



Assessing the external atmospheric input of microplastics: Two strategies based on polymer composition and aging characteristics

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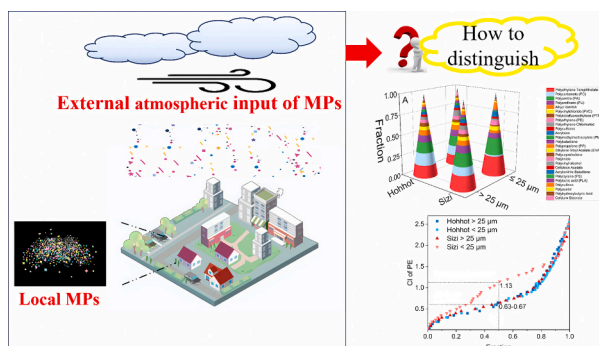
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HIGHLIGHTS

- Microplastics (MPs) in a sparsely populated area on the Mongolian Plateau were characterized.
- Propose methodological innovation for tracing MPs by Bray-Curtis similarity indexes.
- Carbonyl index-based Bray-Curtis similarity index indicates higher aging degree of the exogenous small MPs.
- Composition-based Bray-Curtis similarity index suggests different sources of large and small MPs.

GRAPHICAL ABSTRACT



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ABSTRACT

Microplastics (MPs) can be transported over long distances in the environment, hence, distinguishing between MPs generated locally and those introduced from external sources is necessary for regional MP pollution management. In this study, MPs pollution in the dust of Siziwang banner (Sizi), a sparsely populated area on the Mongolian Plateau, and Hohhot, a city with large populations, was observed. The high proportion of small MPs in Sizi (<25 μm), combined with the fact that most air masses reaching the area have undergone long-distance transport, supports the presence of external input through atmosphere. Based on the significantly different composition distributions and surface characteristics of the small sized MPs in Sizi and Hohhot, a composition-based Bray-Curtis similarity index (Comp-BCs) and a carbonyl index-based BCs index (CI-BCs) were established. Contributions of the external MPs input to small MPs in Sizi were estimated as 23–36 %, indicating that the role of atmospheric input on MPs pollution in sparsely populated areas should not be overlooked.

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0048-9697/© 2024 Elsevier B.V. All rights reserved, including those for text and data mining, AI training, and similar technologies.

1. Introduction

Microplastics (MPs) are widely present in the environment (Bergmann et al., 2019; Chen et al., 2023a; Ding et al., 2023) and have become an urgent global environmental issue. Numerous studies have attributed the presence of microplastics to local sources, (Wang et al., 2019), such as fragmentation of plastic waste (Jansen et al., 2023) and the release of washing (O'Brien et al., 2020) and municipal sewage (Tian et al., 2021). However, external sources are increasingly being proven to be an indispensable component of microplastic pollution (Allen et al., 2019; Hee et al., 2023; Huang et al., 2021; Wang et al., 2021). For example, MPs in atmospheric dust fall were detected in remote wilderness areas and national parks in the western United States (Brahney et al., 2020), indicating that atmospheric deposition is a pathway for the input of external MPs. Assessing the contribution of external MPs is critical for further clarifying the sources of MPs pollution and developing corresponding pollution control plans. However, there are no reliable methods to distinguish these external MPs with the local source pollution.

Composition MPs distributed in different areas or originated from different industries may have significant compositional differences (Wang et al., 2019). For example, the polycarbonate (PC) MPs primarily come from hard plastic packaging shells, and the indoor polyethylene terephthalate (PET) MPs mainly origin from textiles (Ballent et al., 2016). Composition of plastic polymers was used to trace the commodity origin of MPs (Brahney et al., 2020; Wang et al., 2019), and recently, the ratio of the mass concentration of PET and polyamide (PA) was applied to distinguish the textile and nontextile sources of MPs (Peng et al., 2023). Theoretically, composition characteristics can be further utilized to identify MPs from various sources.

Surface characteristic of environmental particles has been used to trace the source of aerosol pollution. For example, the extent to which black carbon is coated by secondary aerosols, an indicator of the aging degree of black carbon, was used to verify the presence of long

transported black carbon (Xu et al., 2020). Similarly, the aging of MPs surface presents under the action of ultraviolet irradiation and microbial activity (Wang et al., 2019). Therefore, a higher carbonyl index (CI), an indicator for assessing the degree of MPs aging (Wang et al., 2019; Yang et al., 2023), may reflect the potential of long transport of MPs (Yang et al., 2023).

Theoretically the contribution of local and external MPs might be identified by the characteristics of MPs, especially for areas where external pollution contributes significantly. In order to establish credible methods to assess the external atmospheric input of MPs, the areas located at the southern and northern foothills of the Yinshan Mountains on the Mongolian Plateau was selected as the research area (Fig. 1). The target areas, Siziwang Banner (Sizi) and Hohhot city, are located in the East Asian monsoon region with a predominance of northwest wind. Sizi, a town with a population of about 200,000 and primarily engaged in animal husbandry, is surrounded by plains in all directions except the south, making it susceptible to the transport of atmospheric MPs from various directions except the south. Hohhot, the capital of the Inner Mongolia Autonomous Region, China, a heavily industrialized city with a population of approximately 3.5 million, is partially enveloped by the mountain range, which to some extent protects Hohhot from the external atmospheric input of atmospheric MPs.

In this study, dust was collected in Sizi and Hohhot, and the size distribution, composition and characteristics of surface functional groups of MPs were analyzed. Based on the composition and aging degree of MPs with different sizes, the external MPs was identified and quantified. This study offers a novel methodology to trace the pollution of atmospheric MPs, providing a foundation for the development of regulatory and mitigation strategies.

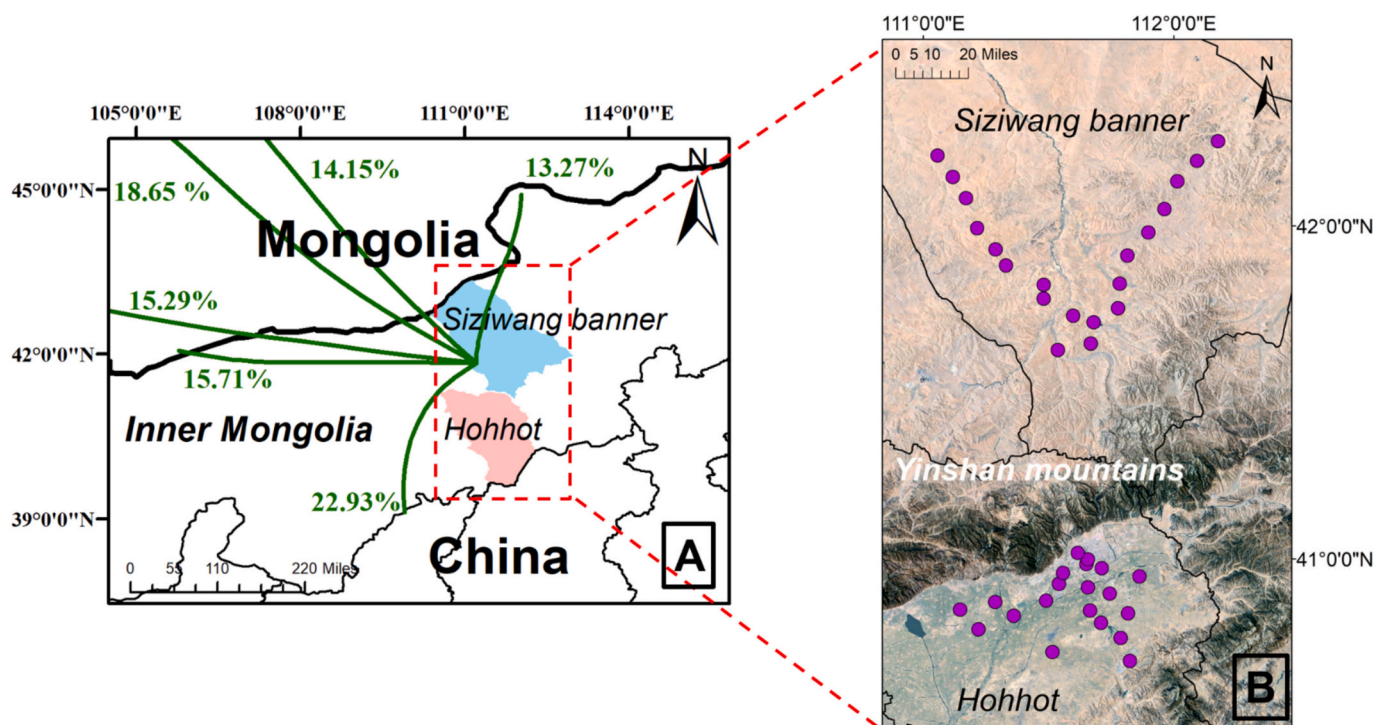


Fig. 1. Map of sampling locations for outdoor dust. Two research areas, Siziwang Banner and Hohhot, are outlined in red dotted box (A) and magnified in the right image (B). The outdoor dust samples were collected in Siziwang Banner ($n = 20$) and Hohhot ($n = 20$), respectively, and the purple dots (B) represent the sampling location of each sample. The green curves shown in the left image represent the 24 h backward trajectories of air masses in Siziwang manner, with the percentage representing the proportion of the air mass in that direction to the total trajectories (A).

2. Materials and methods

2.1. Chemicals and materials

HPLC-grade ethanol (ANPEL Laboratory Technologies Inc. Shanghai, China), analytical-grade $ZnCl_2$ (Damao Chemical Reagent Factory, Tianjin, China), H_2O_2 solution (30 %, Bohua Chemical Reagent Factory, Beijing, China), and Milli-Q water were used in this study.

2.2. Research area and sample collection

In September 2021, a total of 40 outdoor dust samples were collected from Sizi ($111^\circ 42' 0''$ E, $41^\circ 31' 48''$ N) and Hohhot ($111^\circ 40' 12''$ E, $40^\circ 45' 36''$ N). The locations of sampling sites were shown in Fig. 1B. Hohhot and Sizi are regions characterized by low river occurrence, and both areas fall under the temperate continental climate type with few precipitations, i.e. 242.8 mm and 133.2 mm in Hohhot and Sizi in 2021, respectively (<https://data.cma.cn>, last access: 30 December 2023).

Hog bristle brushes were used to sweep the outdoor dust on the road (approximately 2 g for each). The ground at all sampling points was dry and flat. There were no obvious sources of plastic or microplastic, such as garbage bins, train stations and factories, within 500 m of the sampling point. There was no precipitation within a week prior to sampling, and the weather was quiet wind when sampling. The road system in Sizi region is underdeveloped. Consequently, dust samples were collected at intervals of approximately 5 km along two highways (Fig. 1B). Each sample site was located >200 m from the road to mitigate the traffic impact. Sampling points in Hohhot are primarily distributed across the downtown area (Fig. S1), with each point approximately 5 km apart. Additionally, five sampling sites have also been selected in the suburban areas near the city center.

MPs in the environment exist in the form of solid particles and span a wide range of sizes, making the representativeness of MPs an inherent issue within this researching field. To maximize the representativeness of the samples, five parallel samples were collected at each sampling site. The collected dust samples were put into a paper bag lined with aluminum foil. After transported to lab, the samples were sieved through a 2 mm pre-washed metal sieve and then stored in a 4 °C refrigerator.

2.3. Sample pre-treatment

The MPs in the sieved outdoor dust samples (<2 mm) were separated by floating them using $ZnCl_2$ solution after digesting with H_2O_2 (Peng et al., 2022). Firstly, 0.2 g outdoor dust was accurately weighted, then digested with 30 mL H_2O_2 solution (30 %) in a 250 mL tall form beaker. When there were no more bubbles can be observed, the beaker was transferred to a 70 °C water bath for 8 h to remove natural organic matter. After the dust sample was completely dried, 70 mL $ZnCl_2$ solution (52 %) was added into the beaker and vortexed for 1 min to stir evenly. Leaving the beaker to stand for 12 h to separate MPs from dust. The floated particles were filtered through a metal filter (pore size of 10 μ m, Jiuding High Tech filtration equipment Co., LTD, Beijing, China). Then the filter was transferred into a 50 mL glass tube with 20 mL of HPLC-grade ethanol and sonicated at 40000 Hz for 30 min. Then the filter was removed by a stainless steel tweezers, and the ethanol solution was concentrated into 1 mL with nitrogen. The ethanol solution was dropped on a high reflection glass window for LDIR detection after the ethanol volatilized.

2.4. MPs detection

A LDIR chemical imaging system (Agilent Technologies Inc., 8700, CA) equipped with a Microplastics Library 1.0.1 software was used to identify MPs from the separated particles. The detection limit of LDIR is 10 μ m, and only particles with a matching degree higher than 65 % with the standard spectrum of plastic polymer composition could be

identified as MPs (Peng et al., 2022). The maximum length in one dimension of identified MPs provide by LDIR was regarded as the size of MPs.

As PE was detected in all of samples of this study, CI of PE can be obtained as the ratio of the absorbance area of carbonyl group ($1680\text{--}1779\text{ cm}^{-1}$) and the absorbance area of methylene ($1420\text{--}1490\text{ cm}^{-1}$) obtained by LDIR (Zhang et al., 2021).

2.5. Air masses trajectory clustering

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPPLIT) model, which has been widely used to trace the source of atmospheric MPs (Hee et al., 2023; Huang et al., 2021), was used to illustrate the backward trajectories of air masses arrived at the south of Mongolia Plateau during September 2020 to August 2021. The model was run in backward mode for 24 h simulations, with 1-h time intervals. Calculated backward trajectories were clustered into six main trajectories (Fig. 1A) by MeteoinfoMap 2.2.4 (China) (Wang, 2014), representing the main source directions of the air masses.

2.6. Composition-based and carbonyl index-based Bray-Curtis similarity indexes

A tool to evaluate the species similarity between two ecosystem based on the relative abundance of species (Ricotta and Podani, 2017), was cited to quantify the difference of composition, as well as the difference of CI between the large and small MPs in Hohhot and Sizi. A composition fraction – based Bray-curtis similarity (Comp – BCs) between large MPs and small MPs groups can be calculated as follows,

$$\text{Comp - BCs} = 1 - \frac{\sum_{t=1}^k |f_{t(L)} - f_{t(S)}|}{\sum_{t=1}^k (f_{t(L)} + f_{t(S)})} \quad (1)$$

where $f_{t(L)}$ and $f_{t(S)}$ are the values of fractions (f) of each polymer composition t in large (L) and small (S) MPs groups, respectively (Table S2); and k is the number of types of polymers, that is 26 in this study.

Bray-Curtis similarity index of CI (CI-BCs) between the large and small PE MPs can be calculated as Eq. (2),

$$\text{CI - BCs} = 1 - \frac{\sum_{i=1}^k |f_{i(L)} - f_{i(S)}|}{\sum_{i=1}^k (f_{i(L)} + f_{i(S)})} \quad (2)$$

where $f_{i(L)}$ and $f_{i(S)}$ are fractions (f) of each 0.1 interval range (i) of CI of PE in the large sized (L) PE group and the small sized (S) PE group, respectively (Table S3); and k is the total interval number, that is 26 in this study because the CI of all target PE ranged between 0 and 2.6.

2.7. Quality assurance and quality control

Dust samples were transported and stored in paper bags lined with aluminum foil. The bristle brush used for sampling was soaked in Milli-Q water in advance and then dried in a fume hood. Stainless steel tweezers and glass containers used for pre-treatment were wrapped with foil paper and heated in a muffle furnace at 500 °C for 3 h to remove potential plastic pollution. All reagents were passed through a glass fiber filter with a pore size of 1 μ m to remove background interference from MPs. Plastic products were avoided except for the PP pipette tips, which were rinsed with filtered pure water before use. The procedure blanks were subjected to the same treatment as the outdoor dust samples. Procedure blanks were analyzed with every 10 samples for detection by LDIR. The average number of particles detected in the procedure blanks

was 24 ± 12 n/g, with the main type being cellulosic, and no MPs were detected by LDIR.

2.8. Statistical analysis

Spearman's correlation Mann-Whitney U test, were conducted in SPSS 25.0 software (IBM, NY, U.S.A.). Significance was considered when $p < 0.05$. The principal coordinates analysis (PCoA), adonis analysis, Orthogonal partial least-squares discrimination analysis (OPLS-DA) and Volcano plots were performed using the Omicshare platform (<https://www.omicshare.com/tools>). All figures were generated in Origin 2023b software (OriginLab Corporation, MA, USA).

3. Results

3.1. Concentration and size distribution of MPs in the outdoor dust

In the outdoor dust of Hohhot, 61,000 – 102,250 n/g of MPs were detected, with an average of 78,625 n/g (Fig. 2A). In comparison, significantly lower ($p < 0.05$) MPs concentrations, 30,500 – 60,250 n/g with an average of 42,888 n/g, were detected in Sizi (Fig. 2A). Totally, the MPs concentrations increased with the decrease of MPs size (Fig. 2B). >50 % of MPs were below 25 μm (Fig. 2B), which is the size range of particles considered to have the potential for long-distance transport in the atmosphere (Brahney et al., 2020). And it is worth noting that the proportion of MPs below 25 μm of Sizi (64–71 %) was significantly higher ($p < 0.05$) than that of Hohhot (49–62 %) (Fig. 2B).

3.2. Atmospheric microplastics source of Siziwang banner

To trace the potential atmospheric input of MPs in Sizi, the HYSPLIT model, a widely used tool to explore the transport pathways of atmospheric particles (Allen et al., 2019; Huang et al., 2021; Wang et al., 2021), was employed to calculate air mass backward trajectories in Sizi. It was showed that the air mass mainly came from the northwest direction, accounting for 50 % (summarized as 15.71 % + 15.29 % + 18.65 % + 14.15 %) of the total air mass sources (Fig. 1A). Moreover, compared to the air mass from other directions, the air mass from the northwest showed the longest transport distance, reaching up to approximately 1000 km within 24 h (Table S1).

3.3. Comparison of the composition of MPs with different size

A total of 26 types of polymers were identified and 25 of them were presented in both of the two sites (Fig. 3A). PET was the most frequently detected polymer in Sizi and Hohhot. As the raw material of polyester fiber, PET is widely distributed in global dust samples (Dris et al., 2017; Peng et al., 2023). Similar polymer composition distribution was observed in small and large MPs in outdoor dust of Hohhot, and the top three polymers of were PET, PA and PC, accounting for 37.8 %, 43.1 % and 42.9 %, respectively (Fig. 3A). Consistent distribution characteristics of polymer components were also observed in the large MPs of Sizi. However, the composition distribution of the small MPs of Sizi varied

greatly. For example, polypropylene (PP) is the third most abundant polymer in the small MPs of Sizi, accounting for ~10 % of total detected MPs.

The differences in the distribution of polymer composition in the MPs can be further identified by a principal coordinate analysis (PCoA). The fractions of 26 plastic polymers in each outdoor dust sample are considered as 26 properties of this sample, which was described as the "composition community" in Fig. 3B and C. Based on the 20 outdoor dust samples of each group (large MPs of Hohhot, small MPs of Hohhot, large MPs of Sizi, small MPs of Sizi), 20 composition communities of MPs were obtained, respectively. According to the β diversity of composition communities shown by PCoA (Fig. 3B and C), no significant difference of MPs composition presented between the large and small MPs of Hohhot ($p > 0.05$, Fig. 3B), while the composition structure of small MPs of Sizi was significantly different compared to the large MPs ($p < 0.05$, Fig. 3C). Orthogonal partial least-squares discrimination analysis (OPLS-DA) and Volcano Plots, tools to screen metabolites with significant differences in relative abundance between different groups of cell samples (Chen et al., 2021; Sun et al., 2022), were applied to identify the MP polymers with significant differences in component fraction between the large and small MPs of Sizi. The intersection of these two screening methods was identified as the differential polymer composition. It was found that the fractions of PA, PET, PP, and polystyrene (PS) increased, when small MPs in Sizi was treated as the experimental group and large MPs as the control group (Fig. 3D).

To further quantify the extent of the composition difference of MPs, Bray-Curtis similarity index (BCs) was cited to quantify the difference of composition between the large and small MPs in Hohhot and Sizi. The Comp-BCs ranges from 0 to 1, with closer to 1 indicating that the objects being compared are more similar. Comp – BCs of large and small MPs in Hohhot and Sizi were 0.90 and 0.76, respectively, validating that large and small MPs of Sizi may be heterologous.

3.4. Characteristics of the carbonyl index (CI) of MPs

Changes of functional groups on the surface of MPs due to environmental aging can also be used to characterize environmental MPs (Yang et al., 2023; Zhang et al., 2021). Based on the spectrum of LDIR of PE MPs, a significant higher average CI of PE in Sizi (1.00 ± 0.56) than that in Hohhot (0.82 ± 0.56) ($p < 0.01$) was found. For the large sized PE (>25 μm) in Sizi and Hohhot, their average CI were equal to 0.82 (Fig. S2), which is similar to the average CI of small sized PE (<25 μm) in Hohhot (0.83). Similar median CI values were also obtained for MPs of these three groups, which were 0.63 and 0.67 for the large sized PE in Sizi and Hohhot, and 0.66 for the small sized PE in Hohhot (Fig. 4). In comparison, significantly higher CI of small sized PE in Sizi (average: 1.08; median: 1.13) was observed (Fig. S2, Fig. 4), exhibiting a different distribution pattern compared with the other three MPs groups (Fig. 4).

Bray-Curtis similarity index (BCs) was also cited to quantify the difference of CI between MPs with different sizes. CI – BCs between large and small PE in Hohhot was 0.89, reflecting that the environmental aging experienced by small and large PE MPs in Hohhot is basically the same. Differently, CI – BCs between the large and small PE in Sizi was 0.64, illustrating a more significant difference in the aging degree between the large and small sized PE.

4. Discussion

Characteristics of MPs in outdoor dust of Sizi, a sparsely populated town, and Hohhot, a medium-sized industrial city adjacent to Sizi, were analyzed. A higher portion of MPs below 25 μm was found in Sizi (Fig. 2B). MPs below 25 μm are considered to have the potential for long-distance transport through atmosphere (Brahney et al., 2020; Chen et al., 2023c), as >70 % of observed MPs in western U.S. protected lands are smaller than 25 μm . Therefore, it suggests the MPs in Sizi are more prone to be affected by atmospheric input. Considering the target area is

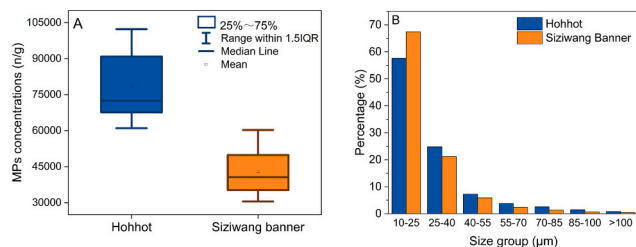


Fig. 2. Concentration (A) and size distribution (B) of MPs in the outdoor dust of Hohhot and Siziwang banner.

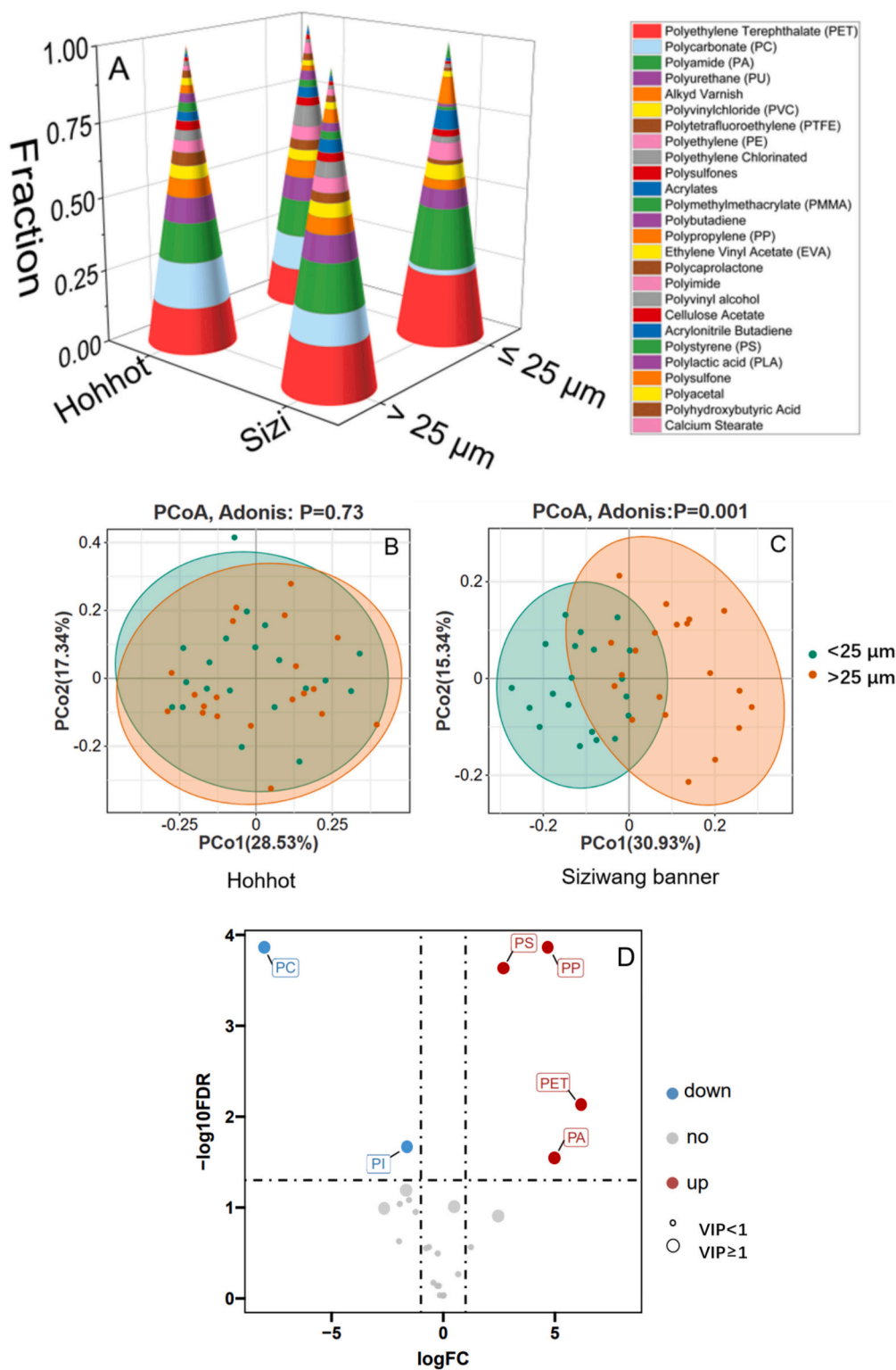


Fig. 3. The polymer composition distribution of large sized (>25 μm) and small sized (<25 μm) MPs in Hohhot and Sizi banner (A). β diversity of “composition communities” of MPs between large and small MPs in Hohhot (B) and Sizi banner (C), with each green dot (or each orange dot) represents a composition of 26 polymers in one sample. Volcano plots of MPs in Sizi banner, with dots above the horizontal dashed line representing polymers that exhibit significant differences in their fractions between large and small MPs (D). Small MPs was set as experimental group and large MPs was control group and the larger dots represent polymers screened by OPLS-DA analysis that exhibit significant differences in their fractions between large and small MPs (the significance is considered as the value of VIP ≥ 1). The number of increasing (red dots) and decreasing (blue dots) types of polymers (D). Dots above the horizontal dashed line representing polymers that exhibit significant differences in their fractions between large and small MPs. When small MPs was set as experimental group and large MPs was set as control group, the larger dots in Fig. 3D represent polymers screened by OPLS-DA analysis that exhibit significant differences in their fractions between large and small MPs (the significance is considered as the value of VIP ≥ 1). If the fraction of a polymer in small sized MPs is significantly higher than that in large sized MPs, it is defined as an increasing polymer and is marked in red. Conversely, if the fraction of a polymer in small sized MPs is significantly lower than in large sized MPs, it is defined as a decreasing polymer and is marked in blue. The increasing composition was considered when the logarithm of the fold change (logFC) was >1.

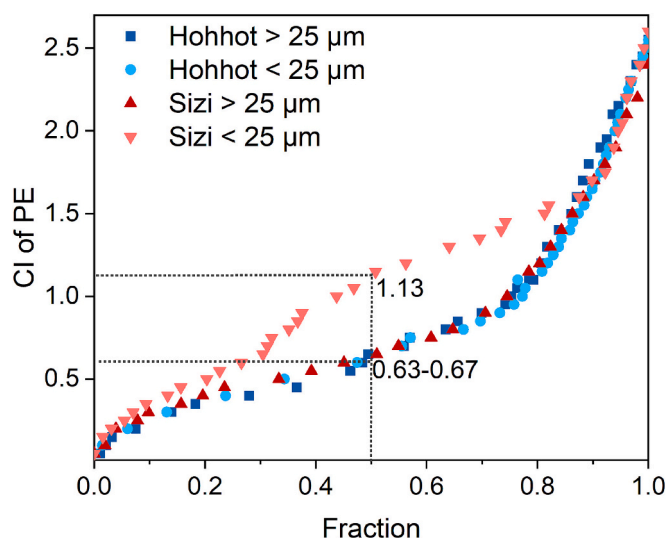


Fig. 4. CI of PE with different sizes in Siziwang banner and Hohhot. The median CI of small sized PE (<25 μm) of Sizi and Hohhot was 1.13 and 0.66, respectively, and the median CI of large sized PE (>25 μm) was 0.63 and 0.67, respectively.

not a region characterized by high river occurrence and has a low annual rainfall (as described in Section 2.2 above), atmospheric transport should be the primary pathway for MPs input. Sizi was affected by a large number of air masses from the northwest that had traveled long distances (Fig. 1A and Table S1). This indicates that atmospheric MPs from the northwest may undergo long-distance transport. The flat Mongolian Plateau is located to the northwest of Sizi. Due to the obstruction of the Yinshan Mountains (Fig. S3), the small atmospheric MPs from the northwest tend to settle on the plain of Sizi after long-distance transport, rather than further transport to Hohhot.

Smaller MPs are more easily transported in the atmospheric environment (Brahney et al., 2020; Chen et al., 2023b). Therefore, in the areas more heavily polluted by external sources, the small sized MPs should be more affected by the external atmospheric input than the large sized MPs. This is consistent with the significant differences in composition distributions observed between small and large sized MPs in Sizi (Fig. 3), which indicates the contribution of the external small sized MPs from atmospheric transport. Small sized MPs have higher capacity for long-distance transport through the atmosphere and may also undergo more extensive environmental aging, which can explain the significant higher CI of small sized PE in Sizi (Fig. 4). Both smaller Comp – BCs and CI – BCs were found in Sizi, further indicate the heterologous pollution of small and large MPs. Such results suggest that the presence of external MPs can be validated based on the differences of polymer composition and aging characteristics between small and large sized MPs.

Although the difference in composition distributions between MPs with different sizes in the absence of external MPs pollution has not been reported, we notice that in megacities, which are less susceptible to external MPs pollution, atmospheric MPs of different sizes show similar composition. For example, in Guangzhou, one of the largest cities in southern China, MPs larger than 200 μm and MPs with a main size of 50–70 μm show similar composition distributions (Huang et al., 2021; Yuan et al., 2023), in which PET is >70 %, and the other primary components being PAN, PA, and PP. Therefore, it was assumed that the composition distribution of locally originated MPs with different size is the same in the absence of external MP pollution, and the composition based external pollution contribution (Comp-EPC) of MPs can be calculated as follows,

$$\text{Comp - EPC} = \sum_{i=1}^k f_{i(S)} - f_{i(L)} \quad (3)$$

where $f_{i(S)}$ and $f_{i(L)}$ are the fractions (f) of polymer t that has a higher fraction in small sized (S) MPs than in large sized (L) MPs (Table S2); and k is the number of polymers that have a higher fraction in small sized (S) MPs than in large sized (L) MPs (Table S2). Comp – EPC in Sizi and Hohhot were 0.23 and 0.11, suggesting the contributions of external small sized MPs of Sizi and Hohhot were 23 % and 11 %, approximately. Assuming that locally originated large and small sized PE have similar CI overall, the CI based external pollution contribution (CI-EPC) can be calculated as follows,

$$\text{CI - EPC} = \sum_{i=1}^k f_{i(S)} - f_{i(L)} \quad (4)$$

where $f_{i(S)}$ and $f_{i(L)}$ are the fractions (f) of each 0.1 interval range (i) of CI of PE that has a higher fraction in small sized (S) PE than in large sized (L) PE (Table S3); and k is number of intervals that have a higher fraction in small sized (S) PE than in large sized (L) PE (Table S3). CI – EPC in Sizi and Hohhot were 0.36 and 0.11, suggesting the contributions of external atmospheric input of small sized MPs in Sizi were 36 %, while that in Hohhot were 11 %.

5. Conclusion

The presence of external MPs was identified in Sizi, based on differences of polymer composition and aging characteristics between small and large sized MP. Furthermore, the contribution of external MPs can be assessed by composition based and CI based quantification methods, which were established with reference to bioinformatics methodologies. These two methods also have promise for quantifying MPs inputs caused by atmospheric transport in polar, high-altitude, and other sparsely populated regions with low population. Due to the lack of significant differences in the composition and aging characteristics between MPs with different sizes in Hohhot, the input of MPs in Hohhot requires further assessment. Given that MPs in the environment is commonly positively correlated with local population (Liu et al., 2019), methods for assessing the contribution of external MPs in high levels of MPs pollution are yet to be established. Higher composition based and CI based external pollution contributions were observed in Sizi, indicating that these two methods are reliable for assessing the extent of external MPs pollution. However, future studies are needed to refine the calculation of the external MPs contribution, particularly by examining the differences in composition and aging characteristics among MPs of varying sizes when no external inputs are present.

CRedit authorship contribution statement

Hanling Yang: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Yining Xue:** Investigation, Formal analysis. **Jintao Yang:** Investigation, Formal analysis. **Balt Suvdantsetseg:** Supervision, Methodology. **Khureldavaa Otgonbayar:** Investigation. **Chunguang Liu:** Supervision, Methodology. **Hongwen Sun:** Supervision. **Lei Wang:** Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.176905>.

Data availability

Data will be made available on request.

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