Heliyon 9 (2023) e15901

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Characterization and quantification of microplastics in indoor environments

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ARTICLE INFO

Keywords:
Indoor fallout
MP characterization
Abundance
Deposition rate

ABSTRACT

Microplastics (MPs) have gradually attracted attention; however, people have paid limited attention to the existence of airborne microplastics, especially in indoor environments. In this study, we tracked microplastic deposition in offices, laboratories, dining halls, and dormitories. Results showed that the average microplastic abundance in the dormitory was the highest (14088.05 pcs/m^3), followed by in the office (13097.13 pcs/m^3), laboratory (7512.55 pcs/m^3) and dining hall (4308.26 pcs/m^3). The microplastics deposited at indoor environment were mostly dark, elongated and solid. The average particle size of the microplastics sampled at the four sampling points was 66.15 μm, but the size of the microplastics in the laboratory environment was smaller and more harmful. Airflow tests using air conditioners showed that turbulence increases the resuspension of microplastics. Our results also show that the frequency of human activities is one of the main factors leading to changes in the content of microplastics in indoor air, and turbulence caused by airflow will lead to the migration of microplastics in the indoor environment. In conclusion, indoor environments are prone to high microplastic concentration, which may pose certain potential risks to human health.

1. Introduction

Plastics have been widely used around the world because of their corrosion resistance, light strength, and low cost [1]. Since the invention of plastic in the early 20th century, global production has increased every year, reaching 359 million tons in 2018. This trend is expected to continue to about four times the current rate by 2050 [2]. Although research into plastic pollution has begun, there was very little research into microplastics (MPs) until they were first mentioned in 2004. In 2019, researches divided plastics roughly into four categories based on their size: large plastics (>25 mm), medium plastics (5–25 mm), microplastics (<5 mm), and nanoplastics (<100 nm). Microplastics were defined by researchers as plastics composed of small materials less than 5 mm in size at an international research symposium in 2008. Garbage accumulates in the environment by virtue of its stability, and microplastics (<5 mm, MPs) have been of increasing concern as a global environmental threat in recent years [3]. Plastic manufacturing or processing may be the main source of MPs, as well as everyday activities such as washing clothes in washing machines [4,5]. Researches proposed in their report in 2020 that secondary production through different decomposition and degradation methods was the primary source of MPs.

MPs come from a wide range of sources, especially in aquatic and terrestrial environments. Over time, MPs continue to physically break down into smaller particles [6,7]; therefore, they are widely eaten by terrestrial and aquatic organisms [8,9]. MPs can be found in many environmental mediums, such as brine, freshwater, potable water, outlet water, soil, sludge, precipitate, and submarine

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https://doi.org/10.1016/j.heliyon.2023.e15901
Received 27 February 2023; Received in revised form 26 April 2023; Accepted 26 April 2023
Available online 28 April 2023

sandstone. MPs have also been detected in aquatic biological clocks, such as clam shells, mussels, whales and sea turtles [10–15].

Despite in-depth research on MPs in marine and terrestrial environments, our understanding of airborne MP dynamics is still limited. We found that the atmospheric environment bears the brunt, whether it is the primary pathway of pollutant transport and diffusion or the main area where human beings are exposed to various pollutants. Soltani et al. reported that the long-distance transport of contaminants across the globe may affect human health, and air pollution can cause health problems [16]. Therefore, MP pollution in the atmospheric environment has become the main concern of researchers. Considering that 68% and 95% of people's time is spent indoors and other closed places, respectively [17], and that micro plastics are used long-term in family settings, it is necessary to investigate the health risks regarding MP exposure in primary living settings. Furthermore, surprisingly, the number of studies on airborne MP exposure is limited [18]. Most atmospheric MP studies have used passive collection methods (atmospheric total deposition). Passive full-deposition or volume-deposition samplers have been widely used because of their simple operation and lack of need for an independent power supply.

The impact of MPs on the environment and human health become an emerging field. In some cases, attempts have been made to collect plastic micro-nano particles from the atmosphere. In addition, the majority of previous researches have explored MPs in outdoor environment; relatively few investigations have been performed for indoor environment. In order to protect vulnerable populations from exposure to potentially detrimental indoor environments, our understanding of MPs levels and distributions must be improved, particularly in China, where such information is scarce. We evaluate the data through the collection and analysis of particulate matter in the collected samples: (1) the type and proportion of dust collected under passive conditions; (2) characteristics of MPs in indoor environments; (3) abundance and depositional rate of MPs in indoor environments; and (4) effects of turbulent gas flow on the resuspension of MPs.

2. Materials and methods

The materials, equipment and methods used for data collection and analysis in the laboratory and at the sampling points involved in this study are described as follows (Fig. S6).

2.1. Sampling and sample handling

All the researchers involved in this study were recruited from Xiamen University of Technology. In this study, we selected 4 sampling points distributed in 4 indoor environment areas of the university (Fig. S1). The researchers were asked to count the main materials of the objects present, number of flow sources and main floor covering material in each indoor environment. In the field surveys, we then obtained additional information for each indoor environmental area to calculate the MP density.

The passive sampling method of Qun Z et al. was adopted for dust sampling [19]. Sampling was conducted at the four sampling sites mentioned above. The sampling frequency of each sampling point ranges from 7 to 14 days each time, with a total of 8 times of sampling [20]. Following the indoor environment passive collection of atmospheric dust in a stainless steel basin (diameter = 28 cm), each sample was then wrapped in tinfoil, packed in a carton and shipped to the laboratory. Each sample was washed three times in the laboratory with ultrapure water and concentrated to 0.25 μm (pore size) through a Buchner funnel with a filter membrane and a 90-mm diameter glass fibre filter paper (Whatman ™, China). A glass Petri dish was prepared for further analysis using prewashed stainless steel, then both sides were flushed with ultrapure water three times, and the dish was air-dried face down to avoid air deposition. To ensure that there were no pollutants attached to the Buchner funnel, the inner part was flushed with ultrapure water more than three times before suction filtration. After cleaning and drying the Petri dishes but before analysis by the researcher, the Petri dishes were closed and sealed with insulating film to restrict the entry of any air particles. The filters were placed in the appropriate Petri dish using prerinsed stainless-steel pliers for further analysis. During laboratory work, relevant equipment was flushed with ultrapure water three times during use and stored in aluminium foil to minimize pollution. To limit any potential particle loss during sample processing, microplastic sample-processing procedures such as dissolution and density separation were not used in this study [21–23]. The dust samples deposited from the atmospheric environment and measured in this study differed from the MPs contained in other mixed environments and did not mix with other substances to cause confusion. The following detailed procedures were then used to easily identify the MPs and dust in the samples.

2.2. Quality assurance process

Some measures were taken to minimize the cross contamination of samples in this study. During sample processing, researchers wore 100% cotton lab coats to avoid using plastic materials as much as possible. Before each experiment, lab surfaces were cleaned with lab paper and 95% antiseptic alcohol. Laboratory equipment was covered with aluminium foil while in standby. The glass fibre filters were examined for possible contamination using a Leica DM500 stereomicroscope with × 100 magnification. Excess particulate matter was removed with pre-treated laboratory equipment. Visual inspections for foreign objects were performed several times over three days. We wrapped and sealed all referenced Petri dishes with aluminium foil. The MP contamination of the equipment associated with the prepared samples was assessed. As with the field blank sample, the researcher randomly selected 3 samples from 36 sample filter membranes to make temporary films and then observed the films with an X100 × body microscope in a pollution-free environment. No significant environmental microplastic contamination was observed during preparation or storage. To control the potential water pollution during the experiment, all the experimental equipment was washed with ultrapure water more than three times. The blank control was not contaminated. To ensure the effectiveness of the samples in the sample-processing program, the filter

membranes in all Petri dishes were made into samples after drying and observed under an X100 × microscope. No residual particles, including MPs, were observed in the culture dishes.

2.3. Microscope analysis

An Olympus CX23 and Leica DM500 with Troup View software were used for the preliminary evaluation of particles on the glass fibre filter papers. The observer used their naked eye to observe the size, shape and colour of particles. The observer then roughly estimated the MP count, size and colour. Due to the lack of fluorescence function in all microscopes, the use of microscopes can lead to the omission of clear microplastics, which can lead to errors.

To solve the above problems, an MDS-HDAF stereo microscope and Spectrum IR software were used as relevant sample indicators to assist in observing the target results. First, the samples on highly reflective glass were rinsed into vials with ethanol, the vials were placed in the observation area, the target position was observed with the microscope, and the magnification focus was adjusted for clarity. Then, images of each sample were taken under the microscope.

2.4. LDIR analysis

The abundance, composition and morphological characteristics of the microplastics in each sample were analyzed by LDIR (Agilent 8700 LDIR) and Clarity software. This machine and software have been used previously to determine the fraction of particles in the air. The morphological characteristics of microplastics measured in this study mainly included the diameter, width, height, area, eccentricity, solidity, and roundness. Only MPs with matching degrees greater than 65% with the Agilent 8700 LDIR database were selected for analysis in this study.

For this analysis, first, we prepared 1.7–1.8 kg/L $ZnCl_2$ (superior pure) solution. After immersing the membrane in ethanol solution for sonication, the membrane was removed and rinsed several times with ethanol. The ethanol solution was dried, zinc chloride solution was added to it, and the solution was sonicated for 5 min, then allowed to stand. The supernatant was taken for vacuum filtration, and the resulting membrane was immersed in ethanol solution for sonication so that the substances on the filter membrane were dispersed in the ethanol solution. The filter membrane in the ethanol solution was removed, the filter membrane was cleaned with ethanol many times, the ethanol solution was concentrated, and then the ethanol solution was added dropwise to the high inverse glass. The LDIR test was carried out after the ethanol was completely volatilized. For LDIR testing, the particle analysis mode and microplastic library establishment method were selected, and the automatic test method (matching degree >0.65, particle size range 20–500 μm) was set and tested. LDIR can ensure the acquisition of the destination date and efficiently compensate for observation deviations.

2.5. Micro-FTIR analysis

To further observe the correlation traits of the sampled MPs, MDS-HDAF stereo microscopes and PerkinElmer FT-IR Microscope Spotlight 400 MIR instruments were used to perform experiments. The surfaces of the high-reflectivity glass sheets were observed under an optical microscope, and suspected MP samples of different shapes on the high-reflectivity glass sheets were selected and transferred to zinc selenide salt sheets. The samples on the zinc selenide tablets were then tested for micro-FTIR. Through the screening test, the MPs in each sample were selected for detailed analysis. Based on the step-by-step and meticulous qualitative analysis of the MP samples, the errors caused by individual experimental technical methods were reduced, and the data became more real, accurate and of practical significance.

2.6. Reman analysis

A DXR2xi Raman imaging microscope (Thermo ™) was used to further verify the accuracy of the experimental data. The data obtained from the equipment (such as the comparison of Raman Feng) were then used to summarize and analyse the data obtained from other instruments, thereby reducing the nonnegligible error caused by any single instrument.

3. Results and discussion

MPs were found in all samples from indoor environmental areas. The source, type and abundance of MPs were examined in detail according to individual family factors.

3.1. Characteristics of Indoor Microplastics

Dust pollution is one of the important causes of human exposure to various environmental pollutants (USEPA, 2011). In total, the glass fibre filter membrane samples in all glass dishes totalled 36 films. In the passively collected particulate samples, the measured composition varied greatly depending on the indoor environment sampled. Obviously, the data obtained in this study are consistent with the results of a 2020 study, which determined that different environments have different particles. The predominant particles measured were coal (67%) and MPs (21%) in the office setting; coal (45%) and MPs (51%) in the laboratory; coal (72%) and MPs (4%) in the dining hall; and coal (19%) and MPs (36%) in the dormitory (Fig. 1). Other researchers in 2022 reported a growing

environmental footprint of plastics driven by coal combustion. This result corresponded to our findings. We found that the combustion of fossil fuels led to the large amount of coal in the air particles sampled from the dining hall. Indoor air particles are composed mainly of coal, non-MPs, and different types of MPs. A study released in 2019 that they believed that MPs were an important component of particulate matter in indoor environments. Their survey results are similar to our findings. The proportion of components measured in this work varied significantly depending on the sampling environment. A researcher predicted in 1998 and 2018 that when MPs were inhaled into the body, it would cause health risks and may lead to relevant effects on body organs; exposure to MPs in the air, especially in the working environment, may lead to increased personal health risks and infection with difficult and miscellaneous diseases. In addition, from 2014 to 2017, many proposed that MPs may also be relevant carriers of priority pollutants, persistent organic pollutants and pathogenic microorganisms in the atmospheric environment. These pollutants can enter the body via MPs and may cause more damage than expected. At the same time, the above researchers also noticed that the risk of air exposure is very important to health and cannot be ignored in investigations and research exploring the impacts of public health.

Relevant researchers [24] reported that the fibre length of atmospheric dust ranges mainly from 50–250 μm and 200–700 μm to 50–2000 μm. In this work, the average particle size of microplastics in indoor environments is 66.15 μm. Among the studied environments, the average particle size of office microplastics was 66.85 μm; the average particle size of atmospheric laboratory MPs was 46.96 μm; the average particle size of dining hall MPs was 96.71 μm; and the average particle size of dormitory MPs was 54.07 μm (Table 1). We speculated that the particle size of microplastics in the atmospheric laboratory may have been smaller and more harmful than those of the other three indoor sampling environments (Fig. 2). We found that our research data results are highly similar to the previous research results of researchers who measured the diameters of petrochemical plastics in atmospheric environments [25–28].

Colour has also used by other researchers as a method of classification [29]. We determined the following MP colours through visual observations with two microscopes: black, transparent, blue, reddish brown and other rare colours (Fig. S2). Among them, white, gold, chestnut, transparent, khaki, solid wood, orange green, plum, light rose, bright grey, bright sky blue, bright golden yellow,

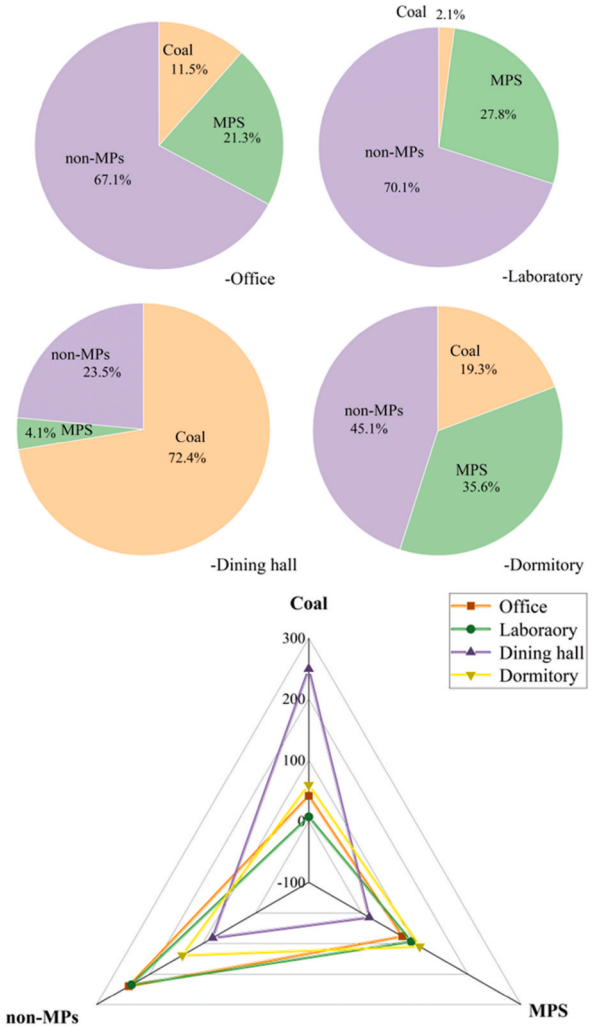

Fig. 1. Characteristics of indoor microplastics.

Table 1
Relevant research data in different indoor environments.

Category	Place			
	Office	Laboratory	dining hall	dormitory
abundance (pcs/m^3)	14088.05	13097.13	7512.55	4308.26
Particle size (***μm***)	66.85	46.96	96.71	54.07
Colour quantity ratio (pcs/m^3)	13.0	7.6	1.9	1.3

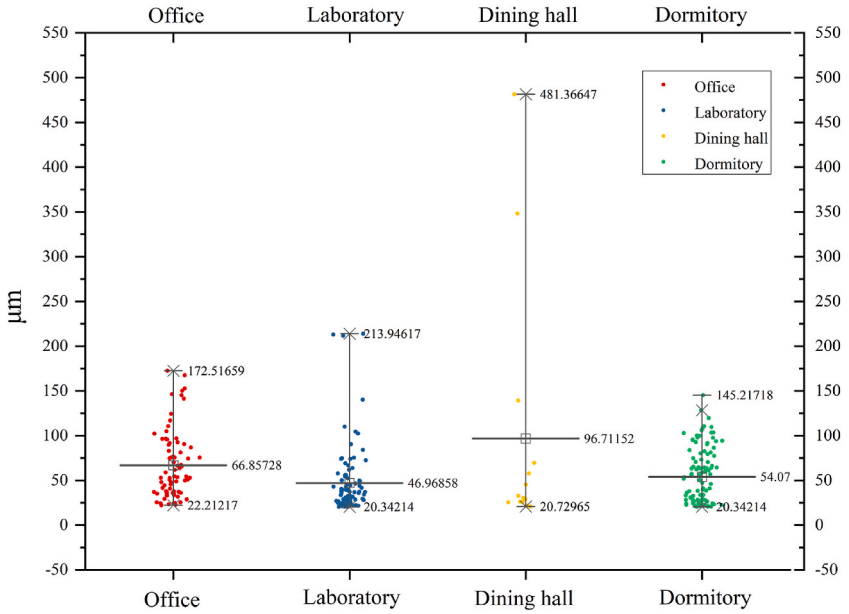

Fig. 2. Comparative analysis of microplastic particle size in different indoor environments.

medium purple, and middle sea blue belonged to the light colour system, while black, blue, purple, brown, green, red, reddish-brown, yellow–green, indigo, olive, heavy brown, fire brick, Peruvian, lime grey, bright blue grey, navy, dark green, dark sky blue, dark pink, dark red, dark blue, dark grey, dark purple, dark green, dark tile grey, dark golden yellow, dark magenta, dark red, dark olive green, medium grey-blue, and golden unicorn belonged to the dark colour family. The selection and classification of the above colours were determined based on the supporting material (Table S2).

The office, atmospheric laboratory, dining hall and dormitory contained mainly dark microplastics, which accounted for 92.86%, 88.46%, 65.96% and 52.94% of the total sampled MPs, respectively (Fig. S3). We found obvious differences in the colour composition of microplastics among different indoor environments (Table 1). In comparison, A report from 2019 reported that black particles were the most common colour of MP particles in Shanghai's suspended atmospheric environment, accounting for a quarter of the total. The samples collected from mountain glaciers released which showed that the main particles were also black. In contrast, white was the dominant colour of MPs in snowflakes in the western Italian Alps [30]. Visual evaluations of colour have inherent limitations and result in certain polymer identification errors. We found that the colour of particles could be evaluated and identified by the ability of particles to absorb the visible spectrum of a specific wavelength emitted from the particle surface. The error in this process was smaller when the particle colour was evaluated with the naked eye. However, using different light sources in the microscope may cause different scattered colours to enter the observer's eye, resulting in the misidentification of colours [30]. Therefore, assessing the colours of MPs by light microscopy alone is not a reliable way to distinguish MP types.

Table 2
The number of particles with different solids in different indoor environments.

Place	Solidity			
	0–0.25	0.25–0.5	0.5–0.75	0.75–1
Office	0	11	15	50
Laboratory	3	17	38	35
Dining hall	0	3	2	9
Dormitory	1	39	21	48

The shape characteristics of the sampled microplastics in indoor environments were mostly fibrous, blocky, granular, and irregular. Similar to the research method mentioned above, due to the large number of inconvenient statistics, we divided the statistics by the solidity within the range of 0–1 (Table S1). The numbers of particles corresponding to different solids in the different indoor environments are represented in the table below (Table 2). Among the studied areas, the numbers of microplastics with solid values of 0.75–1 in the office (65.79%), dining hall (64.29%) and dormitory (44.04%) and the number of microplastics with solids of 0.5–0.75 in the laboratory (40.86%) were greatest (Fig. 3). We found differences in the shape and composition of microplastics among different indoor environments, but in most indoor environments, the number of microplastic particles with high solidity accounted for the majority. The above results were similar to those reported in previous research [31].

3.2. Compositions of Indoor Microplastics

We conducted a comparative analysis of the composition of MP polymers by random passive sampling in different indoor environments to identify different sources. Since the MP pollution rate in each sample was low, we decided not to subtract the pollution rate from the final result [32]. The microplastic materials in indoor environments were detected as polyamide (PA), polyethylene (PE), *cis*-butadiene rubber (BR), ethylene-vinyl acetate copolymer (EVA), polyvinyl chloride (PVC), petroleum resin (WP-Petroleum resin), polyvinyl butyral (PVB), polyoxymethylene (POM) and other rare microplastic materials (Fig. 4).

These findings were roughly the same as the research results of Qun; the content of polyethylene (PE) in the office was relatively high, accounting for 18.42% of the total. The content of polyvinyl butyral (PVB) in the atmospheric laboratory was relatively high, accounting for 27.96% of the total. The contents of polyamide (PA), polyethylene (PE) and silicone resin in the dining hall accounted for the same proportions, all of which composed 14.29% of the total. The content of phenolic resin in the dormitory was relatively high, accounting for 20.18% of the total (Fig. 5). We found that the composition and proportion of microplastics varied among different indoor environments. In previous studies on indoor dust, it was determined that polyester, polystyrene and polyethylene terephthalate (PET) were the most common MPs in indoor dust. Therefore, through comparisons, it was proven that the relevant data of MPs obtained in our study were consistent with the independent research findings of the above researchers, and it could thus be inferred that the types of polymeric particles in the sampled indoor environments were closely related to the types of polymers common in the social environment. By referring to other literature, we found that the main source of MPs in the indoor environment came from synthetic plastics, which produce a large number of plastic particles when broken. According to research reports, the complete degradation of plastics takes hundreds or thousands of years. MPs are exposed to indoor environments under the action of external forces, and the microplastic particles produced through physical, chemical and biological processes are stable in nature and can remain in indoor environments for a long time. In this study, we did not consider the impacts of these potential sources. The increased contribution of plastics to indoor air pollution may indicate that indoor areas are a source of plastics found in atmospheric fallout. A French study showed that 33% of petrochemicals (plastic polymers) were present in an indoor environment, which was closely related to our findings. The most commonly found polymer was polypropylene, consistent with the results that there are many potential sources of polypropylene in the environment (sofas, chairs, desks, etc.).

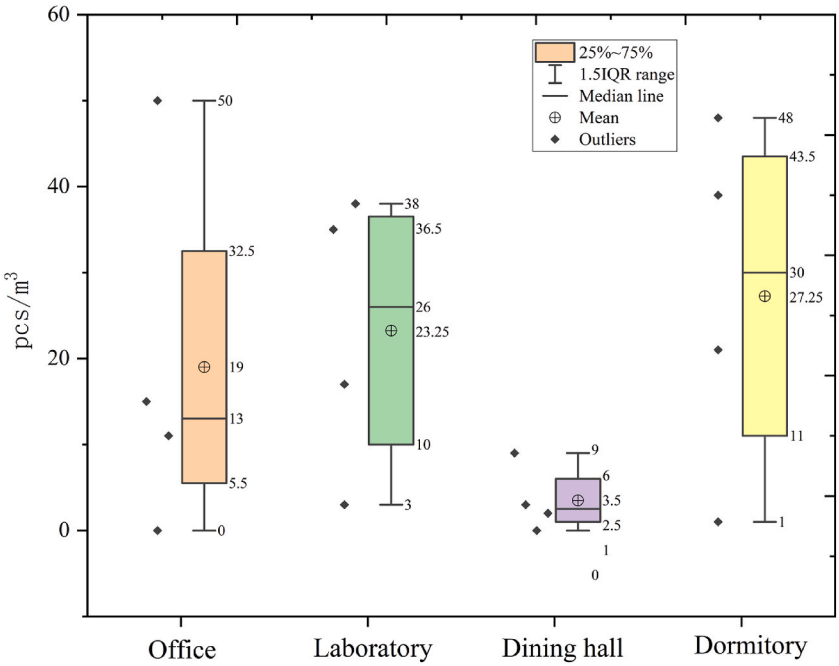

Fig. 3. Comparative analysis of the number of shapes of microplastics in different indoor.

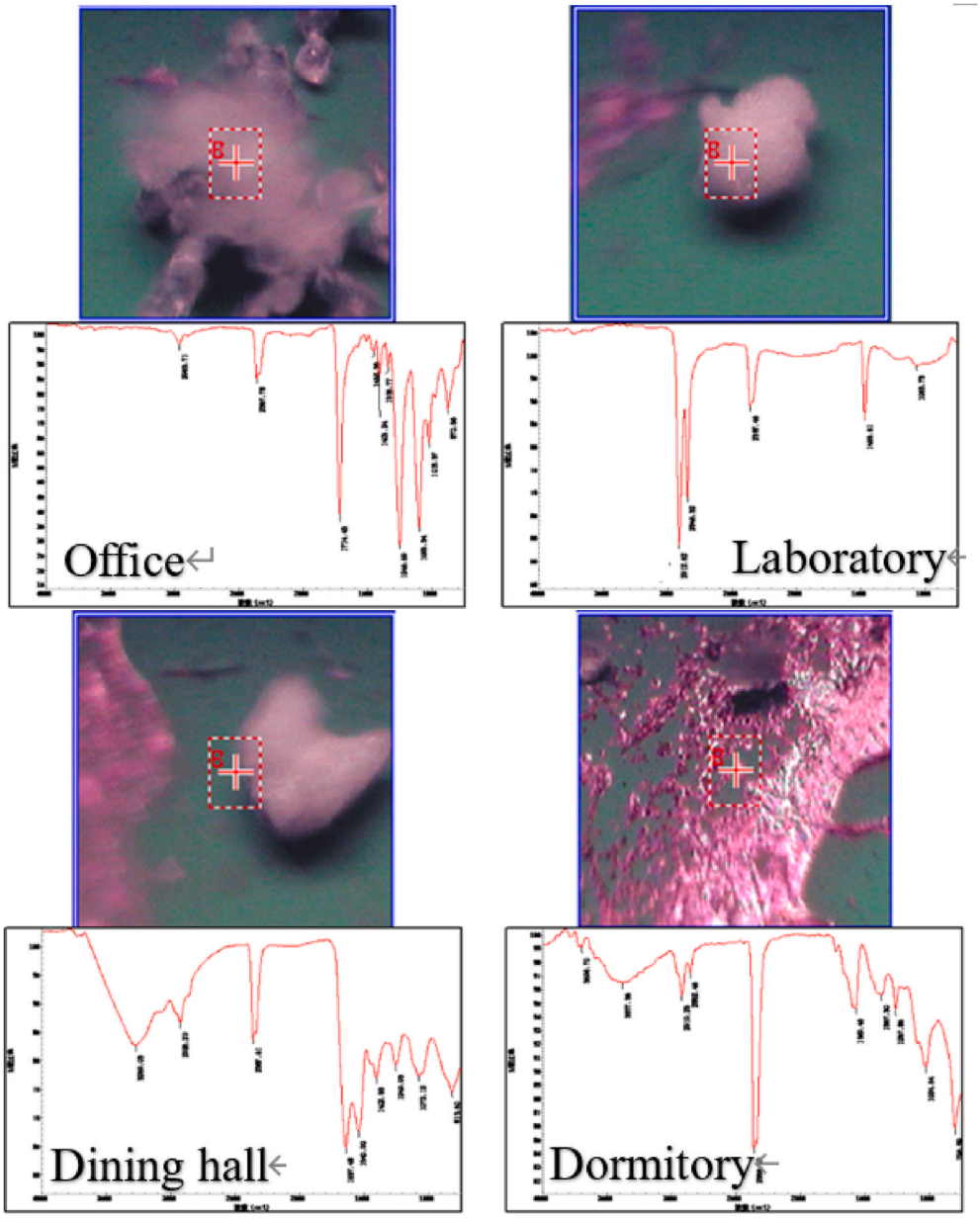

Fig. 4. Selection of the identified MPs with Micro-FTIR analysis.

3.3. Microplastic abundance and influence of airflow

The total MP fallout collected at four sites was counted on each sampling day. In this article, the abundance unit of MPs was unified as pcs/m^3 (Table 1). The average abundance of microplastics in the indoor environment was 9126.81 pcs/m^3. In the four study environments, the average abundance of microplastics was 13097.13 pcs/m^3 in the office, 7512.55 pcs/m^3 in the laboratory, 4308.26 pcs/m^3 in the canteen, and 14088.05 pcs/m^3 in the dormitory (Fig. S4). We found that the abundance of MPs in the dormitory indoor environment was significantly higher than those in the other three indoor sampling environments, but the abundance of MPs was lower than that reported in Australia (Fig. S7). Our data were different from the results of other studies: our indoor MP concentrations ranged from 0.4 to 59.4 pcs/m^3, with a median of 5.4 pcs/m^3. And the results of other studies had shown higher concentrations were observed in apartment A (2.5e18.2 pcs/m^3) and the office (4.0e59.4 pcs/m^3) than in apartment B (1.1e16.3 pcs/m^3). There is a lack of understanding of the exchange rates between indoor and outdoor environments, and differences exist in the use and control of mechanical ventilation. These parameters were likely to affect the observed MP levels.

In 2019, Relevant researcher identified clothing, furniture, decoration and hanging articles as the main contributors to the

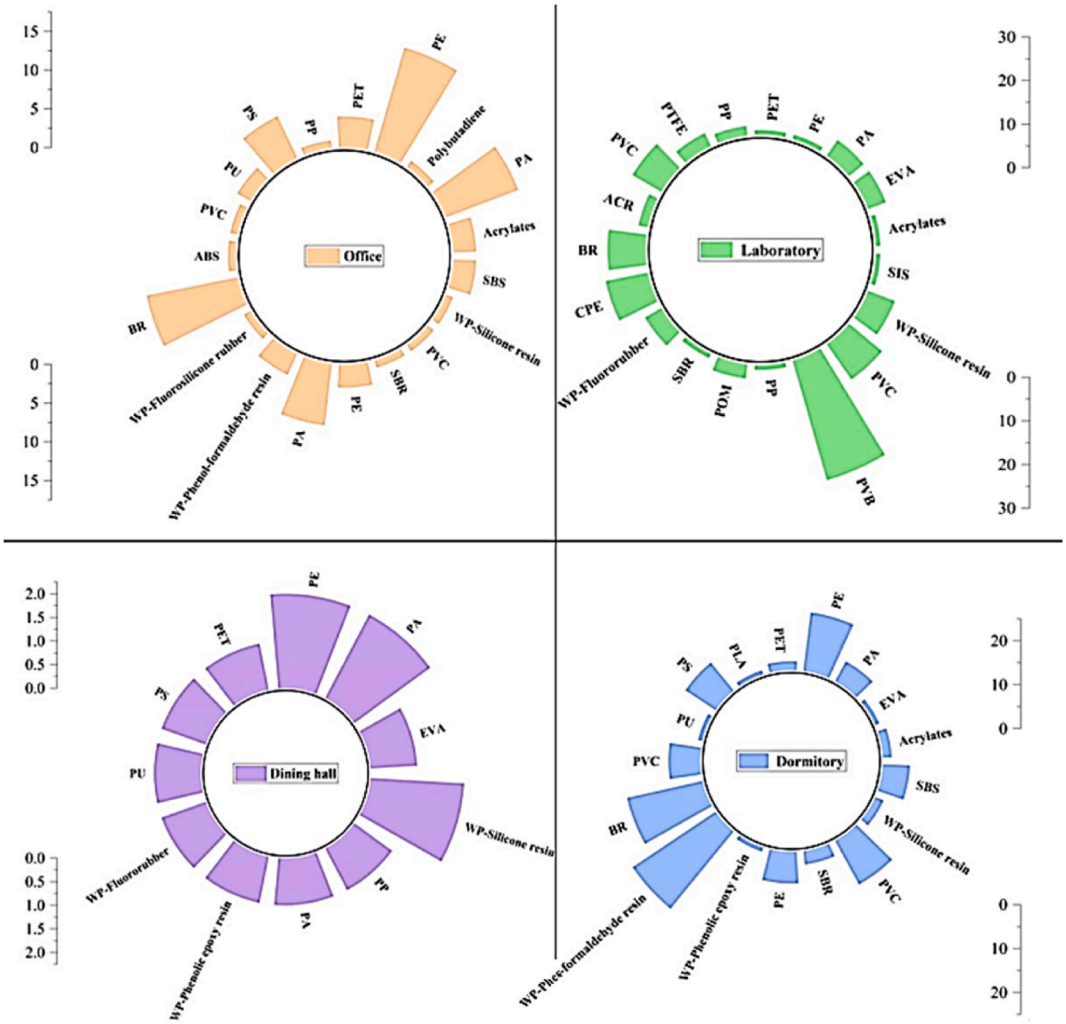

Fig. 5. Comparative analysis of microplastic materials in different indoor environments.

deposition rate of MPs. In previous studies, microplastics have been detected in atmospheric fallout. However, no previous studies have looked at MPs in different settings over time. In this study, MPs in different indoor environments were collected over a week. Similarly, a 2019 indoor study conducted in Aarhus, Denmark, simulated the relevant situation when MPs were exposed to the air in contact with people. Their research report showed that there were 1.7–16.2 fragments and plastic particles/m^3 in total. According to the data results, in the four operating modes of air conditioner, "close", "sleep", "stroke" and "gale", the number of MPs increased significantly with the switching of modes, but in the "gale" mode, the number dropped sharply and became lower than those measured in the "close" state (Fig. S5). We speculate that with an increase in the wind speed, the suspension time of MPs in the air is shorter, and the deposition rate gradually increases, but when certain "threshold" is passed, the movement disorder of MPs increases, and their suspension time becomes longer, resulting in a significant decrease in the deposition rate. Our results are inconsistent with that of study conducted in Australia. In other indoor MP studies, the average deposition rates of MPs in Paris, France, were 6358 pcs/m^2/day and 8.95 pcs/m^3/day in a simulated home environment, while a deposition rate of 13300 pcs/m^2/day was measured in Shanghai, China [32–35]. These findings were inconsistent with other studies showing that trace pollutants migrate from outdoor to indoor environments [36,37]. However, in this study, we speculated that indoor sources were more important than other sources. Similar to the above, the accumulation of plastic and deposited dust in indoor air was 30 times greater than that measured in outdoor air. These inputs may be an important factor in determining the deposition rate of multisuspended particles, but other factors that may affect the accumulation, such as the ventilation rate of buildings, the inclusion of outdoor multi-suspended particulate matter diluted by rain and wind in the sampling study, and the distance from the sampling site to the road, need further investigation. The increased plastic pollution measured in indoor air indicates that indoor air is one of the sources of atmospherically deposited plastic. Therefore, in various MP studies, it is important to perform blank tests due to the high probability of contamination by indoor air. Notably, airflow turbulence in indoor environments has a great influence on the indoor MP distribution, and the MP deposition rate varies greatly under different air conditioning operating modes. Indoor environments with similar characteristics as those studied herein, such as markets,

cinemas and factories, need to be closely watched. Our results clearly show that even in the same place, the abundance of MPs is not constant; instead, it fluctuates greatly with time, and the more human activities there are, the higher the MP abundance is. This view was also confirmed in other studies [38].

4. Conclusion

The characteristics of MPs (include abundance, particle size, and shape) in indoor environments were investigated. We found that MPs are abundant in indoor environments. Importantly, most MPs can be considered "inhalable" because of their small particle size, which is the basis for assessing the risk of MPs exposure to human health. The potential health risks caused by the prevalence of MPs in the indoor environment cannot be ignored. The high abundance of MPs may induce other diseases and pose a potential threat to health.

Author contribution statement

Xiaoyu Zhai: Performed the experiments, Analyzed and interpreted the data, Wrote the paper. Han Zheng: Conceived and designed the experiments, Wrote the paper. Yihao Xu: Performed the experiments, Wrote the paper. Ran Zhao: Analyzed and interpreted the data, Wrote the paper. Weijie Wang: Performed the experiments, Wrote the paper. Huibin Guo: Conceived and designed the experiments, Contributed reagents, materials, analysis tools or data, Wrote the paper.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest statement

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

Additional information

Supplementary content related to this article has been published online at [URL].

Acknowledgement

The authors gratefully thank the National Natural Science Foundation of China (No. 22106128), and the Fujian Provincial Natural Science Foundation (No. 2020J05231).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e15901.

References

[1] S.B. Kurniawan, S.R.S. Abdullah, Current state of marine plastic pollution and its technology for more eminent evidence: a review, J. Clean. Prod. 278 (2020), 123537.
[2] M. Cole, P. Lindeque, C. Halsband, T.S. Galloway, Microplastics as contaminants in the marine environment: a review, Mar. Pollut. Bull. 62 (2011) 2588–2597.
[3] S.L. Wright, F.J. Kelly, Plastic and human health: a micro issue? Environ. Sci. Technol. 51 (12) (2017) 6634–6647.
[4] F. Alqahtani, I. Zafar, Exploring the effect of different waste fillers in manufactured sustainable plastic aggregates matrix on the structural lightweight green concrete, Sustalnabity 15 (3) (2023).
[5] O. Damdelen, A. Tansu, Influence of recycled plastic on the thermal transmittance and sustainable assessment of concrete mixes, J. Construct. Eng. Manag. 148 (12) (2022).
[6] Z. Sun, K. Djidjeli, J.T. Xing, The weak coupling between MPS and BEM for wave structure interaction simulation, Eng. Anal. Bound. Elem. 82 (2017) 111–118.
[7] H.F. Gao, G.F. Wei, A meshless solution of nonlinear elastoplastic problems based on the RRKPM, Results Phys. 31 (2021).
[8] G.O. Anetor, N.L. Nwobi, G.O. Igharo, et al., Environmental pollutants and oxidative stress in terrestrial and aquatic organisms: examination of the total picture and implications for human health, Front. Physiol. 13 (2022).
[9] R. Akran, Natasha, S. Fahad, et al., Trends of electronic waste pollution and its impact on the global environment and ecosystem, Environ. Sci. Pollut. Res. 26 (17) (2019) 16923–16938.
[10] C. Bertoldi, L.Z. Lara, et al., Microplastic abundance quantification via a computer-vision-based chemometrics-assisted approach, Microchem. J. 160 (B) (2021).
[11] C. Bertoldi, L.Z. Lara, F.A.D. Mizushima, et al., First evidence of microplastic contamination in the freshwater of lake guaiba, porto alegre, Brazil, Sci. Total Environ. (2021) 759.
[12] H.C. Lu, S. Ziajahromi, et al., A systematic review of freshwater microplastics in water and sediments: recommendations for harmonisation to enhance future study comparisons, Sci. Total Environ. (2021) 781.
[13] M. Ricciardi, C. Pironti, O. Motta, et al., Microplastics in the aquatic environment: occurrence, persistence, analysis, and human exposure, Water 13 (7) (2021) 973.

[14] J.S. Huang, H. Chen, et al., Microplastic pollution in soils and groundwater: characteristics, analytical methods and impacts, Chem. Eng. J. 425 (2021).
[15] R. Kumar, P. Sharma, et al., Abundance, interaction, ingestion, ecological concerns, and mitigation policies of microplastic pollution in riverine ecosystem: a review, Sci. Total Environ. (2021) 782.
[16] N.S. Soltani, M.P. Taylor, et al., Quantification and exposure assessment of microplastics in Australian indoor house dust, Environ. Pollut. 283 (2021), 117064.
[17] J. Gasperi, S.L. Wright, et al., Microplastics in air: are we breathing it in? Curr. Opin. Environ. Sci. Heal. 1 (2018) 1–5.
[18] Y.X. Chen, X.Y. Li, et al., Air conditioner filters become sinks and sources of indoor microplastics fibers, Environ. Pollut. 292 (2022), 118465.
[19] Z. Qun, Y.P. Zhao, et al., Microplastic fallout in different indoor environments, Environ. Sci. Technol. 54 (11) (2020) 6530–6539.
[20] R. Dris, J. Gasperi, C. Mirande, C. Mandin, M. Guerrouache, V. Langlois, et al., A first overview of textile fibers, including microplastics, in indoor and outdoor environments, Environ. Pollut. 221 (2017) 453–458.
[21] J. Zhang, L. Wang, K. Kannan, Polyethylene terephthalate and polycarbonate microplastics in pet food and feces from the United States, Environ. Sci. Technol. 53 (20) (2019) 12035–12042.
[22] Q. Zhang, Y. Zhao, et al., Microplastic fallout in different indoor environments, Environ. Sci. Technol. 54 (11) (2020) 6530–6539.
[23] Y. Zhang, S. Kang, , et al.M. Sillanpaa, Atmospheric microplastics: a review on current status and perspectives, Earth Sci. Rev. 203 (2020), 103118.
[24] L. Cai, J. Wang, et al., Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence, Environ. Sci. Pollut. Control Ser. 24 (2017) 24928–24935.
[25] R. Dris, J. Gasperi, et al., A first overview of textile fibers, including microplastics, in indoor and outdoor environments, Environ. Pollut. 221 (2017) 453–458.
[26] A. Abbasi, N. Jaafarzadeh, et al., Microplastics in the atmosphere of ahvaz city, Iran, J. Environ. Sci. 126 (2022) 95–102.
[27] T. Li, K. Liu, E.Y. Zeng, et al., Environmental fate of microplastics in an urban river: spatial distribution and seasonal variation, J. Environ. Sci. 322 (2023).
[28] G. Erni-Cassola, M.I. Gibson, et al., Lost, but found with Nile Red: a novel method for detecting and quantifying small microplastics (1 mm to 20 μm) in environmental samples, Environ. Sci. Technol. 51 (23) (2017) 13641–13648.
[29] D. Rachid, G. Johnny, et al., A first overview of textile fibers, including microplastics, in indoor and outdoor environments, Environ. Pollut. 221 (2017) 453–458.
[30] A. Brumberg, K. Hammonds, I. Baker, et al., Single-crystal I-h ice surfaces unveil connection between macroscopic and molecular structure, Proc. Natl. Acad. Sci. U. S. A. 114 (27) (2017) 5349–5354.
[31] Z.L. Liao, X.L. Ji, et al., Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China, J. Hazard Mater. 417 (2021), 126007.
[32] S.B. Lu, R. Qiu, J.N. Hu, et al., Prevalence of microplastics in animal-based traditional medicinal materials: widespread pollution in terrestrial environments, Sci. Total Environ. (2020) 709.
[33] A.M. Youssef, S.M. El-Sayed, Bionanocomposites materials for food packaging applications: concepts and future outlook, Carbohydr. Polym. 193 (2018) 19–27.
[34] S.L. Wright, J. Ulke, et al., Atmospheric microplastic deposition in an urban environment and an evaluation of transport, Environ. Int. 136 (2020), 105411.
[35] M. Tang, S.C. Chen, D.Q. Chang, et al., Filtration efficiency and loading characteristics of PM2. 5 through composite filter media consisting of commercial HVAC electret media and nanofiber layer, Separ. Purif. Technol. 198 (2018) 137–145.
[36] A.I. Catarino, V. Macchia, et al., Low levels of microplastics (MP) in wild mussels indicate that MP ingestion by humans is minimal compared to exposure via household fibres fallout during a meal, Environ. Pollut. 237 (2018) 675–684.
[37] N. Laskar, U. Kumar, Plastics and microplastics: a threat to environment, Environ. Technol. Innov. 14 (2019), 100352.
[38] M. Klein, E.K. Fischer, Microplastic abundance in atmospheric deposition within the metropolitan area of Hamburg, Germany, Sci. Total Environ. 685 (2019) 96–103.