indoor and outdoor MPs concentrations reported in this study are more than those reported in Colombo (indoor: 0.13–0.93 particles/m^3, outdoor: 0.00 – 0.23 particles/m^3), Ahvaz (none–0.017/m^3) and over northwestern Pacific Ocean (0.0046 – 0.064 items/m^3) (Abbasi et al., 2023; Ding et al., 2022; Truong et al., 2021). The outdoor MPs abundance found in this study (0.93 ± 0.32 items/m^3) is comparatively less than the outdoor concentrations of MPs found in other areas i.e., Shanghai.

(average 1.42 n/m3) (Liu et al., 2019a), Bangkok (333.42 ± 142.99 n/m^3) (Sarathana and Winijkul, 2022), megacities of China (northern cities: 358 ± 152 n/m^3, Southeast cities: 230 ± 92 n/ m^3) (Zhu et al., 2021), south Korea (1.96 ± 1.65 particles/m^3) (Choi et al., 2022) and Wenzhou (189 ± 85 n/m^3) (Liao et al., 2021). Multiple factors can contribute to variations in MPs abundances i.e., population densities, level of industrialization, disparate methodology, contrasting source and transport dynamics, varying meteorological, spatiotemporal, socioeconomic, and environmental conditions (Hartmann et al., 2019; Zhang et al., 2020). Furthermore, it is challenging to compare different studies because of the variety of sampling, sample treatment, and sample analysis procedures used.




b
8
6
4
2
0
MPs abundance (Mean± SD)
● Mean
Classroom
Laboratory
Hallway
Outdoor
Sampling sites


c
8
6
4
2
0
MPs abundance (items/m^3)
Indoor samples
Outdoor samples



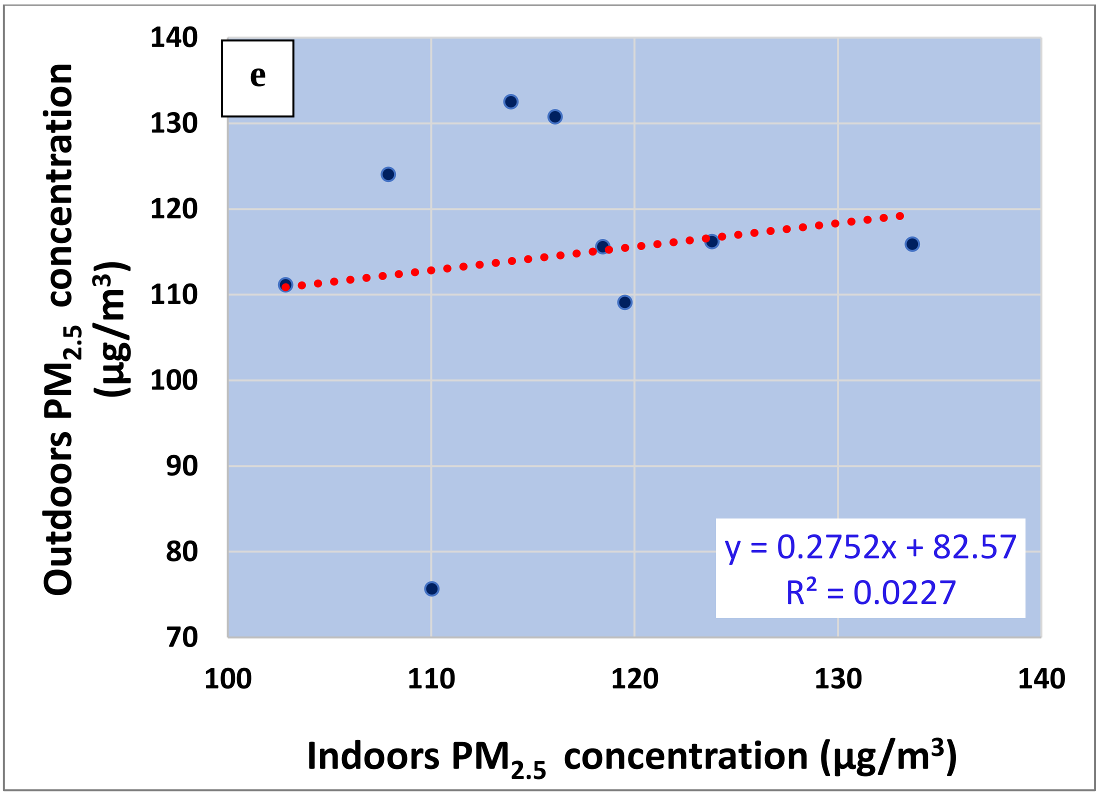


Figure 4.1. (a)Abundance of microplastics (n/m^3) in indoor and outdoor air samples, (b) Comparative abundance (mean ± SD) at all sampling sites. (c) Statistical difference in MPs abundance between indoor and outdoor samples. (d) Correlation between MPs abundance in indoors and outdoors. (e) Correlation between PM2.5 concentration indoors and outdoors.

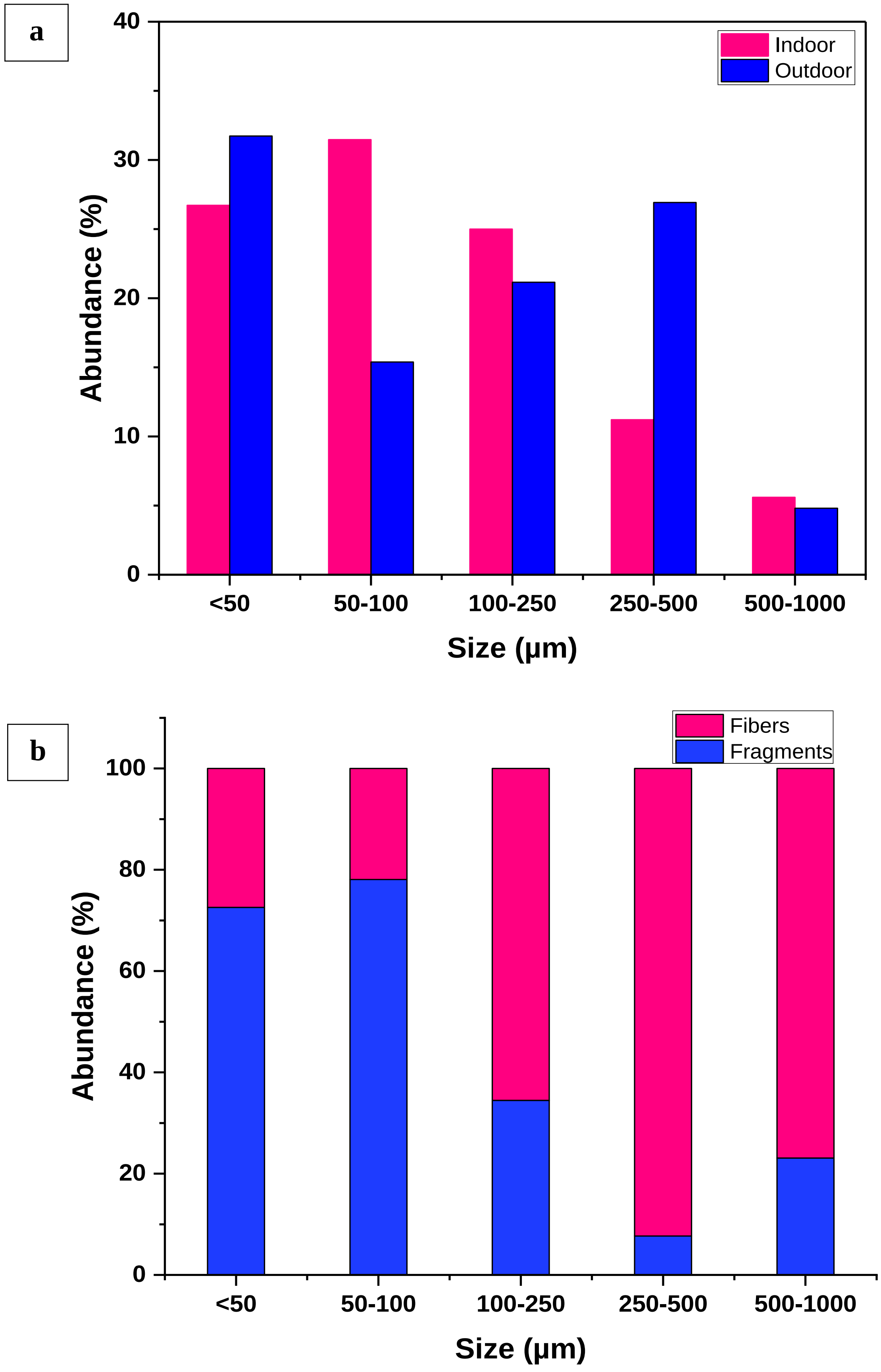
4.2. Size, Color and Shape of microplastics

ImageJ was used to measure the size of different microplastic particles identified under microscope. Microplastics were placed in five groups based on their size, i.e., <50 µm, 50-100 µm, 100-250 µm, 250-500 µm and 500-1000 µm. Microplastics of less than 50 µm size were dominant in outdoor air samples (31.73%) followed by those falling in size range 250-500 µm (26.92%). While in indoor air samples 50-100 µm sized microplastics (31.46%) were prevalent followed by those of less than 50 µm size (26.72%). Microplastics of 500-1000 µm were (mostly fibers) least abundant in both indoors (5.60%) and outdoors (4.80%) (Figure 6. (a)). Small sized microplastics owing to their low weight tend to suspend in atmosphere for longer time periods, in contrast to this larger size microplastics are heavier and get easily deposited. Small size microplastics when get deposited via wet/dry deposition, there is a higher probability of these small sized lighter particles to get resuspended via wind.

Size range for the identified microplastics in this study was 2.70-937.91 (mean = 144.29) µm for indoor MPs and 4.12-893.22 (mean=87.78) µm for outdoor MPs. Choi and his colleagues have also reported 50-100 µm sized microplastic particles as predominant MPs size group in indoor air samples in south Korea, with 20-100 µm constituting 48-96% of total identified MPs (Choi et al., 2022).

In the first group of indoor microplastics of size range less than 50 µm around 72.58% were fragments and 27.42% were fibers, while in outdoor microplastics of <50 µm size, 80.84% were fragments and 15.15% were fibers, indicating dominance of fragment shape type in less than 50 µm sized particles. In outdoor air samples, fibers were prevalent in other bigger size categories i.e., 62.5%, 59.09%, 71.42%, and 80% in 50-100 µm, 100-250 µm, 250-500, and 500-1000 µm groups, respectively. Likewise, in indoor air samples fibers were prevalent in the last three bigger size categories as 65.52%, 92.31%, and 76. 92%, respectively (Figure 6. (b, c)).

Fragments predominated small size groups while fibers predominated larger size groups and the reason behind it is the fact that fragments owing to their low length to width ratio and more thickness get heavier in larger size groups which drives their early deposition. In contrast to fragments, fibers have high length to width ratio and are thinner and lighter even in larger size groups, that’s why they tend to suspend in air for longer time periods.


a
Indoor
Outdoor
Abundance (%)
0
10
20
30
40
<50
50-100
100-250
250-500
500-1000
Size (μm)
b
Fibers
Fragments
Abundance (%)
0
20
40
60
80
100
<50
50-100
100-250
250-500
500-1000
Size (μm)

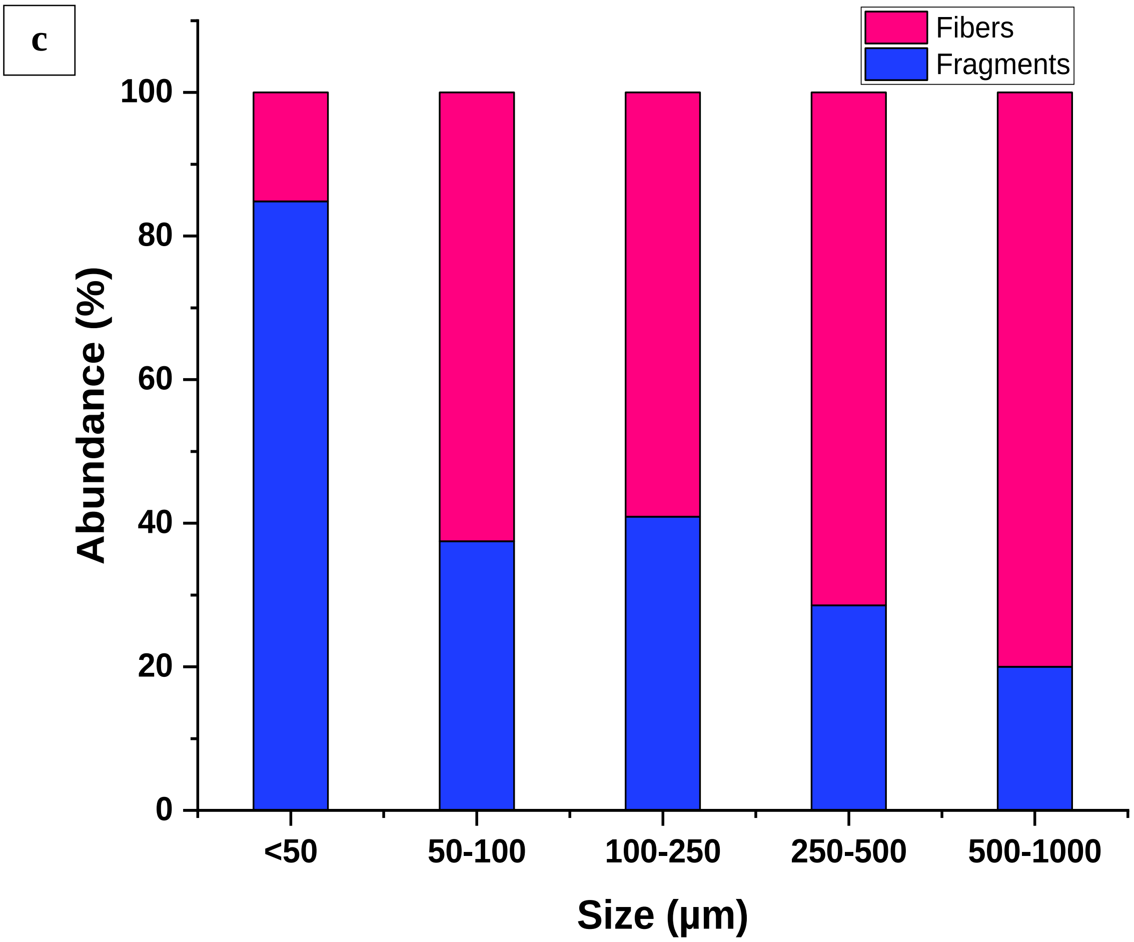


Figure 4.2. (a) Percentage of size range of MPs found in indoor and outdoor samples. (b, c) Percentage abundance of fragments and fiber in different size ranges for (b) Indoor samples and (c) outdoor samples

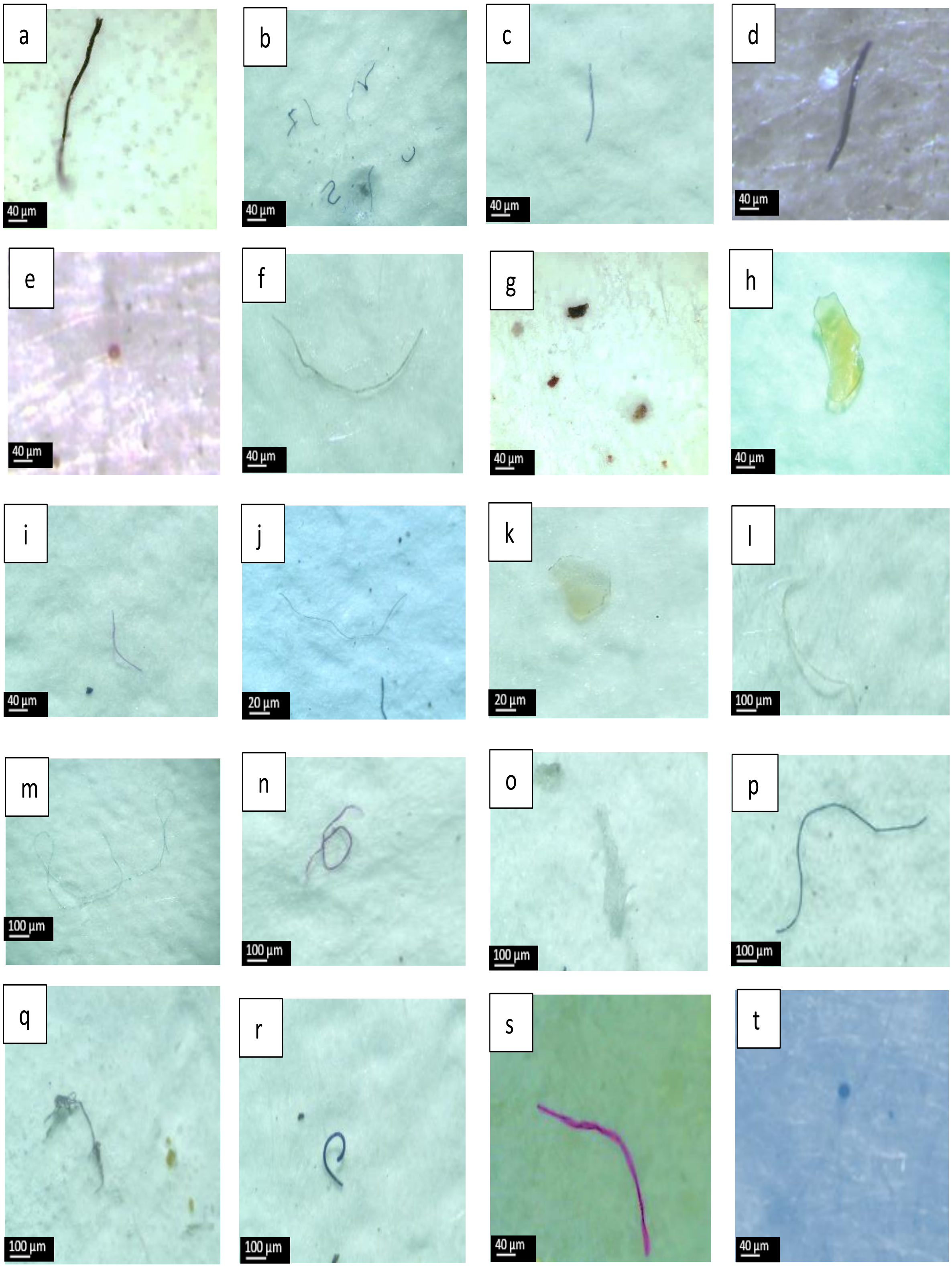
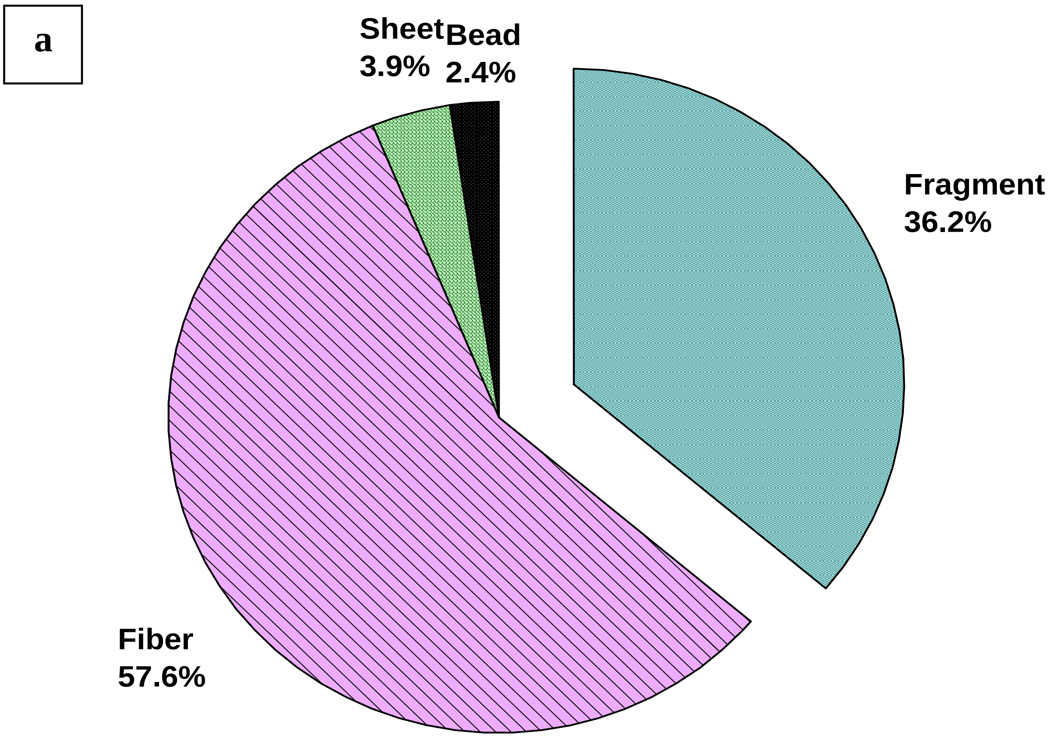


Figure 4.3. Micrographs of airborne microplastics captured during visual analysis using Olympus digital microscope (DSX 1000). (Fibers: a-d, f, i, j, l-n, p q-s; Fragments: g, o, Beads: e, t; Sheets: h, k)

Shapes observed during visual analysis of microplastic particles encompass fibers, fragments, sheets, and beads with fibers identified as prevalent shape type in outdoor (66.3%) and indoor air samples (57.6%) followed by fragments. Beads were exclusively discovered in indoor samples (2.4%), whereas sheets were found in both environments in small amounts i.e., accounting for 3.9 percent of indoor and 3 percent of outdoor samples Figure. 4.4. (a, b).

These findings are in line with past studies, in which fibers and fragments were shown to be the most prevalent type of microplastic (Ahmad et al., 2023; Dris et al., 2015, 2016, 2017; Klein & Fischer, 2019; Liao et al., 2021; Liu, Wang, Fang, et al., 2019; Torres-Agullo et al., 2022; Zhu et al., 2021). White, black, red, and blue colored microplastics were most common in indoor and outdoor air samples (Figure 4.5. (a, b)). Transparent, black, red, blue, brown, green, gray and yellow colored MPs have been found in Shanghai (Liu, Wang, Fang, et al., 2019) and Dongguan (Cai et al., 2017). The majority of the atmospheric MPs in Ahvaz City were black-grey, and white. (Abbasi et al., 2023).



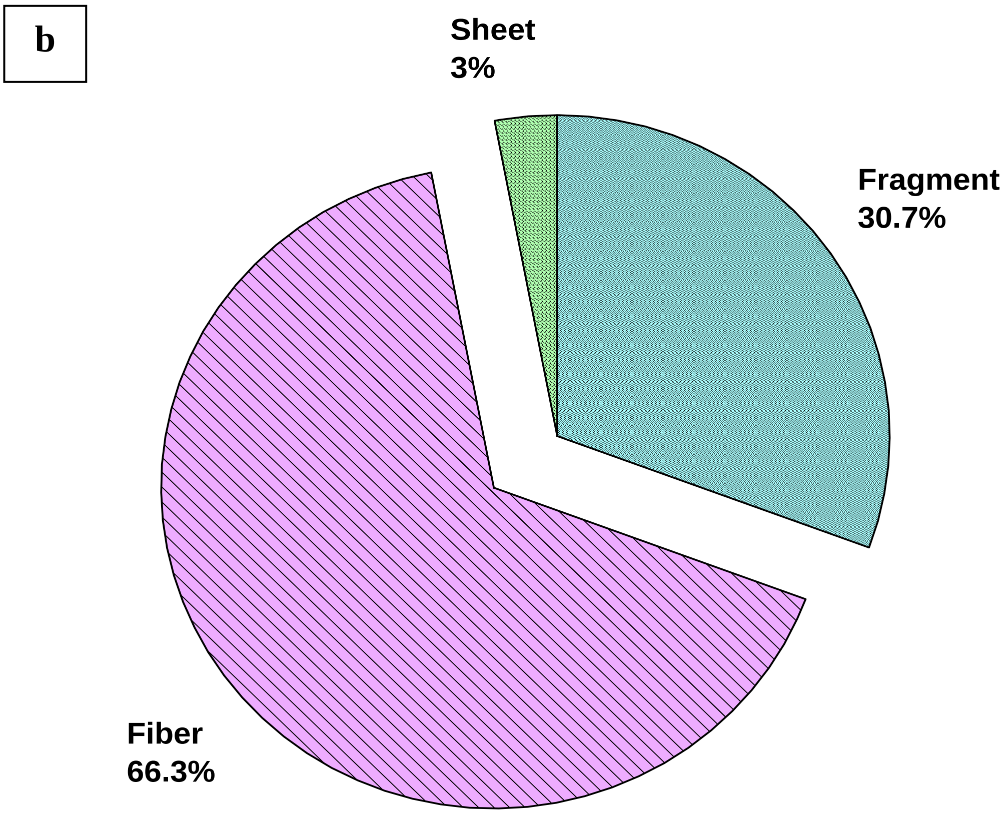
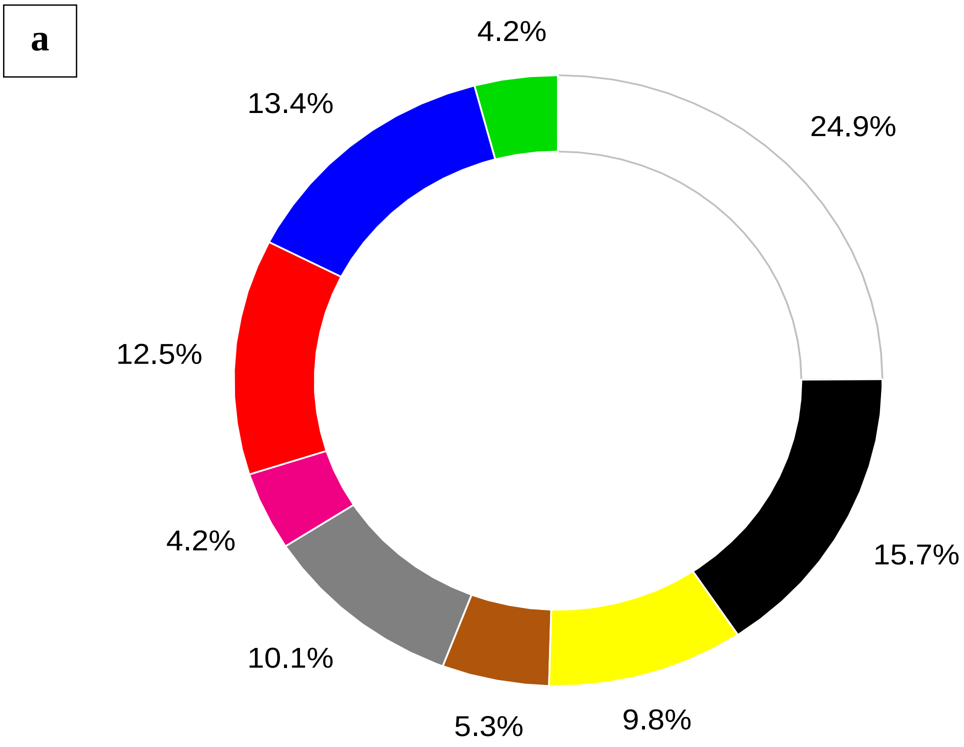


Figure 4.4. Shape based composition of microplastics in (a) Indoor samples and (b) Outdoor samples.



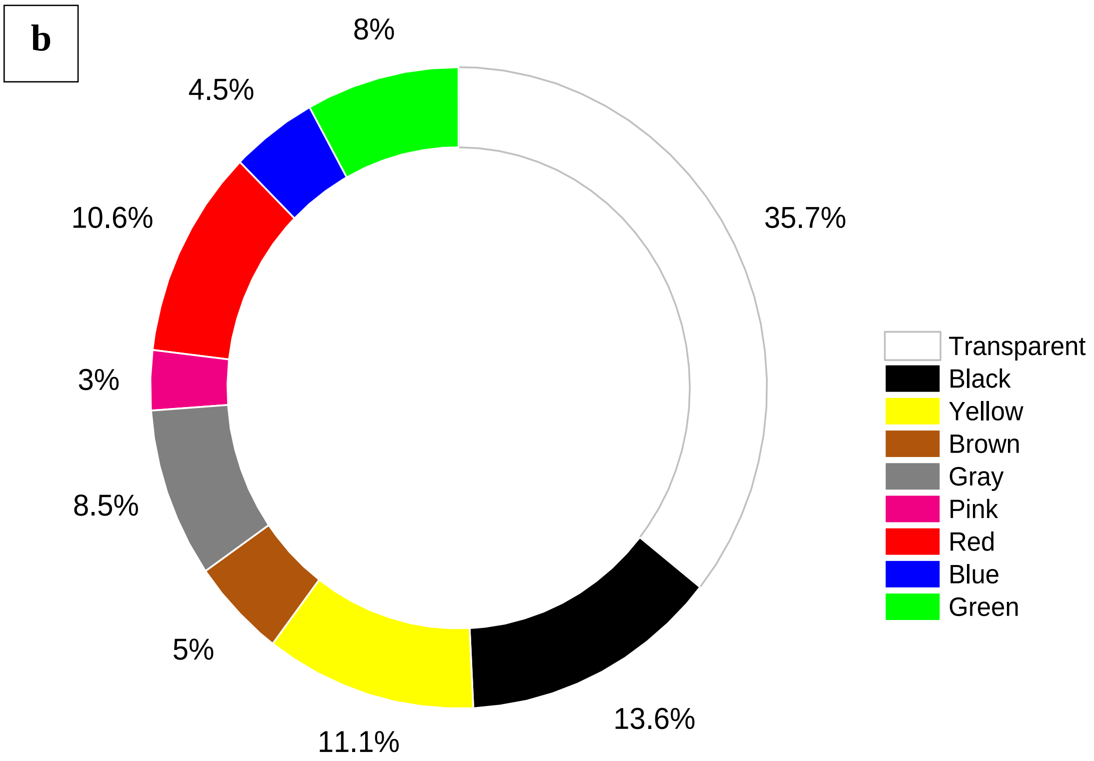
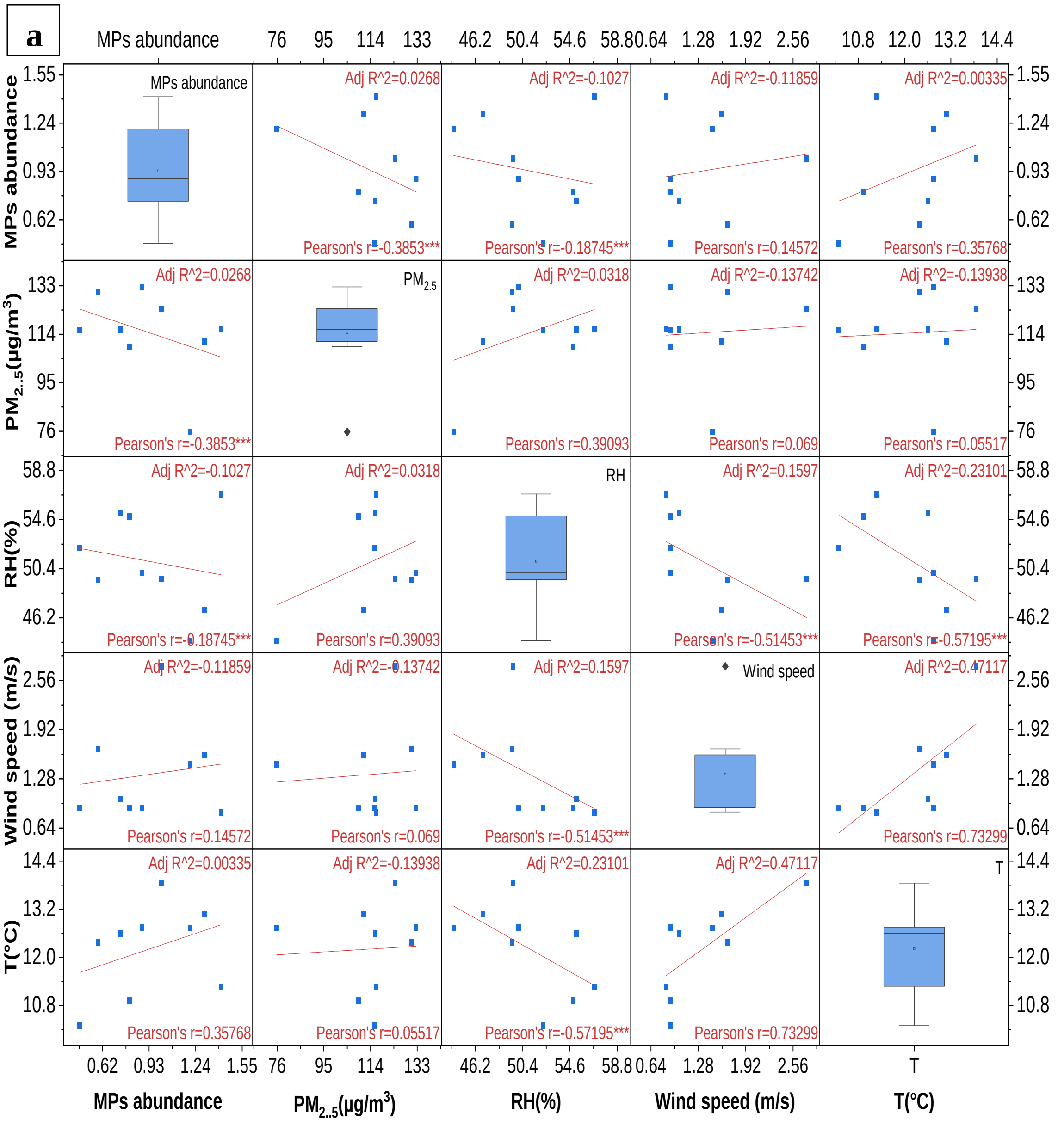


Figure 4.5. Color based classification of microplastics in (a) Indoor samples, and (b) Outdoor samples.

4.3. Impact of selected air quality factors on microplastics abundance

Correlation analysis of microplastics abundance in indoor and outdoor air samples with selected air quality factors i.e., wind speed (m/s), relative humidity (%), temperature (°C) and $PM_{2.5}$ (µg/m^3) showed very weak to negligible impact of these factors on MPs abundance (Figure 4.6. (a, b)) implying that microplastic abundance is not significantly influenced by any of these factors. A study conducted in China's five megacities reported weak linkage between $PM_{2.5}$ concentration and MPs abundance (Zhu et al., 2021).

Previous studies (Shruti et al., 2022; Truong et al., 2021) reported wind and rainfall as significant environmental factors influencing dispersion, deposition and abundance of microplastics in atmosphere. It is complicated to study the relationship between environmental factors and microplastics abundance. Albeit, population size, GDP rate, and anthropogenic activities are reported to be positively correlated with the MPs concentration in a region (Shruti et al., 2022; Zhu et al., 2021). Atmospheric microplastics can disperse over long distances with wind implying airborne microplastics as potential source of MPs in soil, water, plants.


a
MPs abundance
76 95 114 133
46.2 50.4 54.6 58.8
0.64 1.28 1.92 2.56
10.8 12.0 13.2 14.4
MPs abundance
Adj R^2=0.0268
Pearson's r=-0.3853***
Adj R^2=-0.1027
Pearson's r=-0.18745***
Adj R^2=-0.11859
Pearson's r=0.14572
Adj R^2=0.00335
Pearson's r=0.35768
Adj R^2=0.0268
Pearson's r=-0.3853***
PM2.5
Adj R^2=0.0318
Pearson's r=0.39093
Adj R^2=-0.13742
Pearson's r=0.069
Adj R^2=-0.13938
Pearson's r=0.05517
Adj R^2=-0.1027
Pearson's r=-0.18745***
Adj R^2=0.0318
Pearson's r=0.39093
RH
Adj R^2=0.1597
Pearson's r=-0.51453***
Adj R^2=0.23101
Pearson's r=-0.57195***
Adj R^2=-0.11859
Pearson's r=0.14572
Adj R^2=-0.13742
Pearson's r=0.069
Adj R^2=0.1597
Pearson's r=-0.51453***
Wind speed
Adj R^2=0.47117
Pearson's r=0.73299
Adj R^2=0.00335
Pearson's r=0.35768
Adj R^2=-0.13938
Pearson's r=0.05517
Adj R^2=0.23101
Pearson's r=-0.57195***
Adj R^2=0.47117
Pearson's r=0.73299
T
MPs abundance 1.55 1.24 0.93 0.62
PM2.5(μg/m3) 133 114 95 76
RH(%) 58.8 54.6 50.4 46.2
Wind speed (m/s) 2.56 1.92 1.28 0.64
T(°C) 14.4 13.2 12.0 10.8
0.62 0.93 1.24 1.55
76 95 114 133
46.2 50.4 54.6 58.8
0.64 1.28 1.92 2.56
T
MPs abundance
PM2.5(μg/m3)
RH(%)
Wind speed (m/s)
T(°C)

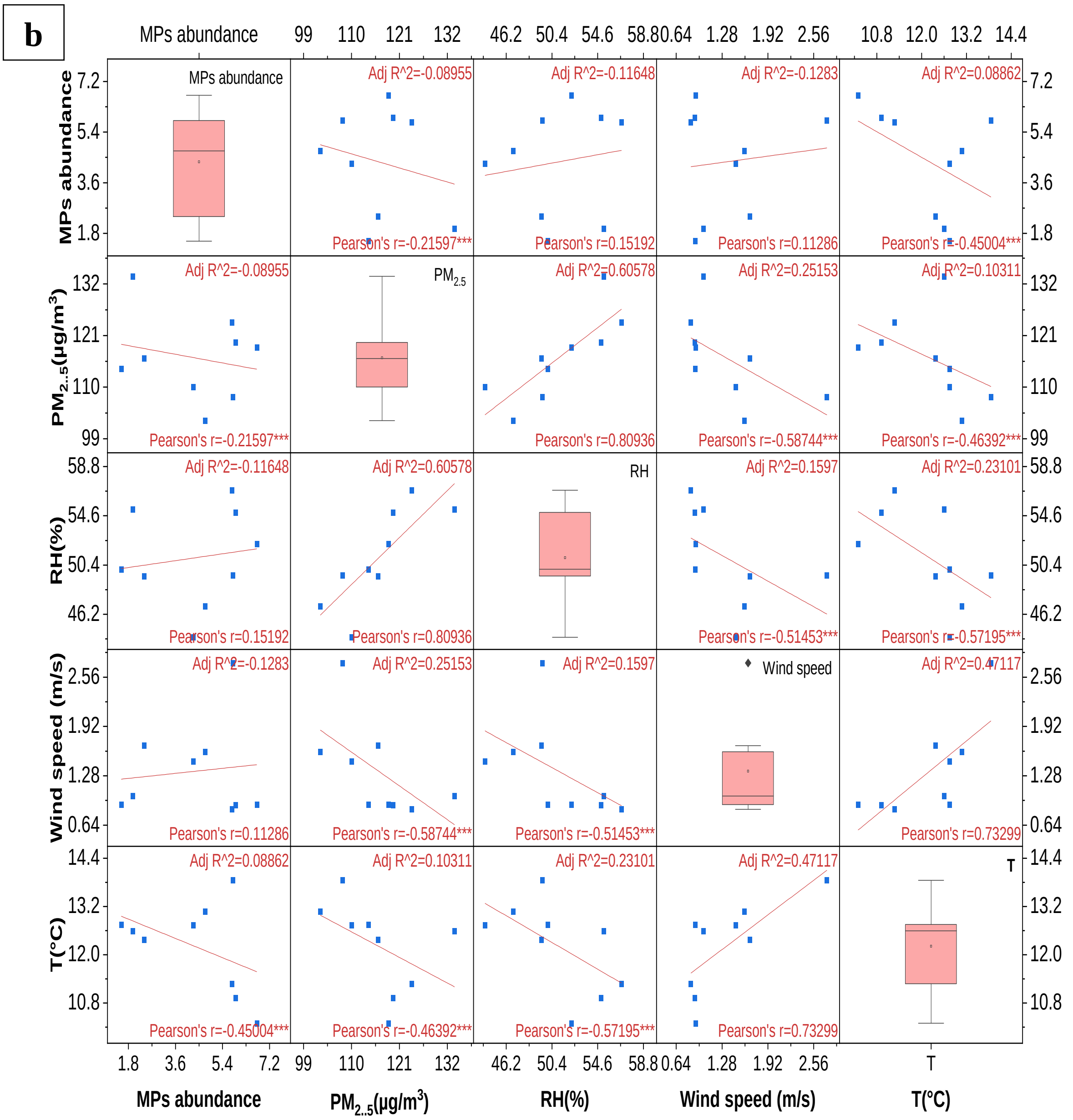


Figure 4.6. Correlation of selected environmental factors T, RH (%), $PM_{2.5}$, Wind speed with MPs abundance (a) Outdoors; and (b) Indoors.

4.4. Polymeric composition

4.4.1. ATR-FTIR

Among the particles randomly selected for ATR-FTIR analysis 6 different types of polymers were identified including Polyethylene terephthalate (PET), Polypropylene (PP), Polyethylene (PE), Low density polyethylene (LDPE), Polystyrene (PS), and Poly (methyl methacrylate) (PMMA). PET (52.2%), PE (22.2%), and PP (10%) were found to be the dominant polymer types in indoor microplastics. In outdoor air samples prevalent polymers included PET (42.2%), PE (30.0%), and PS (14.4%) Figure 4.7. (a, b, c). PMMA fragments were found in hallway (6.67%) overall contributing 2.2% of all identified indoor air polymers) and outdoor air samples (3.3%). Characteristic ATR-FTIR spectra of dominant polymers are shown in Figure 4.8.

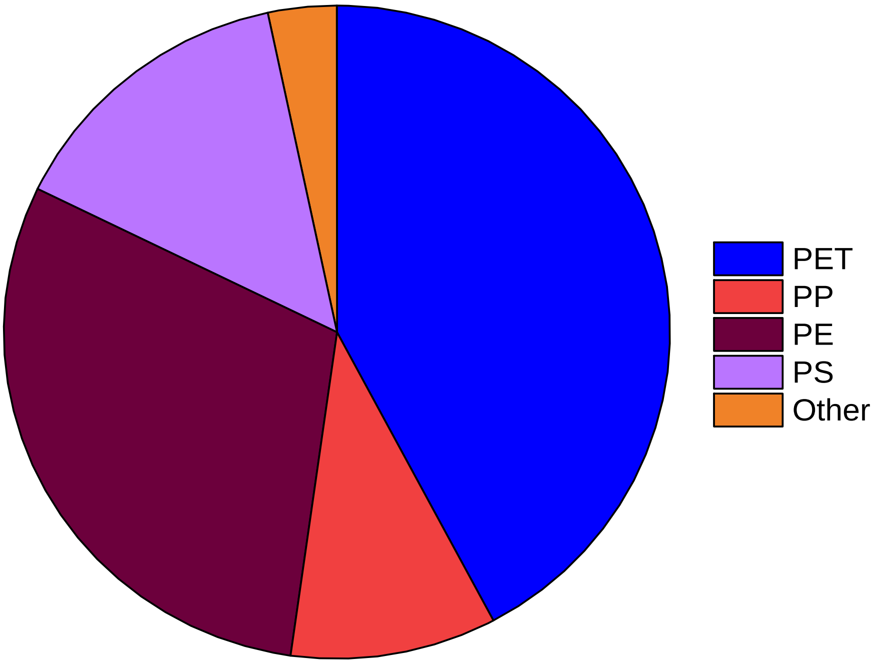
These polymer composition findings are in line with earlier research on microplastics residing indoor and outdoor air. In a study on synthetic atmospheric fibers carried out in Paris, PET was the most prevalent polymer (Dris et al., 2016). PET, PE, and PS were reported to be the three most prevalent polymer types in a recent study on airborne microplastics conducted in the five megacities of China (Zhu et al., 2021). PET has also been found to be the most dominant polymer in household indoor air samples (62%) (Jenner et al., 2021), suspended atmospheric microplastic fibers (50%) in Shanghai (Liu, Wang, Fang, et al., 2019).

A study on atmospheric MPs identified PE and PET as prevalent polymers after cellophane in Mexico (Shruti et al., 2022). In a study on indoor and outdoor air, Perera and his colleagues discovered PET to be the most prevalent type of polymer, followed by PE (Perera et al., 2022). PET, PE, PS, PP were reported along with 11 other polymer types in urban atmospheric deposition of London (Wright et al., 2020). One of the most extensively used plastic polymers in daily life, polyethylene terephthalate is utilized in packaging, bottle production, and the textile sector.

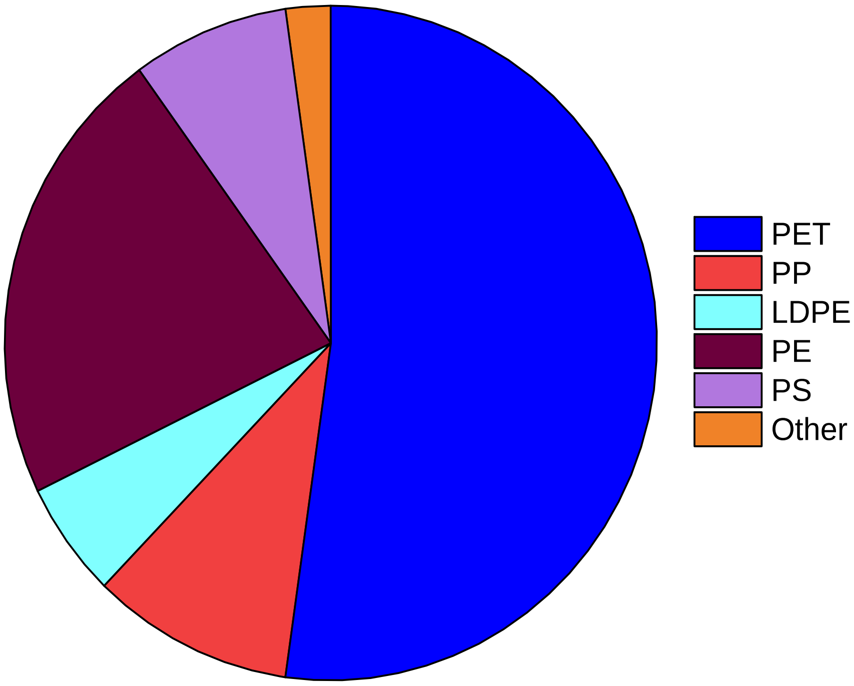
PET, PP and PE are the most used plastic types worldwide. PP is used in packaging of food items, caps of bottles, pipes, and wrappers of snacks (An et al., 2020; Plastics Europe, 2021). Due to the dynamic nature of the air and the way that wind disperses particles from one place to another, the sources of airborne microplastics are complex. Another source of these MPs may include degradation or chopping of macroplastics or synthetic material in industries (Gasperi et al., 2018).

Polymeric composition reported in an area may vary from place to place depending on local plastic waste composition and industrial waste generation and management practices.

a



b



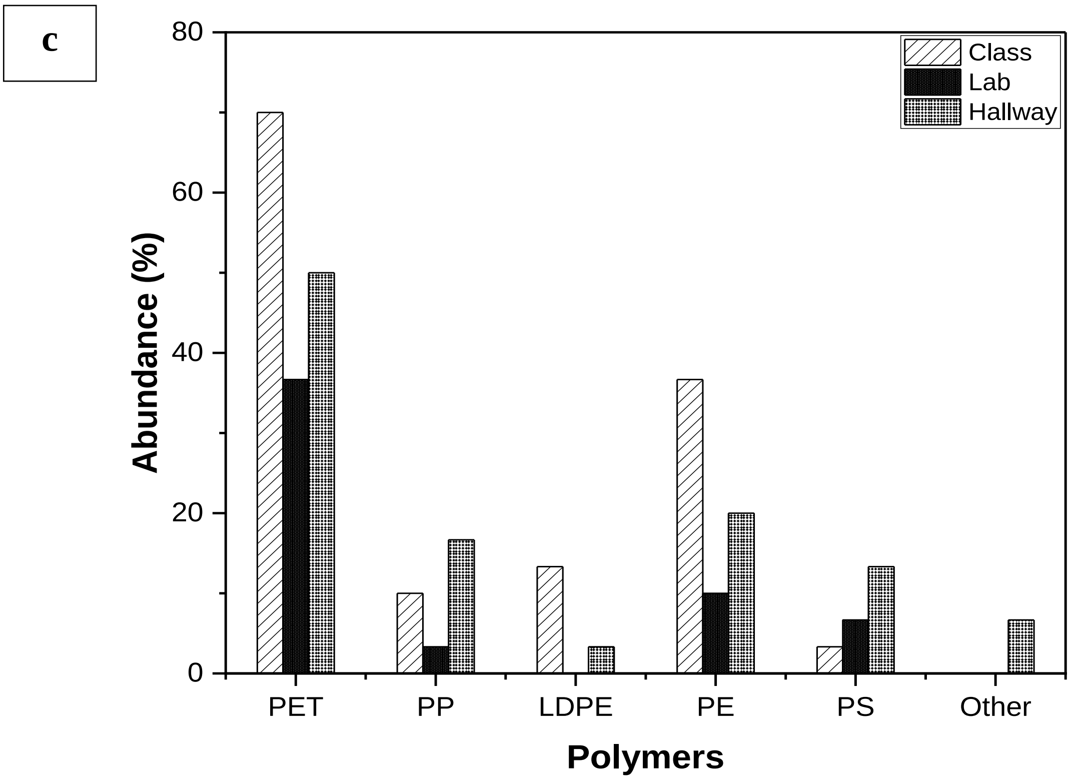
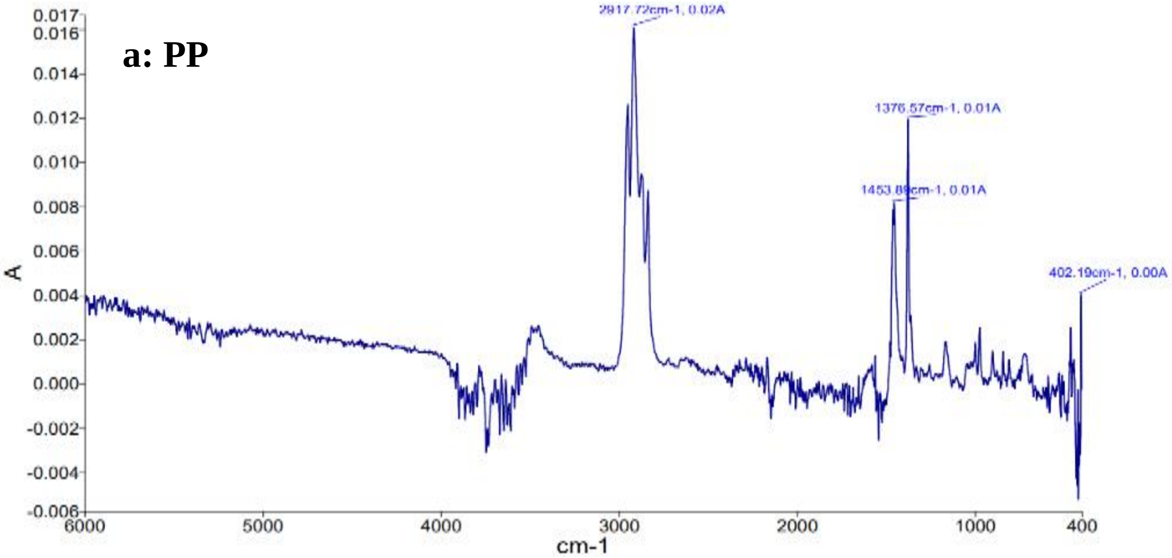
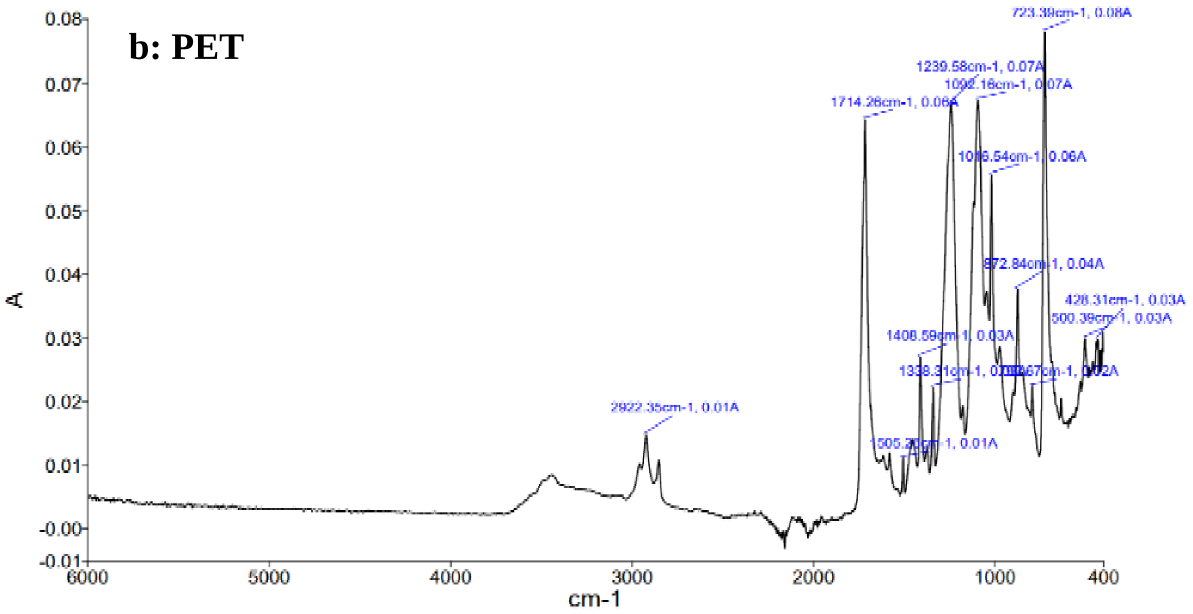
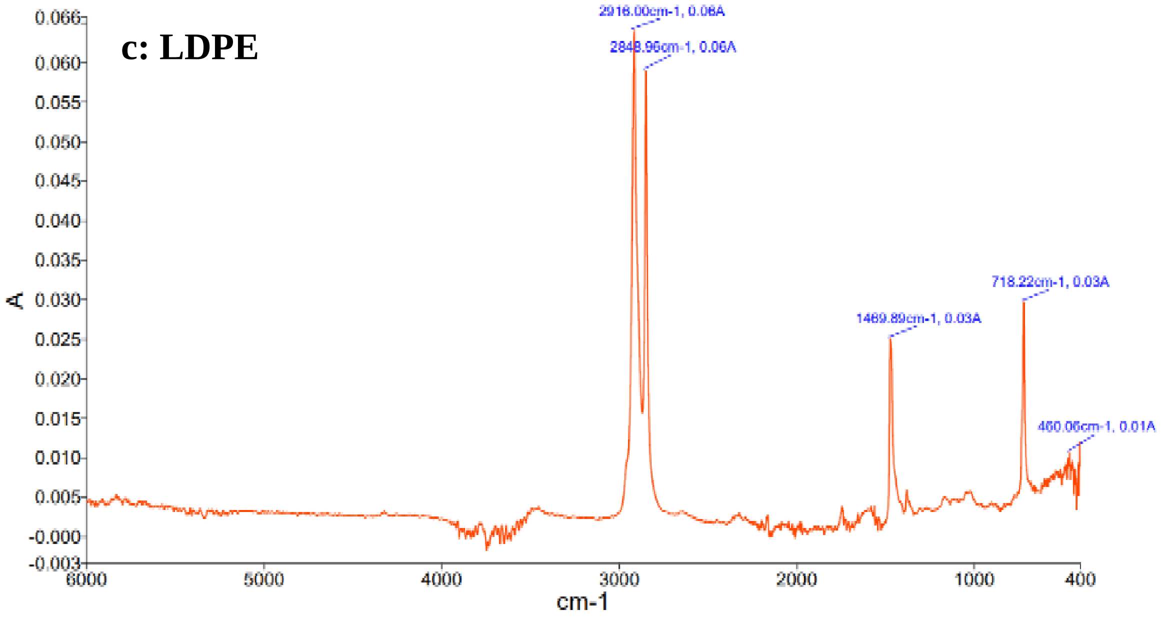
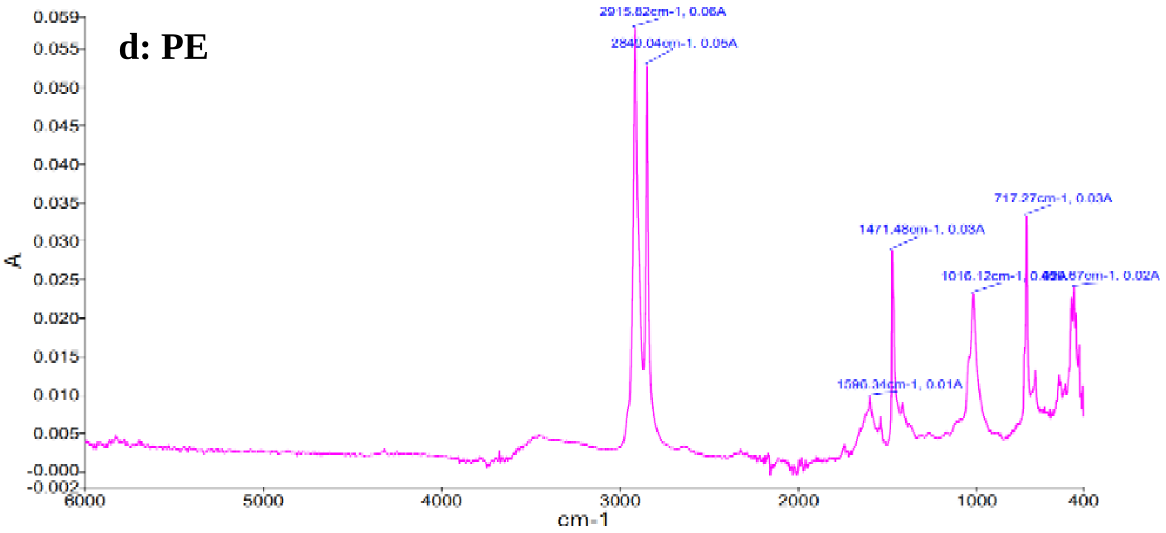


Figure 4.7. Polymer composition of microplastics in (a) outdoor air samples, (b) indoor air samples. (c) Polymer composition of airborne microplastics in different indoor locations.




b: PET
A
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
-0.00
-0.01
6000
5000
4000
3000
2000
1000
400
cm-1
723.39cm-1, 0.08A
1239.58cm-1, 0.07A
1092.16cm-1, 0.07A
1714.26cm-1, 0.06A
1016.54cm-1, 0.06A
872.84cm-1, 0.04A
428.31cm-1, 0.03A
500.39cm-1, 0.03A
1408.59cm-1, 0.03A
1338.31cm-1, 0
.67cm-1, 0.02A
2922.35cm-1, 0.01A
1505.26cm-1, 0.01A


c: LDPE
A
0.066
0.060
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
-0.000
-0.003
6000
5000
4000
3000
2000
1000
400
cm-1
2916.00cm-1, 0.06A
2848.96cm-1, 0.06A
718.22cm-1, 0.03A
1469.89cm-1, 0.03A
460.06cm-1, 0.01A


d: PE
A
0.059
0.055
0.050
0.045
0.040
0.035
0.030
0.025
0.020
0.015
0.010
0.005
-0.000
-0.002
6000
5000
4000
3000
2000
1000
400
cm-1
2915.82cm-1, 0.06A
2849.04cm-1, 0.05A
717.27cm-1, 0.03A
1471.48cm-1, 0.03A
1016.12cm-1, 0.
.87cm-1, 0.02A
1590.34cm-1, 0.01A

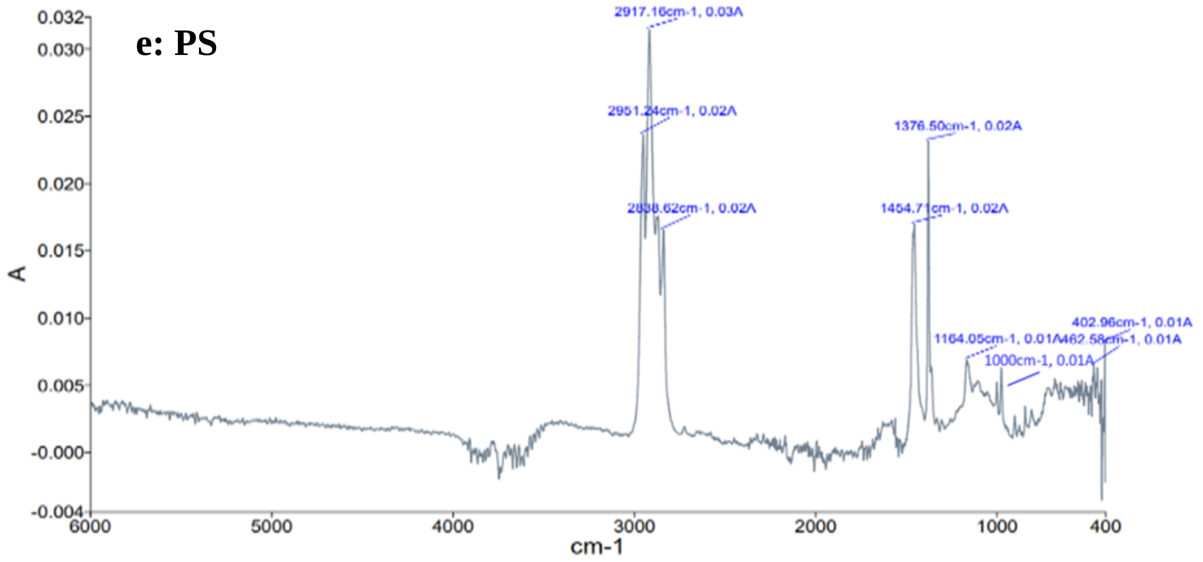


Figure 4.8. Characteristic ATR-FTIR spectra of prevalent microplastic particles.

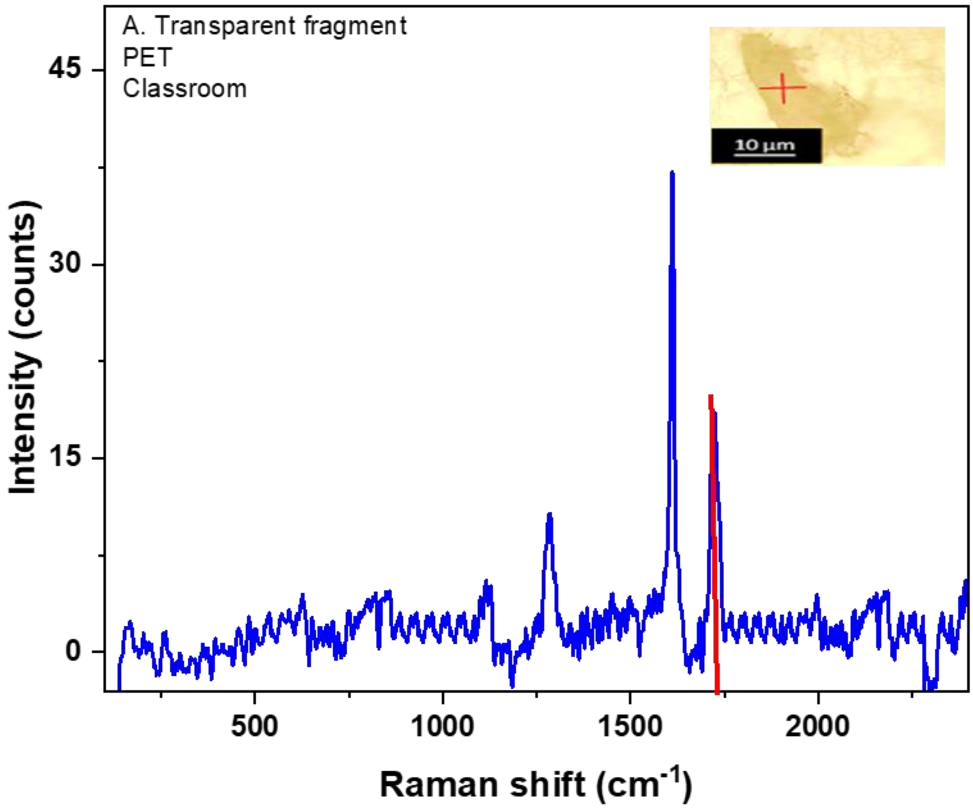
Microplastics can enter atmosphere from various sources i.e., wear and tear (Jan Kole et al., 2017), clothing, weathering of plastic waste, personal care products, textile industry, paint, and wastewater (An et al., 2020). These synthetic particles from the atmosphere can be transported to water, soil, plants and animals via deposition, absorption, and inhalation. Research by WWF in Islamabad and the Ayyubia National Park found that the weight of plastic waste generated each month in total solid waste is about 2700 tons. PET, PP, PS, LDPE, HDPE, and PVC are the most prevalent polymers found in this waste (Ali, 2019). PET is widely used in manufacturing of juice, soft drink, and water bottles in addition to being extensively used in the textile sector to create synthetic fibers (Truong et al., 2021; Yadav et al., 2021).

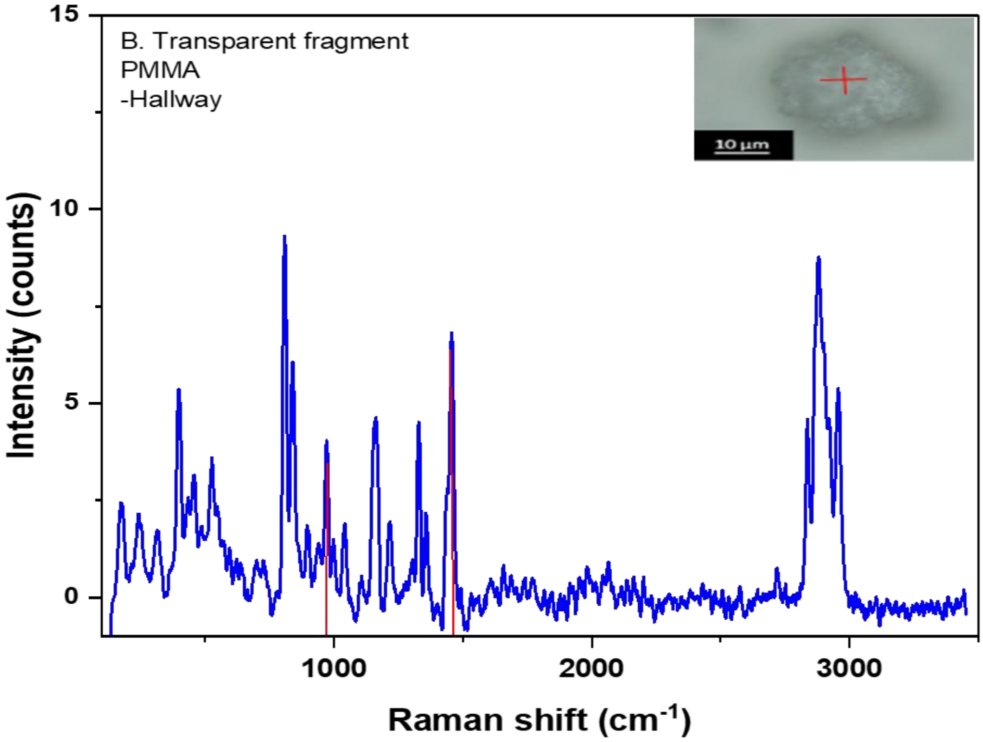
PMMA, a synthetic thermoplastic, owning to its rigidity and transparency, has multiple applications in environment i.e., manufacturing window frames, making aquariums, medical devices, rear lights and other parts of vehicles, screens, and lenses etc. (Plastics Europe, 2021). Considering multiple sources of microplastics in environment, industrial practices, degrading or weathering residential and commercial plastic waste, incineration of solid waste are major sources of airborne MPs (Hale et al., 2020; Kacprzak & Tijing, 2022). Polypropylene, polyethylene and polystyrene are the most prevalent airborne microplastics reported widely in past studies implying their extensive use in atmosphere (Organisation for Economic Co-operation and Development, 2021; Plastics Europe & EPRO, 2016). Further studies are required to investigate the source apportionment of airborne microplastics.

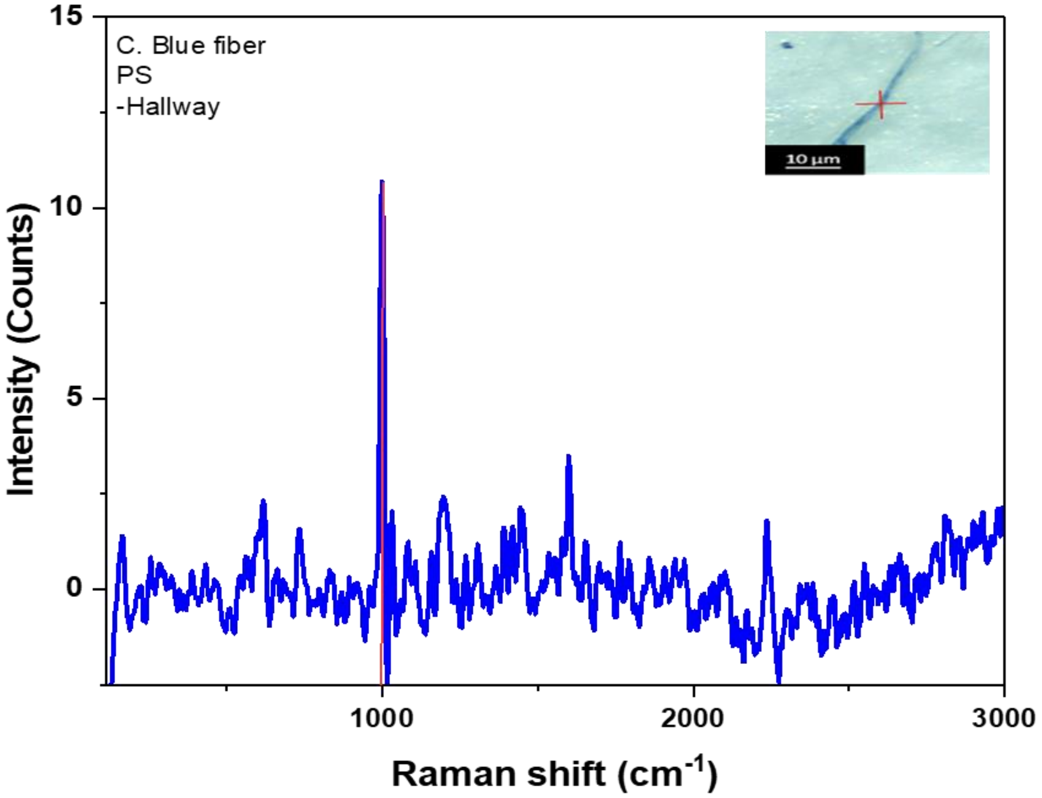
4.4.2. µ-Raman spectroscopy

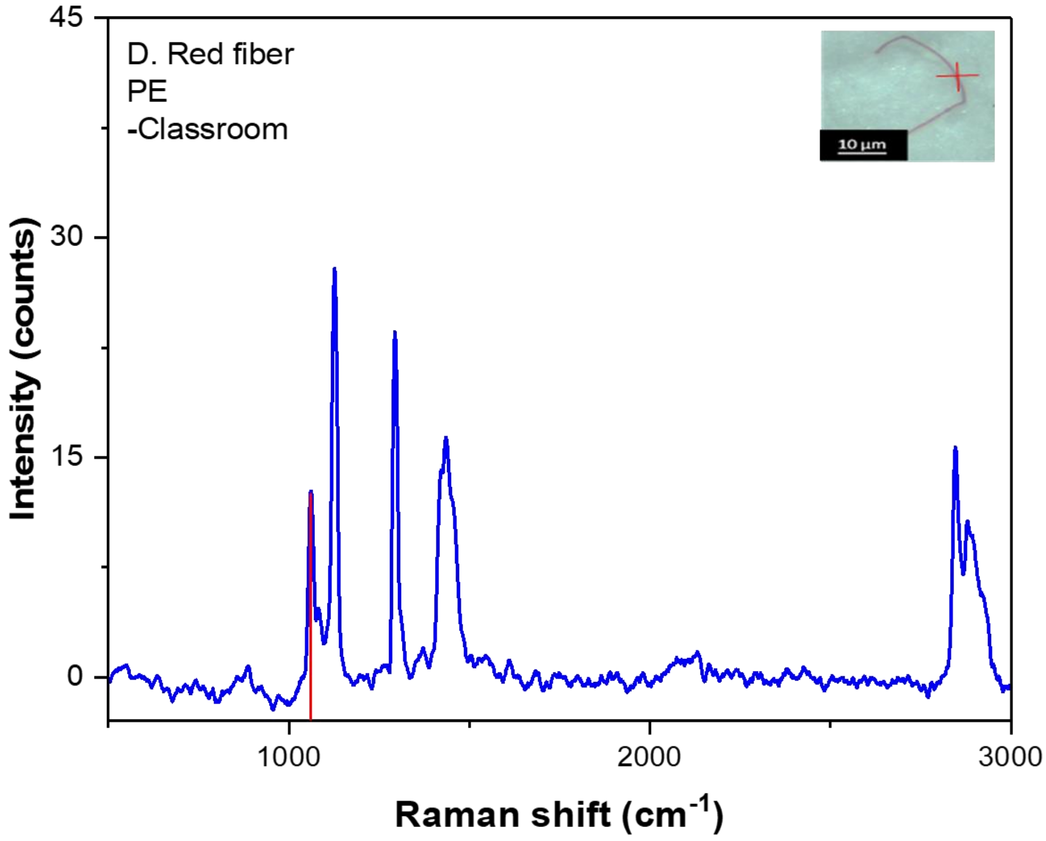
Random suspected microplastic particles of size less than 20 µm were analyzed using µ-Raman spectroscopy to identify their polymer type. Particles were randomly selected from each sample group for spectroscopic analysis with the help of a microneedle. Raman spectral data of these particles was analyzed using Origin Lab to visualize and study existing characteristic peaks of polymers. Utilizing published sources, the reference characteristic peaks of several polymers were identified. This analysis reconfirmed the presence of PET, PE, PP, PS and PMMA polymers in sample particles (Figure 4.9). Microplastic particles in the atmosphere undergo morphological changes due to weathering and may also absorb various contaminants, which may weaken their distinctive peaks to some extent and generate noise in the spectrum.

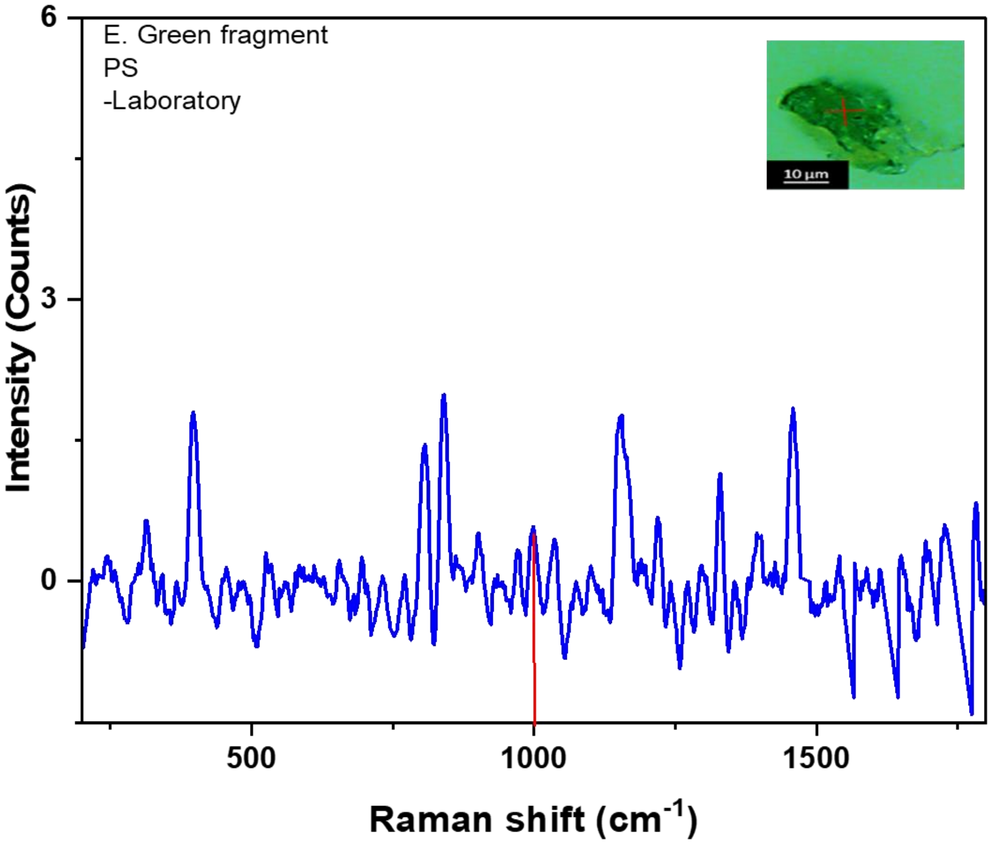
Similar phenomenon of weak spectra due to microplastics weathering has also been reported previously (Dong et al., 2020; Huang et al., 2019; Xiong et al., 2018). The weak spectra of microplastics also imply their long-time suspension in environment, as freshly introduced MPs have more distinct peaks in their spectra with little noise (Dong et al., 2020). From literature it was found that characteristic peak for PS is at 1000 cm^{-1}, for PE at 1059 cm^{-1}, for PP at 402 cm^{-1}, 1157 cm^{-1}, for PET around 1720 cm^{-1}, and for PMMA at 977 cm^{-1} and 1453 cm^{-1} (Boyden et al., 2022; Yao et al., 2022). Polymer composition of randomly selected particles of less than 20 µm as per Raman results was as PET (33.3%), PP (25%), PE (20.8%), PS (12.5%), and PMMA (8.3%). It has been found that Raman corroborated the presence of all the polymers identified by ATR-FTIR except the LDPE. This technique is equally efficient and does not require sample preparation. Since IR spectroscopy cannot analyze particles of less than 20 µm size, there Raman is recommended for analyses of small sized particles. Small sized particles especially PE, and PP have been reported widely and are capable of exacerbating cytotoxicity, thereby increasing health concern. Figure 4.9. Shows the Raman spectra of most common polymer types along with respective micrographs of the analyzed particles.

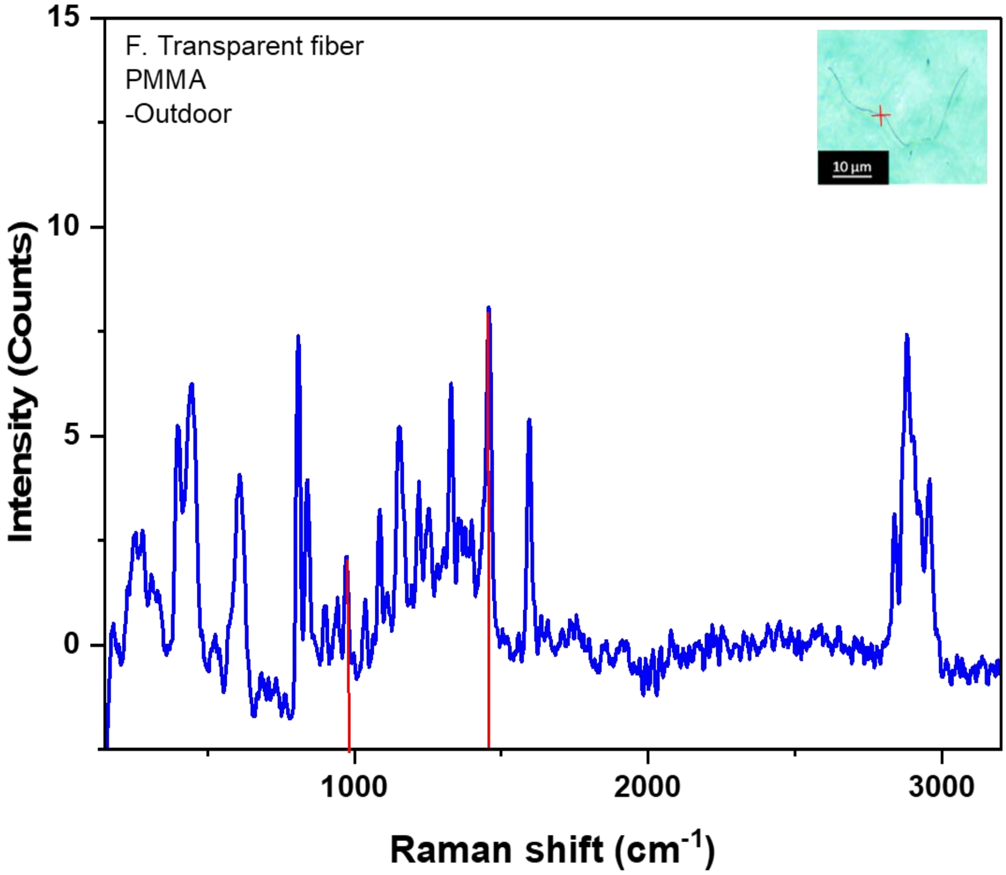

A. Transparent fragment
PET
Classroom
10 µm
Intensity (counts)
0
15
30
45
500
1000
1500
2000
Raman shift (cm^{-1})

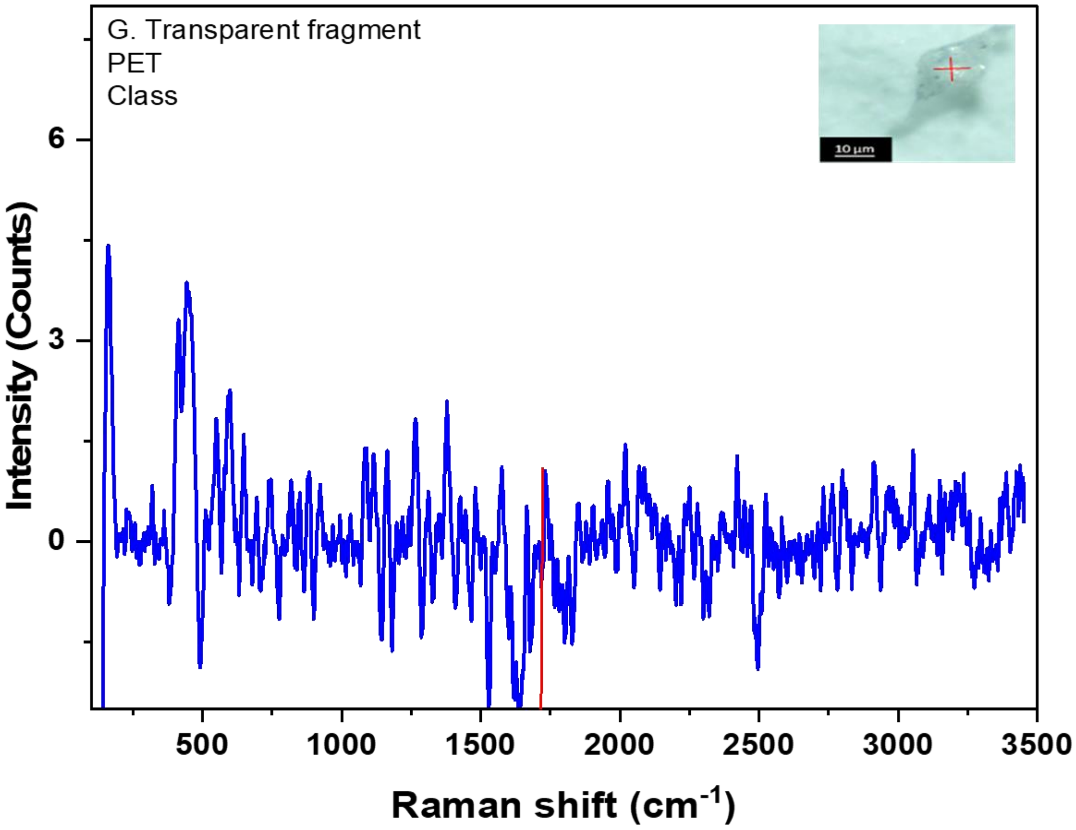

B. Transparent fragment
PMMA
-Hallway
10 µm
Intensity (counts)
0
5
10
15
1000
2000
3000
Raman shift (cm^{-1})

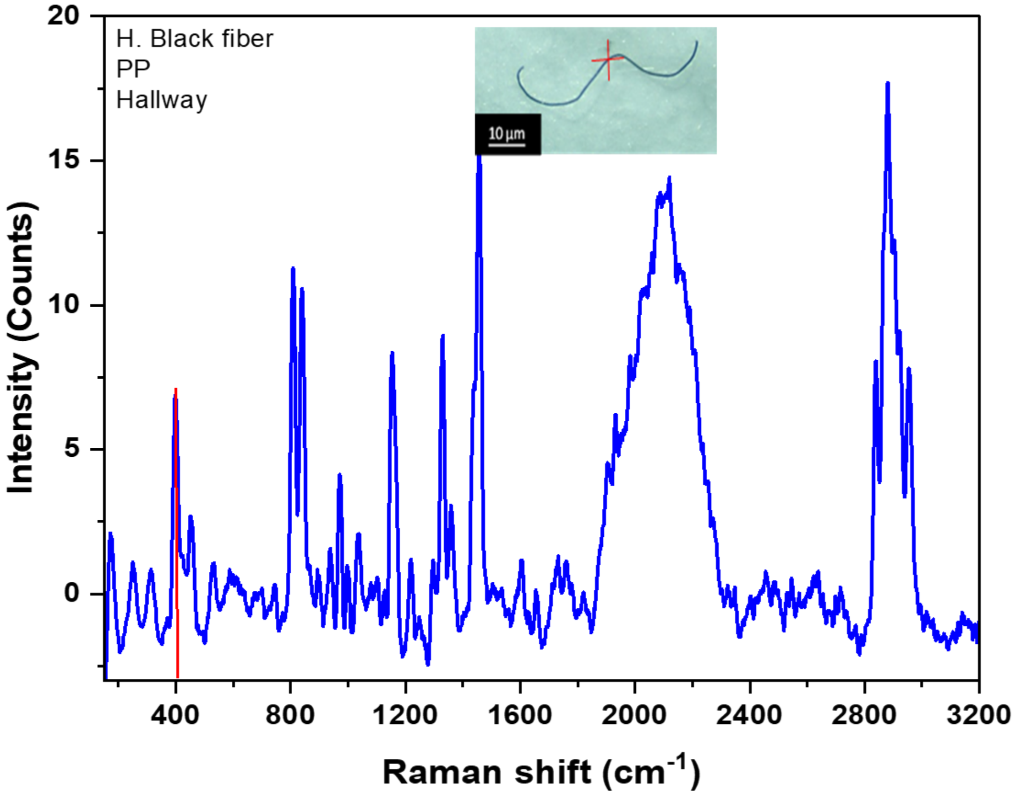

15
10
5
0
Intensity (Counts)
1000
2000
3000
Raman shift (cm^{-1})
C. Blue fiber
PS
-Hallway
10 µm


45
30
15
0
Intensity (counts)
1000
2000
3000
Raman shift (cm^{-1})
D. Red fiber
PE
-Classroom
10 µm


6
3
0
Intensity (Counts)
500
1000
1500
Raman shift (cm-1)
E. Green fragment
PS
-Laboratory
10 µm


15
10
5
0
Intensity (Counts)
1000
2000
3000
Raman shift (cm-1)
F. Transparent fiber
PMMA
-Outdoor
10 µm


G. Transparent fragment
PET
Class
10 µm
Intensity (Counts)
0
3
6
500
1000
1500
2000
2500
3000
3500
Raman shift (cm^{-1})


H. Black fiber
PP
Hallway
10 µm
Intensity (Counts)
0
5
10
15
20
400
800
1200
1600
2000
2400
2800
3200
Raman shift (cm^{-1})

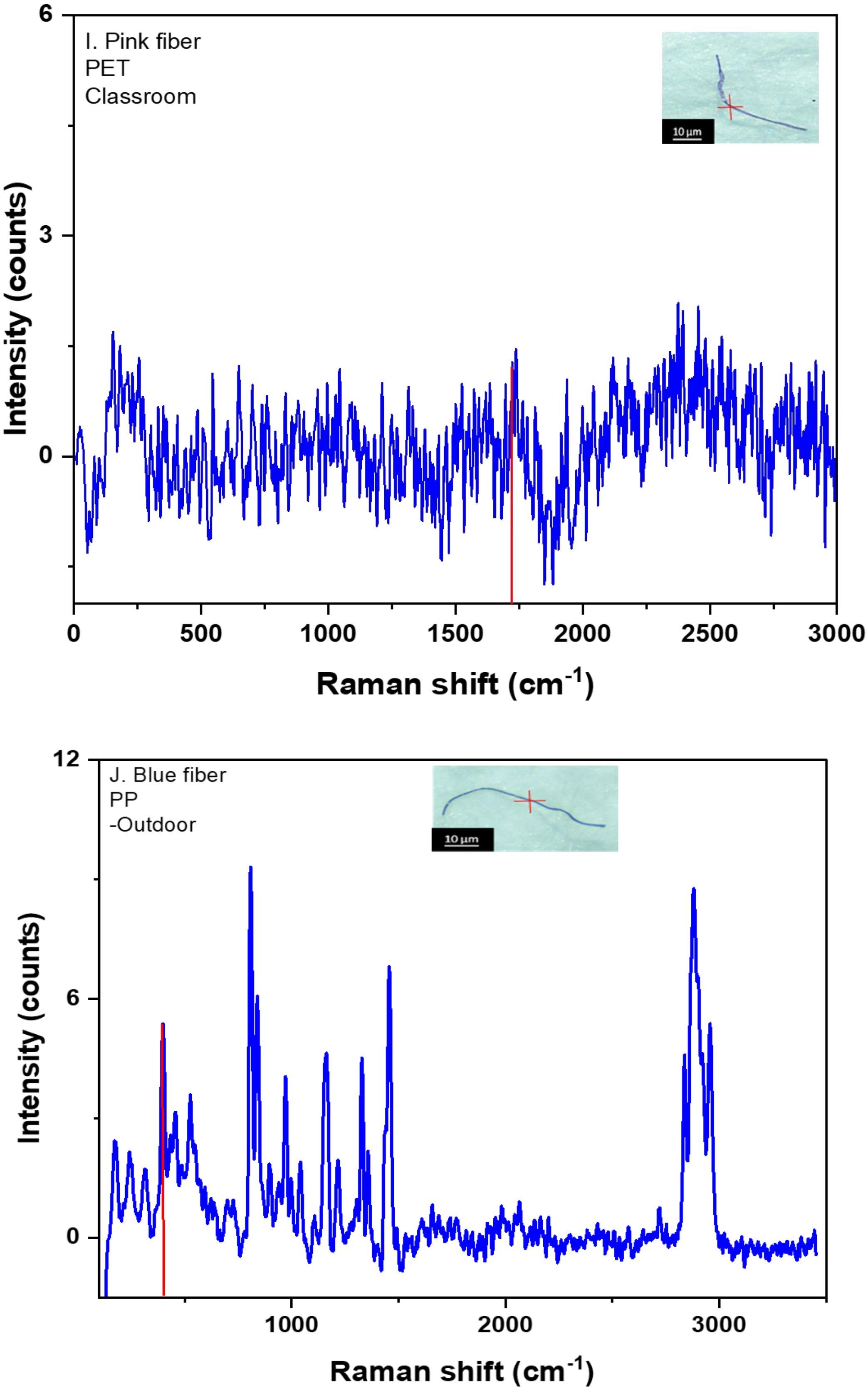


Figure 4.9. Microphotographs and Raman spectra of different microplastic particles found in indoor and outdoor air samples.

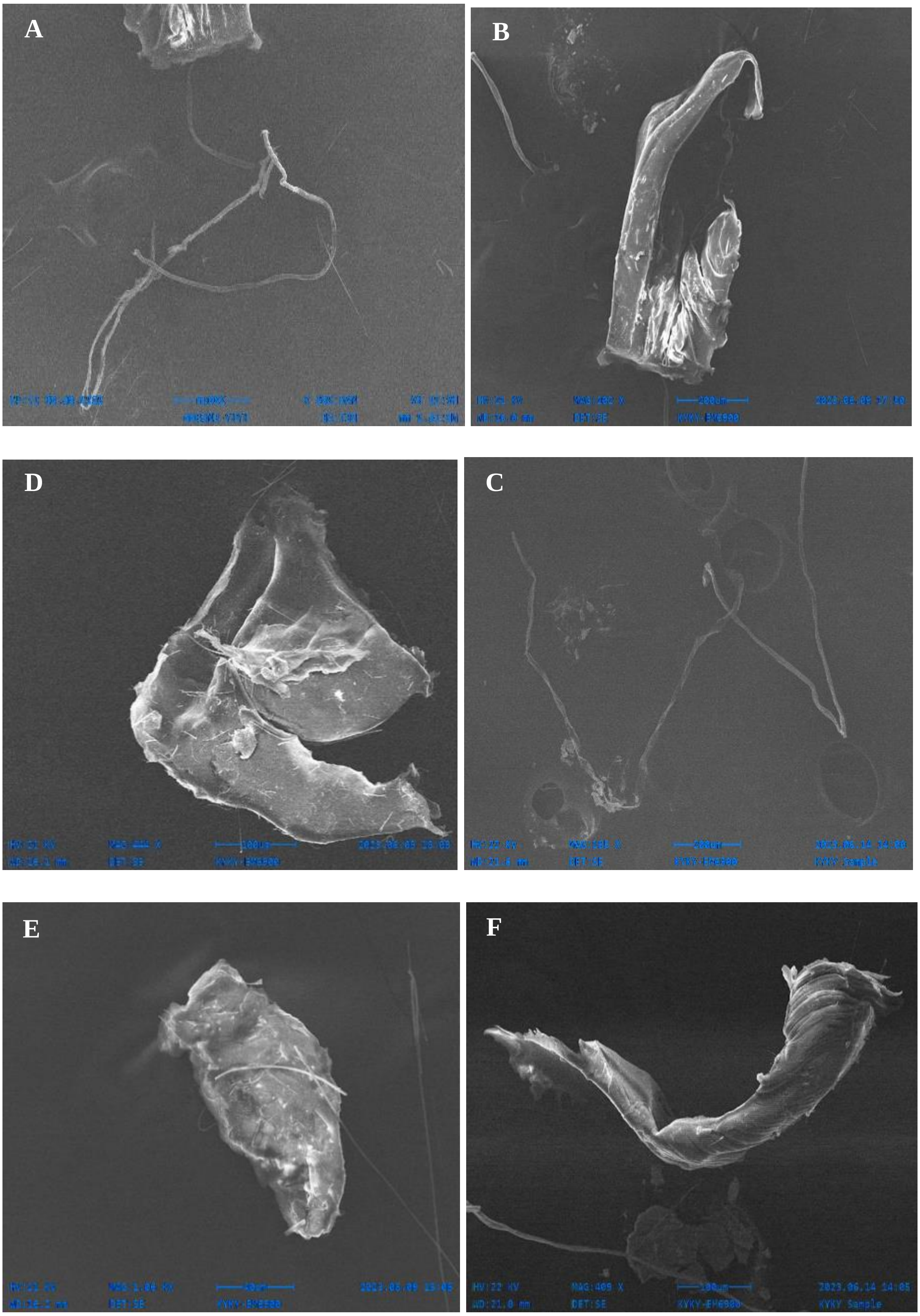
Table 4.1. Wavelength for characteristic peaks of synthetic polymers

Polymers	**Wavelength for characteristic peaks** (Yao et al., 2022)
Polyethylene terephthalate (PET)	1720
Polypropylene (PP)	402
Polyethylene (PE)	1059
Polystyrene (PS)	1000
Polymethyl methacrylate (PMMA)	Dense peak region 1100-1500 with a sharp peak at 1453

4.5. Surface morphology and elemental composition

SEM images (Figure 4.10.) show surface texture of different microplastic particles of different shapes. Surface morphology of particles reveal degradation status of these particles, the more a particle is fractured or cracked, the older it may be in air enduring the process of weathering. Microplastic particles with pits, ragged edges, grooves and cracks, which are indicators of weathering, show that they have been exposed to deterioration (physical and mechanical) while being suspended in the air for a prolonged time (Cai et al., 2017; Pandey et al., 2022; Yao et al., 2022) Some particles, as opposed to those with frayed ends, had smooth surfaces, indicating that they had just been put into the atmosphere. Figure 4.10. (H, I) show small fragments and fibers adhered to the surface of a large fragment. When analyzing distinct particles using EDX, different areas on a particle surface were considered, i.e., the part with adherent foreign material and the part without any foreign material. The results of SEM-EDX are shown in Figure 4.11.

These findings suggest that carbon (C) and oxygen (O) are the fundamental elements of every particle. Other elements such as Copper (Cu), Aluminum (Al), Silicon (Si), Iron (Fe), Sodium (Na), Chlorine (Cl), and Titanium (Ti) were clearly present where the spot comprised foreign materials. These metals were either absorbed from the environment or were added during plastic production. These findings about the elemental makeup of airborne microplastics are consistent with the past research that revealed the presence of elements other than C and O is caused by metal adsorption on the surface of microplastics and foreign substances, such as minerals stuck to particle's surface (Li et al., 2020; Pandey et al., 2022; Shruti et al., 2022; Yao et al., 2022). Various metals, including iron, titanium, aluminium, and silicon, have also reportedly been employed in the manufacturing of plastic as pigments and fillers. (Sobhani et al., 2019).


A
B
HV:25 KV
MAG:282 X
200um
KYKY-EM6900
D
100um
KYKY-EM6900
C
KYKY Sample
E
KYKY-EM6900
F
HV:22 KV
MAG:409 X
100um
2023.06.14 14:05
WD:21.0 mm
DET:SE
KYKY-EM6900
KYKY Sample

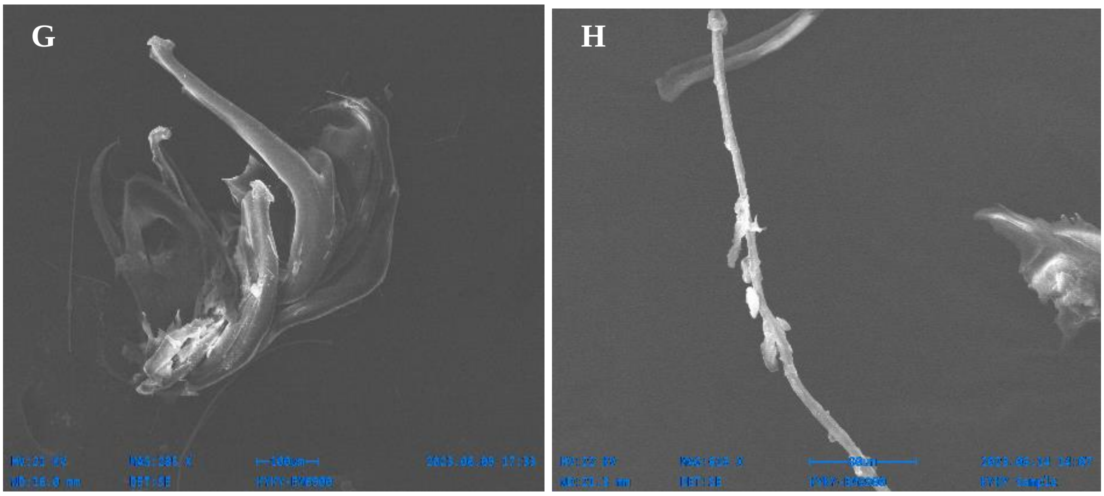
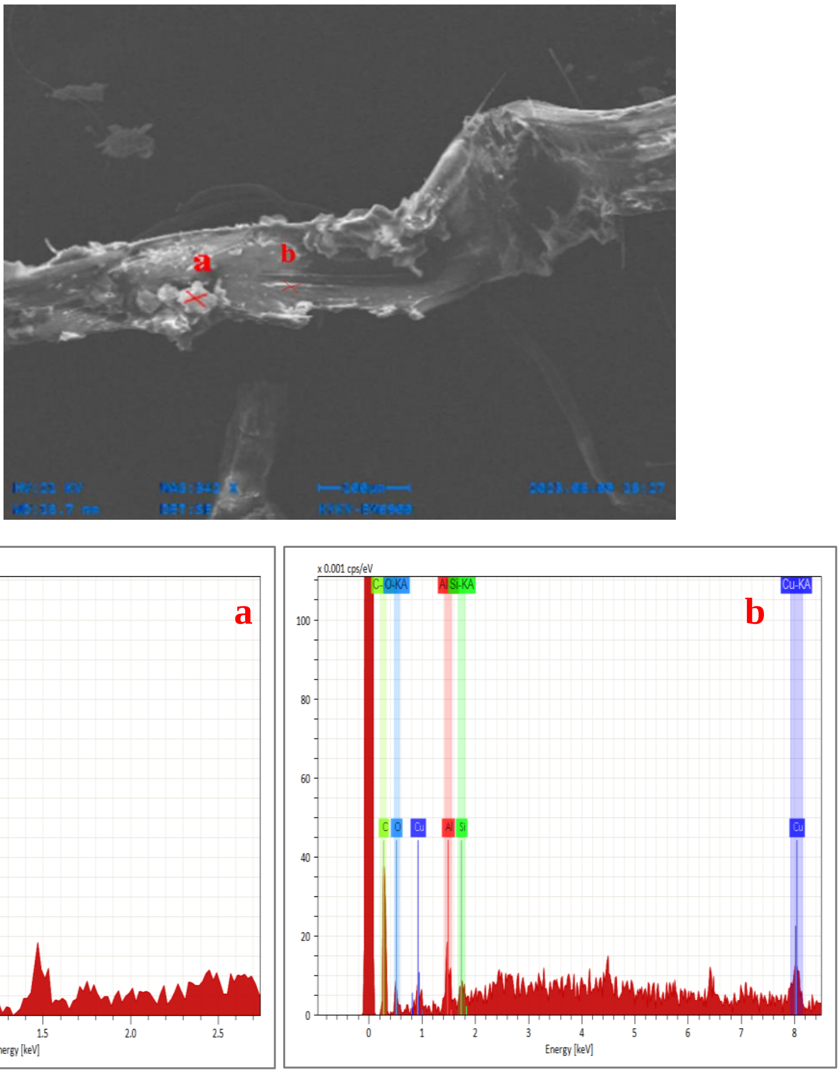
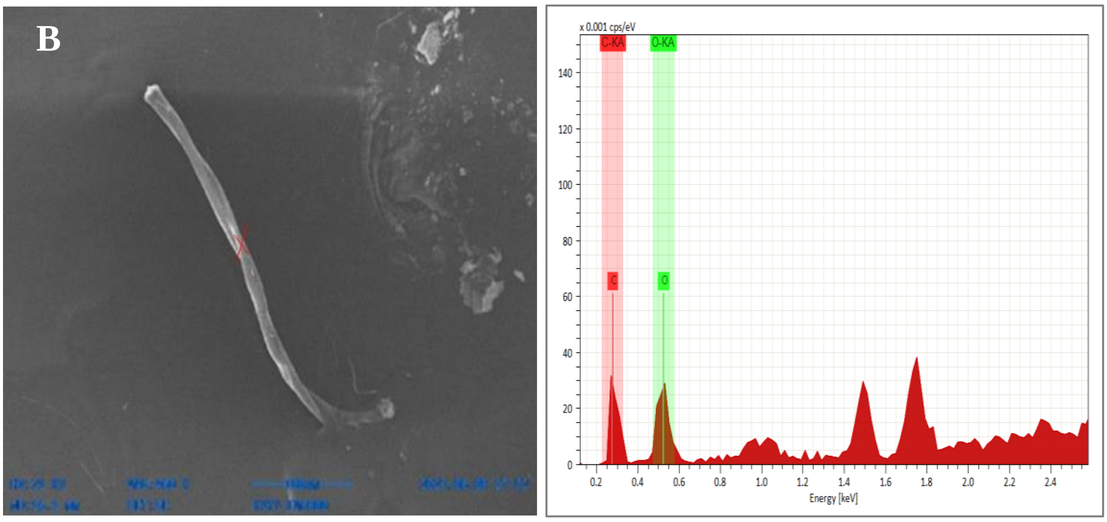
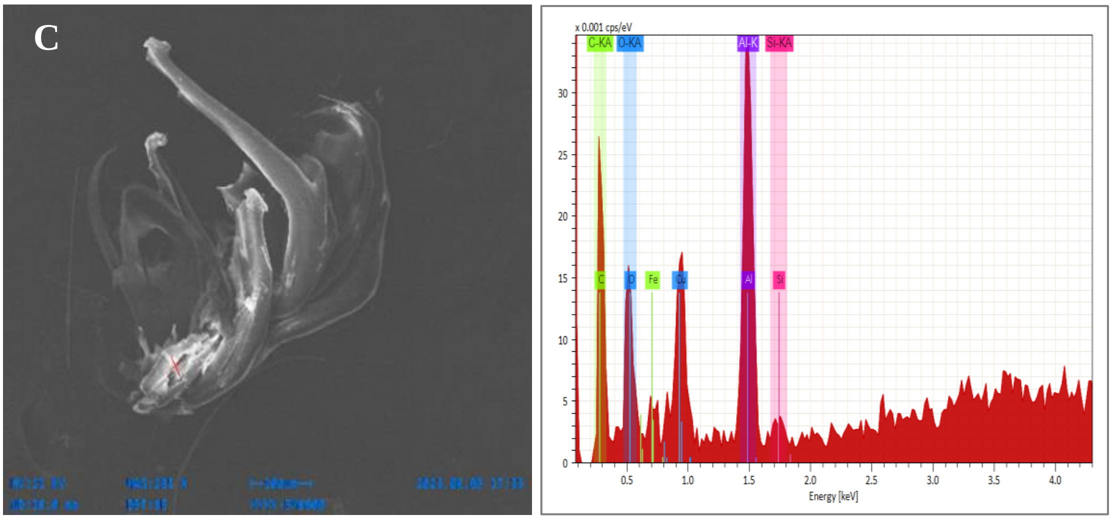
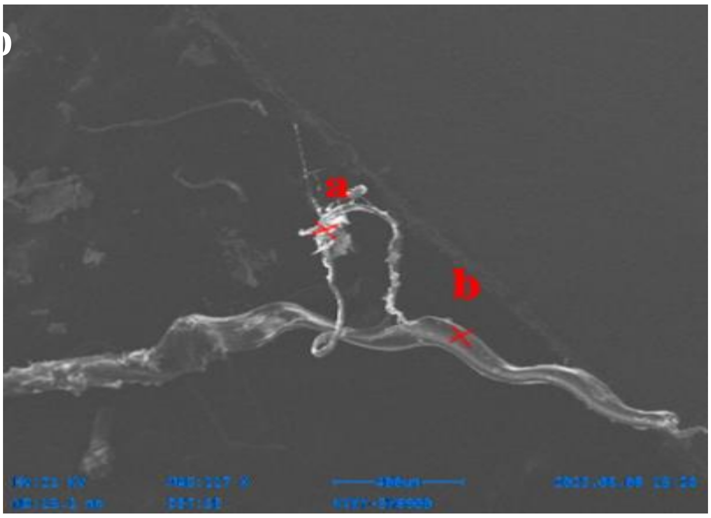


Figure 4.10. SEM images of microplastic particles (fibers: A, C, H; fragments: B, D, E, G, and sheet: F)




B
x 0.001 cps/eV
C-KA
O-KA
C
O
140
120
100
80
60
40
20
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Energy [keV]


C
x 0.001 cps/eV
C-KA
O-KA
Al-K
Si-KA
C
O
Fe
Cu
Al
Si
30
25
20
15
10
5
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Energy [keV]


a
b

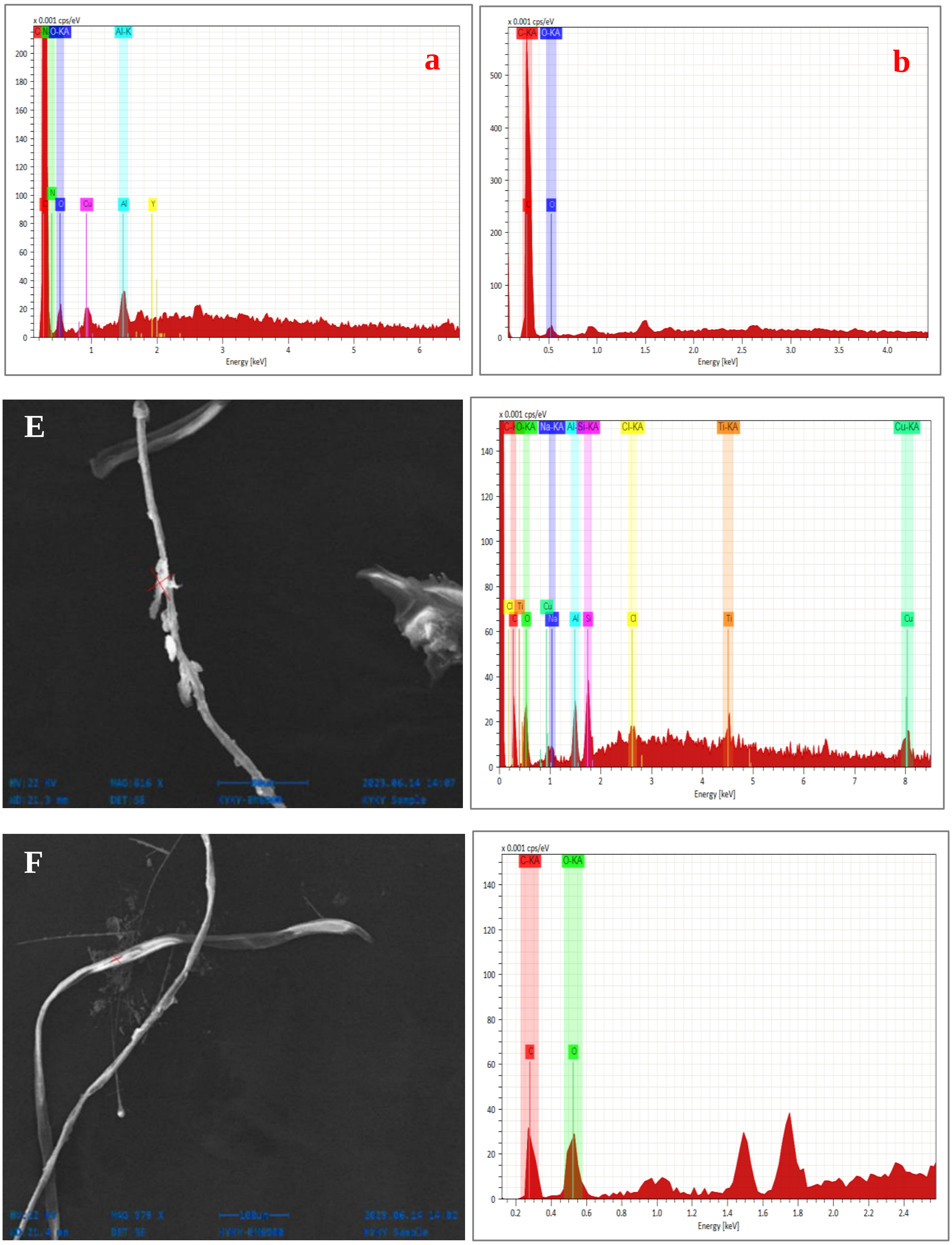


Figure **Error! No text of specified style in document.**11. SEM-EDX of microplastic particles (A) A fragment a) spot containing foreign substance b) spot without any foreign substance, (B) A smooth edged fiber, (C) fragment, (D) a frayed fiber from outdoor air., (E) a fiber with material adhered to its surface, (F) two fibers from outdoor air.

4.6. Comparative analysis of current study with previous research

Table 1. summarizes past study findings to compare them with current study findings. Since all these studies have employed various approaches have considered different parameters which make this comparison less likely. Most of the areas cited in table. 1 are more contaminated than the study area of this research which can be due to various reasons i.e., population size, plastic waste management practices, plastic demand and consumption, social and economic status etc.

Table 4.2. Comparative analysis with past studies on airborne microplastics

Study area	Sampling environment	Approach	Polymer type	Shape	MPs Abundance	Reference
Paris, France	Total atmospheric fallout	Leica MZ12 stereomicroscope	NA	Fiber (>90%)	29-280 particles/m^2/day	(Dris et al., 2015)
Paris, France	Total atmospheric fallout	Stereomicroscope	PET, PA, PU	Fiber	110 ± 96 particles/m^2/day	(Dris et al., 2016).
Paris, France	Indoor and outdoor air	Stereomicroscope, FTIR coupled with ATR	PP, Mixture of PA and cotton, Co-polymer of PE & PP	Fiber	Indoor: (1.0-60.0 fibers/m^3), Outdoor: (0.3-1.5 fibers/m^3).	(Dris et al., 2017)
China	Atmospheric fallout	Digital microscope, µ-FTIR, SEM	PE, PS, PP	Fibers	175-313 items/m^2/d	(Cai et al., 2017)
Germany	Atmospheric deposition	Fluorescence microscope,	PE, EVA	Fiber and	275 MPs/m^2/day	(Klein & Fischer,

		μ-Raman spectroscope	C, PVA, PTFE, PET	fragment (95%)		2019)
East China Normal University	Suspended atmospheric particulate matter	Stereomicroscope, μ-FTIR	PET, EP, PE, ALK, RY, PP, PA, PS	Fibers, Fragments	0.41 n/m^3	(Liu, Wang, Wei, et al., 2019)
Asaluyeh County, Iran	Suspended dust (PM$_{2.5}$), street dust	Fluorescence microscope, SEM	NA	Fibers	0.3-1.1 MPs/m^3	(Abbasi et al., 2019)
Surabaya, Indonesia	Ambient air	Microscope, FTIR	PET, cellophane, polyester	Fibers (>90%)	NA	(Asrin & Dipareza, 2019)
Beijing	Total suspended particles (TSP)	SEM-EDX	NA	Fibers	16.7 × 10^{-3} fibers/ml at 1.5m height, 14.1 × 10^{-3} fibers/ml at 18m height	Li et al., 2020
California, USA	Indoor and outdoor air	Nile red staining, fluorescent microscopy, Gross traditional microscopy, μ-Raman spectroscopy, and μ-FT-IR	PVC, PS, PE, PA	Fibers	Indoor: 3.3±2.9 fibers/m^3, 12.6±8.0 fragment/m^3. Outdoor: 0.6±0.6 fibers/m^3, 5.6±3.2 fragments/m^3	(Gaston et al., 2020)

		spectroscopy				
Wenzhou City China	Active sampling of indoor and outdoor air	Fluorescence stereomicroscope, µ-FTIR	Polyester, PA, PP, PE, PS, PVC	Fragments	indoor air = 1583 ± 1180 n/m^3 Outdoor air = 189 ± 85 n/m^3	(Liao et al., 2021)
China	Total suspended particulate matter	Fluorescence microscope, µ-FTIR	PE, PET, PS, PP, PA, PVC	Fragments (88.2%)	Northern cities: 358±152 n/m^3, Southeast cities: 230±92 n/m^3	(Zhu et al., 2021)
Portugal	Active indoor air sampling	Digital stereomicroscope	NA	Fiber	1.1 particles/m^3	(Xumiao et al., 2021)
Bushehr port, Iran	Particulate matter ($PM_{2.5}$)	Binocular microscope, iLED fluorescence microscope, µ-Raman	PET, Nylon, PE, PS, PP	Fragments (63%)	zero to 14.2 items/m^3	(Akhbarizadeh et al., 2021)
South Korea	Indoor and outdoor air	µ-FT-IR	PP, PE, PES, PS, PTFE, PVC, ALK, AR, PU, PA	Long and synthetic fibers	Suspended air: 0.45–6.64 (2.51±1.77) particles/m^3	(Choi et al., 2022)
Mexico.	Airborne PM_{10}	ATR-FTIR,	CPH,	Fibers	PM10 (0.205 ±	(Shruti et

	and $PM_{2.5}$ in urban, residential, and industrial sites.	epifluorescence microscope, SEM-EDX	PET, PE, Rayon, PA	(>75%)	0.061 items/m^3) PM2.5 (0.110 ± 0.055 items/m^3)	al., 2022)
Sri Lanka	Indoor and outdoor air	Stereomicroscope, FTIR	PET, PE, PS, PP, PA, Acrylic, PES	Fibers (98%)	Indoor: 0.13−0.93 particles/m^3, Outdoor: 0.00−0.23 particles/m^3	(Perera et al., 2022)
Lahore, Sahiwal Pakistan	Deposited dust samples from indoor residential environments	Stereomicroscope, FTIR	Polyester, PET, PE, PU, copolymer of PP	Microfibers (>90%)	Lahore: 241.45 (items/m^2), Sahiwal: 162.1 (Items/m^2)	(Aslam et al., 2022)
Varanasi, India	Atmospheric suspended particulate matter and dust samples	Binocular microscopy, fluorescence microscopy, FTIR, SEM-EDX	PE, PP, PET, PS, PVC, polyester,	Fibers (44%)	NA	(Pandey et al., 2022)
Ahvaz, Iran	Airborne particulate matter (PM_{10}) using high volume sampler	Binocular microscopy, SEM-EDX, µ-Raman spectroscope	PET, PP, PS, Nylon	Fibers	None detected to 0.017/m^3	(Abbasi et al., 2023)
Mosul City, Iraq	Different indoor environments	Stereomicroscope, FTIR	PS, PET, PE,	Fibers (93%)	3.02×10^2 – 4.743×10^3 MPs/m^2/d	(Al-Hussayni et al., 2023)

		spectroscopy	PP, PA, PVC			
Arizona State University	Total Suspended Particulate matter	Digital microscope, µ-Raman spectroscopy	PVC, Polyester, PS, PE	Fibers (≥82%)	0.02-1.1 microplastics/m^3	(Chandrakanthan et al., 2023)
University College London	Indoor and outdoor air	Dissecting microscope	NA	NA	Indoor: 40–50 particles m^{-3}/h, Outdoor: 1–2 particles m^{-3}/h	(Boakes et al., 2023)
Islamabad	Indoor and outdoor air samples	Olympus digital microscope, µ-FTIR, µ-Raman spectroscope, SEM-EDX	PET, PP, PE, LDPE, PS, PMMA	Indoor fibers: 57.6%, Outdoor fibers: 66.3%	Indoor: 4.34 ± 1.93 Items/m^3 Outdoor: 0.93 ± 0.32 Items/m^3	This study

4.7. Attributable health risks

Inhalable airborne microplastics can pose substantial health risks depending on their size, density, chemical composition, and fate in the human body. Despite the fact that MPs have been found in human blood, placenta, spleen, liver, lung, and other body tissues, there is a dearth of study on the effects of MPs on human health (Jenner et al., 2022; Kutralam-Muniasamy et al., 2023; Leslie et al., 2022; Ragusa et al., 2021). Microplastics of size less than 10 µm (especially <5 µm) are more likely to be inhaled and deposited in air sacs. These synthetic sharp edged particles apart from causing other biological impacts may physically damage lung tissues by rupturing alveolar walls (Amato-Lourenço et al., 2021; Enyoh et al., 2019; Xie et al., 2022). Due to their hydrophobic properties, microplastics, a growing portion of particulate matter (Sridharan et al., 2021) have been implicated in the transportation of harmful heavy metals (such as Pb, Cd, Ni, and Zn), persistent organic pollutants, and PAHs (polycyclic aromatic hydrocarbons) (Abbasi et al., 2020). Additionally they may contain dyes, chemicals, pigments and other hazardous chemicals capable of having deleterious impacts on human health (Gasperi et al., 2018).

Microplastics concentration, exposure time and size of the particles can assist in investigating impacts on human body. Since every person has different breathing pattern and live in different conditions, so impacts of MPs cannot be generalized to all, i.e., a worker of textile industry is more exposed to inhalation risk of synthetic fibers compared to a person who does not work in similar environment. Respiratory issues i.e., dyspnea, asthma, coughing, are commonly reported by workers of textile and paint industry who are chronically exposed to synthetic fibers through inhalation (Dris et al., 2017). Their chemical makeup, shape, and size all have a significant impact on whether they degrade or accumulate in the human body. During their time in the air, these particles may absorb hazardous substances at their surfaces and transport them into the human body by inhalation (Zhu et al., 2021). Due to their capacity to withstand mucociliary clearance and disintegration, which makes them more durable in physiological fluids, inhalable microplastic particles can remain in human body tissues for a considerable amount of time. To validate the longevity of synthetic polymeric fibers in the lungs and other human organs, however, more research is required (Law B. D. ,Bunn W. B., 1990). This study has identified airborne MPs, their physical characteristics and chemical composition but it urges further research to investigate human health risks associated with MPs concentration in air.

Microplastics in soil, water, or air can contaminate plants and animals thereby contaminating the whole food chain (Zhang et al., 2020). Given that ultimate consumers of food are humans, these synthetic particles enter the human body and can cause potential impacts at gastrointestinal tract or if inhaled on respiratory system (Zhang et al., 2020). Microplastics have also been found in the lungs of birds owing to the fact that their respiration is much higher than humans which implies higher exposure to airborne pollutants (Tokunaga et al., 2023).

A study conducted on wild birds to estimate their exposure to airborne microplastics reported the presence of MPs in lung tissue samples implying inhalation one of MPs' source in lungs (Tokunaga et al., 2023). Different chemicals are added to plastics during their production for various purposes. These chemicals i.e., bisphenol, phthalates etc. may disrupt endocrine. These endocrine disrupting chemicals may leach out during recycling of some plastics and cause serious health problems to exposed species (Ettore et al., 2008). The public is usually unaware of this information which is another disturbing fact leading to their unintentional exposure (Ettore et al., 2008). Pervasive MPs in soil, water and air make their way to humans, animals, and plants via various roots, thereby accumulating in their body tissues.

A study conducted to investigate impacts posed by microplastics on humans, marine mammals, and sea turtles reported that MPs can change membrane integrity, trigger an immunological response, produce oxidative stress and cytotoxicity, and cause altered gene expression (Meaza et al., 2020). Considerable negative effects, such as the inhibition of cell growth and significant morphological changes in sample cells were identified in a study where human lung cells were exposed to airborne polystyrene particles (Goodman et al., 2021). Long-term exposures to a range of synthetic polymers were thought to be more instructive on the effects posed by MPs (Meaza et al., 2020).

Chapter 5

5. Conclusions

In Pakistan, this study is the first to investigate airborne microplastics to ascertain their existence and to unravel their physical characteristics, polymeric composition, and chemical make-up. Microplastics in indoor and outdoor environments have been quantified (0.93 ± 0.32 Items/m^3 outdoors, 4.34 ± 1.93 Items/m^3 indoors) and categorized based on their color, size, and shape. Indoor contamination can be lowered by improving ventilation condition. Both ATR-FTIR and µ-Raman analysis have identified six different polymer types in indoor and outdoor samples. Particles of less than 20 micrometer were analyzed under µ-Raman spectroscope. Both techniques are effective, efficient, and reliable for studying airborne microplastics and have been used in past studies. It suggested if the concerned particles are less than 20 µm use µ-Raman spectroscope, and if the concerned particle size is above 20 µm both techniques can be employed alternatively. This paper has reviewed discrepancies in airborne MPs analysis approaches found in the literature and suggests a standard methodology. Furthermore, by employing SEM-EDX analysis this study has elucidated morphological characteristics of identified particles and their elemental composition considering two points i.e., parts with foreign substance and without foreign substance adhering to their surface. In many areas especially in megacities of Pakistan, which is among the countries with the worst air quality, there is a dire need for additional research on this subject. For the purpose of doing further research, the health sector, policy makers, and environmental protection departments will find these findings to be helpful.

5.1. Future perspectives

Future perspectives of this research work include:

1. Future research on airborne microplastics should consider the seasonal variations, altitudinal differences, and several other spatial variations that were not considered in this study.
2. Research on the health concerns posed by indoor air microplastics in rural and urban dwellings can assist policymakers better understand these dangers and develop regulations to protect the public's health.
3. Special research on inhalable microplastics is necessary, with a particular emphasis on MPs smaller than 5 µm, which have the ability to evade mucociliary clearance and persist

in body tissues for prolonged periods. Such studies in textile industries, paint industries and areas identified with potentially contaminated air from synthetic particles can help to design appropriate policies to edge off subsequent health issues.

4. Since airborne microplastics have been identified as neglected source of MPs in soil and water in past research (Dris et al., 2016), carrying out such studies in agricultural fields and over aquatic environment will help to quantify atmospheric transportation of microplastics in these environments.
5. There is a need to design biomarkers for microplastics pollution indication.

References

Abbasi, S., Jaafarzadeh, N., Zahedi, A., Ravanbakhsh, M., Abbaszadeh, S., & Turner, A. (2023). Microplastics in the atmosphere of Ahvaz City, Iran. *Journal of Environmental Sciences (China), 126*, 95–102. https://doi.org/10.1016/j.jes.2022.02.044

Abbasi, S., Keshavarzi, B., Moore, F., Turner, A., Kelly, F. J., Dominguez, A. O., & Jaafarzadeh, N. (2019). Distribution and potential health impacts of microplastics and microrubbers in air and street dusts from Asaluyeh County, Iran. *Environmental Pollution*, *244*, 153–164. https://doi.org/10.1016/j.envpol.2018.10.039

Abbasi, S., Moore, F., Keshavarzi, B., Hopke, P. K., Naidu, R., Rahman, M. M., Oleszczuk, P., & Karimi, J. (2020). PET-microplastics as a vector for heavy metals in a simulated plant rhizosphere zone. *Science of the Total Environment*, *744*, 140984. https://doi.org/10.1016/j.scitotenv.2020.140984

Acarer, S. (2023). Microplastics in wastewater treatment plants: Sources, properties, removal efficiency, removal mechanisms, and interactions with pollutants. *Water Science and Technology*, *87*(3), 685–710. https://doi.org/10.2166/wst.2023.022

Ahmad, M., Chen, J., Khan, M. T., Yu, Q., Phairuang, W., Furuuchi, M., Ali, S. W., Nawab, A., & Panyametheekul, S. (2023). Sources, analysis, and health implications of atmospheric microplastics. *Emerging Contaminants*, *9*(3), 100233. https://doi.org/10.1016/j.emcon.2023.100233

Akhbarizadeh, R., Dobaradaran, S., & Amouei, M. (2021). Suspended fine particulate matter (PM 2 . 5), microplastics (MPs), and polycyclic aromatic hydrocarbons (PAHs) in air : Their possible relationships and health implications. *Environmental Research*, *192*(September 2020), 110339. https://doi.org/10.1016/j.envres.2020.110339

Al-Hussayni, R. S., Al-Ahmady, K. K., & Mhemid, R. K. S. (2023). Assessment of Indoor Microplastic Particles Pollution in Selected Sites of Mosul City. *Journal of Ecological Engineering*, *24*(9), 322–332. https://doi.org/10.12911/22998993/168461

Ali, M. H. A. and H. (2019). Baseline Assessment of Current Scenario of Plastic Waste Management Islamabad Capital Territory (Ict) and Ayubia National Park (Anp). *UNESCO Islamabad*, 1–84.

Allen, S., Allen, D., Phoenix, V. R., Le Roux, G., Durántez Jiménez, P., Simonneau, A., Binet, S., & Galop, D. (2019). Atmospheric transport and deposition of microplastics in a remote mountain catchment. *Nature Geoscience*, *12*(5), 339–344. https://doi.org/10.1038/s41561-019-0335-5

Amato-Lourenço, L. F., Carvalho-Oliveira, R., Júnior, G. R., dos Santos Galvão, L., Ando, R. A., & Mauad, T. (2021). Presence of airborne microplastics in human lung tissue. *Journal of Hazardous Materials*, *416*(May). https://doi.org/10.1016/j.jhazmat.2021.126124

Amato-Lourenço, L. F., dos Santos Galvão, L., de Weger, L. A., Hiemstra, P. S., Vijver, M. G., & Mauad, T. (2020). An emerging class of air pollutants: Potential effects of microplastics to respiratory human health? *Science of the Total Environment*, *749*, 141676. https://doi.org/10.1016/j.scitotenv.2020.141676

An, L., Liu, Q., Deng, Y., Wu, W., Gao, Y., & Ling, W. (2020). Sources of Microplastic in the Environment. *Handbook of Environmental Chemistry*, *95*, 143–159. https://doi.org/10.1007/698_2020_449

Anjum, M. S., Ali, S. M., Imad-ud-din, M., Subhani, M. A., Anwar, M. N., Nizami, A. S., Ashraf, U., & Khokhar, M. F. (2021). An Emerged Challenge of Air Pollution and Ever-Increasing Particulate Matter in Pakistan; A Critical Review. *Journal of Hazardous Materials*, *402*(June 2020), 123943. https://doi.org/10.1016/j.jhazmat.2020.123943

Anwar, M. N., Shabbir, M., Tahir, E., Iftikhar, M., Saif, H., Tahir, A., Murtaza, M. A., Khokhar, M. F., Rehan, M., Aghbashlo, M., Tabatabaei, M., & Nizami, A. S. (2021). Emerging challenges of air pollution and particulate matter in China, India, and Pakistan and mitigating solutions. *Journal of Hazardous Materials*, *416*(August 2020), 125851. https://doi.org/10.1016/j.jhazmat.2021.125851

Aslam, I., Qadir, A., & Rashid, S. (2022). A preliminary assessment of microplastics in indoor dust of a developing country in South Asia. *Environmental Monitoring and Assessment*. https://doi.org/10.1007/s10661-022-09928-3

Asrin, N., & Dipareza, A. (2019). Microplastics in Ambient Air (Case Study : Urip Sumoharjo Street and Mayjend Sungkono Street of Surabaya City , Indonesia). *IAETSD Journal for Advanced Research in Applied Sciences, 6*(54), 54–57.

Beaurepaire, M., Dris, R., Gasperi, J., & Tassin, B. (2021). Microplastics in the atmospheric compartment: a comprehensive review on methods, results on their occurrence and determining factors. *Current Opinion in Food Science*, *41*, 159–168. https://doi.org/10.1016/j.cofs.2021.04.010

Boakes, L. C., Patmore, I. R., Bancone, C. E. P., & Rose, N. L. (2023). High temporal resolution records of outdoor and indoor airborne microplastics. *Environmental Science and Pollution Research*, *3*, 39246–39257. https://doi.org/10.1007/s11356-022-24935-0

Boyden, M. N., Kleist, E. M., Asztalos, C. K., & Korter, T. M. (2022). Determination of the polymer composition of mid - twentieth century purses by Raman spectroscopy. *Heritage Science*, 1–10. https://doi.org/10.1186/s40494-022-00743-0

Cai, L., Wang, J., Peng, J., Tan, Z., Zhan, Z., Tan, X., & Chen, Q. (2017). Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence. *Environmental Science and Pollution Research*, *24*(32), 24928–24935. https://doi.org/10.1007/s11356-017-0116-x

Chandrakanthan, K., Fraser, M. P., & Herckes, P. (2023). Airborne microplastics in a suburban location in the desert southwest: Occurrence and identification challenges. *Atmospheric Environment*, *298*(October 2022), 119617. https://doi.org/10.1016/j.atmosenv.2023.119617

Chen, G., Feng, Q., & Wang, J. (2020). Mini-review of microplastics in the atmosphere and their risks to humans. *Science of the Total Environment*, *703*, 135504. https://doi.org/10.1016/j.scitotenv.2019.135504

Chen, G., Fu, Z., Yang, H., & Wang, J. (2020). An overview of analytical methods for detecting microplastics in the atmosphere. *TrAC - Trends in Analytical Chemistry*, *130*, 115981. https://doi.org/10.1016/j.trac.2020.115981

Cheung, P. K., & Fok, L. (2016). Evidence of microbeads from personal care product contaminating the sea. *Marine Pollution Bulletin*, *109*(1), 582–585. https://doi.org/10.1016/j.marpolbul.2016.05.046

Choi, H., Lee, I., Kim, H., Park, J., Cho, S., Oh, S., Lee, M., & Kim, H. (2022). Comparison of Microplastic Characteristics in the Indoor and Outdoor Air of Urban Areas of South Korea. *Water, Air, and Soil Pollution*, *233*(5), 1–10. https://doi.org/10.1007/s11270-022-05650-5

Dehghani, S., Moore, F., & Akhbarizadeh, R. (2017). Microplastic pollution in deposited urban dust, Tehran metropolis, Iran. *Environmental Science and Pollution Research, 24*(25), 20360–20371. https://doi.org/10.1007/s11356-017-9674-1

Deng, L., Li, G., Peng, S., Wu, J., & Che, Y. (2022). Microplastics in personal care products: Exploring public intention of usage by extending the theory of planned behaviour. *Science of the Total Environment*, *848*(July), 157782. https://doi.org/10.1016/j.scitotenv.2022.157782

Ding, J., Sun, C., He, C., Zheng, L., Dai, D., & Li, F. (2022). Atmospheric microplastics in the Northwestern Pacific Ocean: Distribution, source, and deposition. *Science of the Total Environment*, *829*, 154337. https://doi.org/10.1016/j.scitotenv.2022.154337

Dobaradaran, S., Schmidt, T. C., Nabipour, I., Khajeahmadi, N., Tajbakhsh, S., Saeedi, R., Javad Mohammadi, M., Keshtkar, M., Khorsand, M., & Faraji Ghasemi, F. (2018). Characterization of plastic debris and association of metals with microplastics in coastline sediment along the Persian Gulf. *Waste Management*, *78*, 649–658. https://doi.org/10.1016/j.wasman.2018.06.037

Dong, M., Zhang, Q., Xing, X., Chen, W., She, Z., & Luo, Z. (2020). Raman spectra and surface changes of microplastics weathered under natural environments. *Science of the Total Environment*, *739*, 139990. https://doi.org/10.1016/j.scitotenv.2020.139990

Dris, R., Gasperi, J., Mirande, C., Mandin, C., Guerrouache, M., Langlois, V., & Tassin, B. (2017). A first overview of textile fibers, including microplastics, in indoor and outdoor environments. *Environmental Pollution, 221,* 453–458. https://doi.org/10.1016/j.envpol.2016.12.013

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., & Tassin, B. (2015). Microplastic contamination in an urban area: A case study in Greater Paris. *Environmental Chemistry, 12*(5), 592–599. https://doi.org/10.1071/EN14167

Dris, R., Gasperi, J., Saad, M., Mirande, C., & Tassin, B. (2016). Synthetic fibers in atmospheric fallout: A source of microplastics in the environment? *Marine Pollution Bulletin*, *104*(1–2), 290–293. https://doi.org/10.1016/j.marpolbul.2016.01.006

Enyoh, C. E., Verla, A. W., Verla, E. N., Ibe, F. C., & Amaobi, C. E. (2019). Airborne microplastics: a review study on method for analysis, occurrence, movement and risks.

Environmental Monitoring and Assessment, *191*(11). https://doi.org/10.1007/s10661-019-7842-0

Ettore, T., International, M., The, S. C., Seminars, I., Emergencies, P., Federation, T. W., Seminars, E. I., War, N., Emergencies, P., Zichichi, A., Majorana, E., Centre, I., Culture, S., Majorana, E., Federation, T. W., Federation, T. W., World, T. P., Quality, W., Chemicals, E. D., & Moore, C. (2008). *The plastic world : Sources , amounts , ecological impacts and effects on development , reproduction , brain and behavior in aquatic and terrestrial animals and humans*. *108*, 127–130. https://doi.org/10.1016/j.envres.2008.03.008

Fendall, L. S., & Sewell, M. A. (2009). Contributing to marine pollution by washing your face: Microplastics in facial cleansers. *Marine Pollution Bulletin*, *58*(8), 1225–1228. https://doi.org/10.1016/j.marpolbul.2009.04.025

Gasperi, J., Wright, S. L., Dris, R., Collard, F., Mandin, C., Guerrouache, M., Langlois, V., Kelly, F. J., & Tassin, B. (2018). Microplastics in air: Are we breathing it in? *Current Opinion in Environmental Science and Health*, *1*, 1–5. https://doi.org/10.1016/j.coesh.2017.10.002

Gaston, E., Woo, M., Steele, C., Sukumaran, S., & Anderson, S. (2020). Microplastics Differ Between Indoor and Outdoor Air Masses: Insights from Multiple Microscopy Methodologies. In *Applied Spectroscopy* (Vol. 74, Issue 9). https://doi.org/10.1177/0003702820920652

Goodman, K. E., Hare, J. T., Khamis, Z. I., Hua, T., & Sang, Q. X. A. (2021). Exposure of Human Lung Cells to Polystyrene Microplastics Significantly Retards Cell Proliferation and Triggers Morphological Changes. *Chemical Research in Toxicology*, *34*(4), 1069–1081. https://doi.org/10.1021/acs.chemrestox.0c00486

Hale, R. C., Seeley, M. E., La Guardia, M. J., Mai, L., & Zeng, E. Y. (2020). A Global Perspective on Microplastics. *Journal of Geophysical Research: Oceans*, *125*(1), 1–40. https://doi.org/10.1029/2018JC014719

Hartmann, N. B., Hüffer, T., Thompson, R. C., Hassellöv, M., Verschoor, A., Daugaard, A. E., Rist, S., Karlsson, T., Brennholt, N., Cole, M., Herrling, M. P., Hess, M. C., Ivleva, N. P., Lusher, A. L., & Wagner, M. (2019). Are We Speaking the Same Language? Recommendations for a Definition and Categorization Framework for Plastic Debris.

Environmental Science and Technology, *53*(3), 1039–1047. https://doi.org/10.1021/acs.est.8b05297

Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: A review of the methods used for identification and quantification. *Environmental Science and Technology*, *46*(6), 3060–3075. https://doi.org/10.1021/es2031505

Huang, Y., Yan, M., Xu, K., Nie, H., Gong, H., & Wang, J. (2019). Distribution characteristics of microplastics in Zhubi Reef from South China Sea. *Environmental Pollution*, *255*, 113133. https://doi.org/10.1016/j.envpol.2019.113133

Jan Kole, P., Löhr, A. J., Van Belleghem, F. G. A. J., & Ragas, A. M. J. (2017). Wear and tear of tyres: A stealthy source of microplastics in the environment. *International Journal of Environmental Research and Public Health*, *14*(10). https://doi.org/10.3390/ijerph14101265

Jenner, L. C., Rotchell, J. M., Bennett, R. T., Cowen, M., Tentzeris, V., & Sadofsky, L. R. (2022). Detection of microplastics in human lung tissue using μFTIR spectroscopy. *Science of the Total Environment*, *831*(March), 154907. https://doi.org/10.1016/j.scitotenv.2022.154907

Jenner, L. C., Sadofsky, L. R., Danopoulos, E., & Rotchell, J. M. (2021). Household indoor microplastics within the Humber region (United Kingdom): Quantification and chemical characterisation of particles present. *Atmospheric Environment*, *259*(January), 118512. https://doi.org/10.1016/j.atmosenv.2021.118512

Kacprzak, S., & Tijing, L. D. (2022). Microplastics in indoor environment: Sources, mitigation and fate. *Journal of Environmental Chemical Engineering*, *10*(2), 107359. https://doi.org/10.1016/j.jece.2022.107359

Kirchsteiger, B., & Kasper-giebl, A. (2023). *Fine micro- and nanoplastics particles (PM 2 . 5) in urban air and their relation to polycyclic aromatic hydrocarbons*. *301*(February). https://doi.org/10.1016/j.atmosenv.2023.119670

Klein, M., & Fischer, E. K. (2019). Microplastic abundance in atmospheric deposition within the Metropolitan area of Hamburg, Germany. *Science of the Total Environment*, *685*, 96–103. https://doi.org/10.1016/j.scitotenv.2019.05.405

Konechnaya, O., Lüchtrath, S., Dsikowitzky, L., & Schwarzbauer, J. (2020). Optimized microplastic analysis based on size fractionation, density separation and μ-FTIR. *Water Science and Technology*, *81*(4), 834–844. https://doi.org/10.2166/wst.2020.173

Kutralam-Muniasamy, G., Shruti, V. C., Pérez-Guevara, F., & Roy, P. D. (2023). Microplastic diagnostics in humans: “The 3Ps” Progress, problems, and prospects. *Science of the Total Environment*, *856*(October 2022). https://doi.org/10.1016/j.scitotenv.2022.159164

Law B. D. ,Bunn W. B., H. T. W. (1990). *Solubility of Polymeric Organic Fibers*. 321–339.

Leslie, H. A., van Velzen, M. J. M., Brandsma, S. H., Vethaak, A. D., Garcia-Vallejo, J. J., & Lamoree, M. H. (2022). Discovery and quantification of plastic particle pollution in human blood. *Environment International*, *163*(March), 107199. https://doi.org/10.1016/j.envint.2022.107199

Li, Y., Shao, L., Wang, W., Zhang, M., Feng, X., Li, W., & Zhang, D. (2020). Airborne fiber particles: Types, size and concentration observed in Beijing. *Science of the Total Environment*, *705*, 135967. https://doi.org/10.1016/j.scitotenv.2019.135967

Liao, Z., Ji, X., Ma, Y., Lv, B., Huang, W., Zhu, X., Fang, M., Wang, Q., Wang, X., Dahlgren, R., & Shang, X. (2021). Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China. *Journal of Hazardous Materials*, *417*(May), 126007. https://doi.org/10.1016/j.jhazmat.2021.126007

Liu, K., Wang, X., Fang, T., Xu, P., Zhu, L., & Li, D. (2019). Source and potential risk assessment of suspended atmospheric microplastics in Shanghai. *Science of the Total Environment*, *675*, 462–471. https://doi.org/10.1016/j.scitotenv.2019.04.110

Liu, K., Wang, X., Wei, N., Song, Z., & Li, D. (2019). Accurate quantification and transport estimation of suspended atmospheric microplastics in megacities: Implications for human health. *Environment International*, *132*(August), 105127. https://doi.org/10.1016/j.envint.2019.105127

Liu, K., Zhang, F., Song, Z., Zong, C., Wei, N., & Li, D. (2019). A novel method enabling the accurate quantification of microplastics in the water column of deep ocean. *Marine Pollution Bulletin*, *146*(May), 462–465. https://doi.org/10.1016/j.marpolbul.2019.07.008

Masura, J., Baker, J., Foster, G., & Arthur, C. (2015). Laboratory methods for the analysis of microplastics in the marine environment. *NOAA Marine Debris Program National*, *July*, 1–31. https://marinedebris.noaa.gov/sites/default/files/publications-files/noaa_microplastics_methods_manual.pdf

Mbachu, O., Jenkins, G., Pratt, C., & Kaparaju, P. (2020). A New Contaminant Superhighway? A Review of Sources, Measurement Techniques and Fate of Atmospheric Microplastics. *Water, Air, and Soil Pollution*, *231*(2). https://doi.org/10.1007/s11270-020-4459-4

Mizuguchi, H., Takeda, H., Kinoshita, K., Takeuchi, M., Takayanagi, T., Teramae, N., Pipkin, W., Matsui, K., Watanabe, A., & Watanabe, C. (2023). Direct analysis of airborne microplastics collected on quartz filters by pyrolysis-gas chromatography/mass spectrometry. *Journal of Analytical and Applied Pyrolysis*, *171*(March), 105946. https://doi.org/10.1016/j.jaap.2023.105946

Napper, I. E., Bakir, A., Rowland, S. J., & Thompson, R. C. (2015). Characterisation, quantity and sorptive properties of microplastics extracted from cosmetics. *Marine Pollution Bulletin*, *99*(1–2), 178–185. https://doi.org/10.1016/j.marpolbul.2015.07.029

Organisation for Economic Co-operation and Development. (2021). *Global Plastics Outlook Policy Scenarios to 2060 policy highlights*.

Ortega, D. E., & Cortés-Arriagada, D. (2023). Atmospheric microplastics and nanoplastics as vectors of primary air pollutants - A theoretical study on the polyethylene terephthalate (PET) case. *Environmental Pollution*, *318*(December 2022). https://doi.org/10.1016/j.envpol.2022.120860

Pandey, D., Banerjee, T., Badola, N., & Chauhan, J. S. (2022). Evidences of microplastics in aerosols and street dust: a case study of Varanasi City, India. *Environmental Science and Pollution Research*, *29*(54), 82006–82013. https://doi.org/10.1007/s11356-022-21514-1

Perera, K., Ziajahromi, S., Bengtson Nash, S., Manage, P. M., & Leusch, F. D. L. (2022). Airborne Microplastics in Indoor and Outdoor Environments of a Developing Country in South Asia: Abundance, Distribution, Morphology, and Possible Sources. *Environmental Science and Technology*, *56*(23), 16676–16685. https://doi.org/10.1021/acs.est.2c05885

Perera, K., Ziajahromi, S., Nash, S. B., & Leusch, F. D. L. (2023). Microplastics in

Australian indoor air: Abundance, characteristics, and implications for human exposure. *Science of the Total Environment*, *889*(March), 164292. https://doi.org/10.1016/j.scitotenv.2023.164292

Plastics Europe. (2021). Plastics Europe Association of Plastics Manufacturers Plastics—The Facts 2021 An analysis of European Plastics Production, Demand and Waste Data. *Plastics - the Facts 2021*, 34. https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/

Plastics Europe, & EPRO. (2016). Plastics – the Facts 2016. *Plastics – the Facts 2016*, 37. www.plasticseurope.de/informations

Prata, J. C., Castro, J. L., da Costa, J. P., Duarte, A. C., Cerqueira, M., & Rocha-Santos, T. (2020). An easy method for processing and identification of natural and synthetic microfibers and microplastics in indoor and outdoor air. *MethodsX*, *7*, 1–9. https://doi.org/10.1016/j.mex.2019.11.032

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., Papa, F., Rongioletti, M. C. A., Baiocco, F., Draghi, S., D’Amore, E., Rinaldo, D., Matta, M., & Giorgini, E. (2021). Plasticenta: First evidence of microplastics in human placenta. *Environment International*, *146*, 106274. https://doi.org/10.1016/j.envint.2020.106274

Rasheed, A., Aneja, V. P., Aiyyer, A., & Rafique, U. (2015). Measurement and analysis of fine particulate matter (PM2.5) in urban areas of Pakistan. *Aerosol and Air Quality Research*, *15*(2), 426–439. https://doi.org/10.4209/aaqr.2014.10.0269

Rosso, B., Corami, F., Barbante, C., & Gambaro, A. (2023). Quantification and identification of airborne small microplastics (<100 μm) and other microlitter components in atmospheric aerosol via a novel elutriation and oleo-extraction method. *Environmental Pollution, 318*(September 2022), 120889. https://doi.org/10.1016/j.envpol.2022.120889

Shruti, V. C., Kutralam-Muniasamy, G., Pérez-Guevara, F., Roy, P. D., & Martínez, I. E. (2022). Occurrence and characteristics of atmospheric microplastics in Mexico City. *Science of the Total Environment*, *847*(July). https://doi.org/10.1016/j.scitotenv.2022.157601

Sobhani, Z., Al Amin, M., Naidu, R., Megharaj, M., & Fang, C. (2019). Identification and visualisation of microplastics by Raman mapping. *Analytica Chimica Acta*, *1077*, 191–

199. https://doi.org/10.1016/j.aca.2019.05.021

Su, Y., Zhang, Z., Wu, D., Zhan, L., Shi, H., & Xie, B. (2019). Occurrence of microplastics in landfill systems and their fate with landfill age. *Water Research*, *164*. https://doi.org/10.1016/j.watres.2019.114968

Tian, L., Jinjin, C., Ji, R., Ma, Y., & Yu, X. (2022). Microplastics in agricultural soils: sources, effects, and their fate. *Current Opinion in Environmental Science and Health*, *25*, 100311. https://doi.org/10.1016/j.coesh.2021.100311

Tokunaga, Y., Okochi, H., Tani, Y., Niida, Y., Tachibana, T., Saigawa, K., Katayama, K., Moriguchi, S., Kato, T., & Hayama, S. ichi. (2023). Airborne microplastics detected in the lungs of wild birds in Japan. *Chemosphere*, *321*(January), 138032. https://doi.org/10.1016/j.chemosphere.2023.138032

Torres-Agullo, A., Karanasiou, A., Moreno, T., & Lacorte, S. (2022). Airborne microplastic particle concentrations and characterization in indoor urban microenvironments. *Environmental Pollution*, *308*(March), 119707. https://doi.org/10.1016/j.envpol.2022.119707

Truong, T. N. S., Strady, E., Kieu-Le, T. C., Tran, Q. V., Le, T. M. T., & Thuong, Q. T. (2021). Microplastic in atmospheric fallouts of a developing Southeast Asian megacity under tropical climate. *Chemosphere*, *272*. https://doi.org/10.1016/j.chemosphere.2021.129874

Tunahan Kaya, A., Yurtsever, M., & Çiftçi Bayraktar, S. (2018). Ubiquitous exposure to microfiber pollution in the air. *European Physical Journal Plus*, *133*(11). https://doi.org/10.1140/epjp/i2018-12372-7

Veetil, V., Jithin, N., Sakshi, J., & Farooqui, M. O. (2020). Assessment of Microplastics in Roadside Suspended Dust from Urban and Rural Environment of Nagpur , India. *International Journal of Environmental Research*, *14*(6), 629–640. https://doi.org/10.1007/s41742-020-00283-0

Vianello, A., Jensen, R. L., Liu, L., & Vollertsen, J. (2019). Simulating human exposure to indoor airborne microplastics using a Breathing Thermal Manikin. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-45054-w

Vitali, C., Peters, R. J. B., Janssen, H. G., & Nielen, M. W. F. (2023). Microplastics and nanoplastics in food, water, and beverages; part I. occurrence. *TrAC - Trends in Analytical Chemistry*, *159*, 116670. https://doi.org/10.1016/j.trac.2022.116670

Wright, S. L., & Kelly, F. J. (2017). Plastic and Human Health: A Micro Issue? *Environmental Science and Technology*, *51*(12), 6634–6647. https://doi.org/10.1021/acs.est.7b00423

Wright, S. L., Ulke, J., Font, A., Chan, K. L. A., & Kelly, F. J. (2020). Atmospheric microplastic deposition in an urban environment and an evaluation of transport. *Environment International*, *136*(November 2019), 105411. https://doi.org/10.1016/j.envint.2019.105411

Xie, Y., Li, Y., Feng, Y., Cheng, W., & Wang, Y. (2022). Inhalable microplastics prevails in air: Exploring the size detection limit. *Environment International*, *162*(February), 107151. https://doi.org/10.1016/j.envint.2022.107151

Xiong, X., Zhang, K., Chen, X., Shi, H., Luo, Z., & Wu, C. (2018). Sources and distribution of microplastics in China's largest inland lake – Qinghai Lake. *Environmental Pollution*, *235*, 899–906. https://doi.org/10.1016/j.envpol.2017.12.081

Xumiao, L., Prata, J. C., Alves, J. R., Duarte, A. C., Rocha-Santos, T., & Cerqueira, M. (2021). Airborne microplastics and fibers in indoor residential environments in Aveiro, Portugal. *Environmental Advances*, *6*. https://doi.org/10.1016/j.envadv.2021.100134

Yadav, H., Sethulekshmi, S., Shriwastav, A., Zhang, Q., Zhao, Y., Du, F., Cai, H., Wang, G., Shi, H., Cox, K. D., Covernton, G. A., Davies, H. L., Dower, J. F., Juanes, F., Dudas, S. E., Chen, G., Feng, Q., Wang, J., Ageel, H. K., … Birkved, M. (2021). Overview on the occurrence of microplastics in air and implications from the use of face masks during the COVID-19 pandemic. *Science of the Total Environment*, *24*(1), 149555. https://doi.org/10.1016/j.envres.2022.113735

Yao, Y., Glamoclija, M., Murphy, A., & Gao, Y. (2022). Characterization of microplastics in indoor and ambient air in northern New Jersey. *Environmental Research*, *207*(May 2021), 112142. https://doi.org/10.1016/j.envres.2021.112142

Zhai, X., Zheng, H., Xu, Y., Zhao, R., Wang, W., & Guo, H. (2023). Heliyon Characterization and quantification of microplastics in indoor environments. *Heliyon*, *9*(5), e15901. https://doi.org/10.1016/j.heliyon.2023.e15901

Zhou, B., Wang, J., Zhang, H., Shi, H., Fei, Y., Huang, S., Tong, Y., Wen, D., Luo, Y., & Barceló, D. (2020). Microplastics in agricultural soils on the coastal plain of Hangzhou Bay, east China: Multiple sources other than plastic mulching film. *Journal of Hazardous Materials*, *388*(August 2019), 121814. https://doi.org/10.1016/j.jhazmat.2019.121814

Zhu, X., Huang, W., Fang, M., Liao, Z., Wang, Y., Xu, L., Mu, Q., Shi, C., Lu, C., Deng, H., Dahlgren, R., & Shang, X. (2021). Airborne Microplastic Concentrations in Five Megacities of Northern and Southeast China. *Environmental Science and Technology*, *55*(19), 12871–12881. https://doi.org/10.1021/acs.est.1c03618