Microplastics release from victuals packaging materials during daily usage

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Abstract
Plastic packaging materials are widely used because of their advantages of light weight, low cost, and convenience, especially as victuals packaging materials. Approximately 146 million metric tons of plastics were used for packaging in 2015, but most of these plastics had already been discarded and followed by serious white pollution. What's worse, the victuals packaging materials, especially polystyrene (PS) foam containers, can release microplastics (MPs) during daily usage. Through the combination of various appropriate chemical (eg, spectroscopy) and physical (eg, microscopy) characterization and analysis, the existence of MPs is proved and MPs can be intuitively observed. Although the impacts of MPs on ecosystems and human health are still under discussion, existing studies have shown that MPs can be integrated into habitats through soil transportation, affecting the health of various terrestrial invertebrates. Faced with this shocking reality, reducing the use of PS foam containers at high temperatures and developing healthy materials to substitute these plastics are promising solutions.

KEYWORDS
chemical and physical characterizations, microplastics, plastic wastes, polystyrene foam containers, victuals packaging materials
1 | INTRODUCTION

The large-scale production and use of plastics can date back to the 1950s. Plastic, with its advantages of light weight, low cost, as well as good processability, has become the fourth basic material after steel, wood, and cement.\(^1,2\) It is estimated that about 9.2 billion metric tons of plastics had been produced globally as of 2017, with a large quantity of general-purpose plastics being discarded.\(^2,4\) However, due to technical, economic, and logistical reasons, far too little plastic waste is actually recycled. For example, only 14% of the world’s plastic packaging waste is collected for recycling, in comparison, more than 70% is disposed of in landfill or directly lost into the environment.\(^2,5\) Moreover, most plastics are durable and can maintain good structure and performance during their service life, but for plastic packaging materials, usually used for less than a week, their durability becomes a drawback and is causing tremendous growth of plastic waste.

Under the influence of sunlight, temperature changes, mechanic abrasion, and other effects, plastics break into smaller fragments, the so-called microplastics (MPs, plastic particles <5 mm), which was first proposed by Thompson et al in 2004.\(^6\) They come from a large variety of sources; comprise different additive content, shapes, sizes, colors, as well as types of materials; and include a mixture of diverse chemicals.\(^7\) So far, a large number of relevant researches have reported that MPs are ubiquitous in ecosystems. MPs have been detected in oceans, rivers, sea ice, snow, soils, aquatic plants and animals, terrestrial plants, and so on.\(^8-15\) According to a recent study, evaluating approximately 15% of Americans' caloric intake, the authors estimated that people could consume tens of thousands of MPs each year depending on age and sex.\(^16\) Although the impacts of MPs on ecosystems and human health are still under discussion, existing studies have shown that MPs can be integrated into habitats through soil transportation, affecting the predation and health of various terrestrial invertebrates.\(^17,18\) The ubiquitous pollution of MPs to the environment, as well as its possible associated risks to the ecosystems and ultimately to human health, has recently attracted a great deal of attention from the public and the scientific community.\(^19-24\)

Plastics are widely used as packaging materials because of their low cost, light weight, good processability, as well as high performance. It is estimated that about 146 million metric tons of plastics were used for packaging in 2015.\(^2\) Plastic packaging reduces food waste by prolonging their shelf life and enables us to transport them conveniently.\(^25\) However, plastic packaging will release MPs during daily usage and the comprehensive and systematic research on victuals packaging MPs is still limited. Herein, we proved that the victuals packaging materials can release MPs during daily usage by various appropriate characterization methods of chemistry and materials science, choosing polystyrene (PS) foam containers as the representative. Through the combination of chemical (eg, Raman spectroscopy, Fourier transform infrared (FTIR) spectroscopy, X-ray diffraction (XRD), and X-ray photoelectron spectroscopy (XPS)) and physical (eg, polarizing microscope, scanning electron microscopy (SEM), and atomic force microscopy (AFM)) characterization and analysis, we confirmed the existence of MPs and intuitively observed them.

2 | RESULTS AND DISCUSSION

2.1 | Plastic waste in the environment

Plastic waste management is a universal issue affecting every single person in the world. According to the World Bank, an estimated 2.01 billion metric tons of municipal solid waste were generated in 2016, with plastic accounting for 12% of global waste.\(^26\) The world generates about 89 g of plastic waste per capita per day, which is roughly equivalent to three plastic water bottles. We calculated plastic waste generation in 2016 by using waste generation and characterization data reported by the World Bank for 217 countries in 2018 (Table S1). Figure 1 shows the global plastic waste generation in 2016, in which the world is divided into seven regions. At an international level, countries in the East Asia and Pacific and the Europe and Central Asia regions accounted for 46% of the world’s plastic waste by magnitude. The Middle East and North Africa and the Sub-Saharan Africa regions produced the least amount of waste, together accounting for 14% of the world’s plastic waste. The North America region generated 15%, or 34.68 million metric tons, of the world’s plastic waste, and the Latin America and the Caribbean as well as the South Asia both produced about 12% of global plastic. Such a huge amount of plastic waste is causing major environmental challenges, and especially in recent years, MPs have been detected in various ecosystems.

2.2 | Victuals packaging materials release microplastics

Plastic packaging materials have penetrated into every aspect of people’s lives, and the food industry is no exception. When entering a supermarket, we will find that almost all the goods are packaged in plastic. However, in
this work, it was proved that some commonly commercial victuals packaging materials would release MPs by the combination of physical (eg, microscope) and chemical (eg, spectroscopy) characterization and analysis. For most of victuals packaging materials, due to their short lifetime, the temperature is the most critical factor affecting the release of MPs during daily usage. Therefore, in this work, we selected and treated some victuals packaging materials at proper temperature to simulate their use scenarios. PS foam containers, polyethylene (PE) preservative film and polypropylene (PP) teabags (Figure 2A-C) were steeped in deionized water at 50°C, 75°C, 95°C for 1 hour respectively, and then shaken for 60 seconds in a shaker at 160 rpm, followed by steeping for 1 hour. Through the above treatment, we simulated the use scenarios of victuals packaging materials and then found that these packaging materials would release MPs of various sizes and shapes. The MPs released from PS foam containers (PS MPs) and PE preservative film (PE MPs) are irregularly shaped, as well as the MPs released from PP teabags (PP MPs) are usually fibrous (Figure 2D-I). In terms of size, both micron- and submicron-sized MPs can be released from victuals packaging materials (Figures S1-S5). In these victuals packaging materials, PS foam containers are the widely used disposable hot food containers in the past decades because of their low cost, high compression resistance, and good heat preservation performance, but followed by serious white pollution. Moreover, at only 50°C, PS foam containers can release a large number of different forms of MPs, which is much more than those of other packaging materials, posing a huge potential threat to our health. Therefore, we chose PS foam containers for a more detailed analysis.

Subsequently, we applied various appropriate characterization methods of materials science to the study of MPs and proved that the observed MPs originate from the corresponding victuals packaging materials. It is conceivable that after the release of MPs, the quality of plastics would decrease. Therefore, we conducted an experiment in which PS foam containers were steeped in deionized water with temperatures of 25°C, 50°C, 75°C, and 95°C for 24 hours, respectively. The PS foam containers indeed lose weight after exposing to deionized water for 24 hours, and the release of MPs is affected by temperature (Figure 3A). The reduced quality increases with the increase of temperature, and the weight loss can reach ~1.5% at 95°C, which reminds us to avoid using them to hold hot water or food as much as possible. Meanwhile, we observed that the PS MPs dispersion shows the Tyndall effect. By the analysis of dynamic light scattering (DLS) using a Nano Zetasizer, we found that
FIGURE 2  Microplastics (MPs) released from some victuals packaging materials. A-C, The photographs of (A) PS foam containers, (B) PE preservative film, and (C) PP teabags, respectively. D-F, SEM images of (D) PS MPs, (E) PE MPs, and (F) PP MPs, respectively. G-I, SEM images of (G) PS MPs, (H) PE MPs, and (I) PP MPs with larger magnification, respectively.

FIGURE 3  PS foam containers release PS MPs. A, The weight loss of PS foam containers after steeping in deionized water with temperatures of 25°C, 50°C, 75°C, and 95°C for 24 hours. B, The DLS size distribution of submicron-sized PS MPs. Insert figure shows the Tyndall effect of PS MPs dispersion.
the size of submicron-sized PS MPs was ∼250 nm (Figure 3B).

2.3 | Microplastics originate from victuals packaging materials

To confirm that the MPs indeed originate from their corresponding victuals packaging materials, we used molecular spectroscopy (i.e., Raman spectroscopy and FTIR spectroscopy, etc.) to analyze the composition of MPs and original victuals packaging materials. Molecular spectra originate from the transitions between molecular energy levels, and the pattern of such energy levels is the unique characteristic of a molecule, indicating it is usually sufficient to recognize the molecule by only knowing the distinctive characteristics of the pattern.27,28 Raman spectra of PS MPs are in accordance with the PS foam containers, with a wavenumber range of 100 cm⁻¹ to 3200 cm⁻¹ and excitation wavelength at 785 nm to mitigate fluorescence signals. The Raman peak at 1000 cm⁻¹ corresponds to breathing vibration of benzene ring (Figure 4A). The PS MPs and the original PS foam containers have similar FTIR absorption, with detection of the same characteristic peaks from 500 cm⁻¹ to 4000 cm⁻¹ (Figure 4B). The FTIR peaks at 1601 cm⁻¹ and 1492 cm⁻¹ can be associated with benzene ring skeletal vibration (δ) (C–C), and peaks at 695 cm⁻¹ and 755 cm⁻¹ are as results of out-of-plane bending vibration (δ) of unsaturated hydrocarbon groups on benzene ring (≡C–H); the peaks at 1452 cm⁻¹, 2849 cm⁻¹, and 2920 cm⁻¹ can be assigned to symmetric bending vibration (δs), symmetric stretching vibration (νs), and asymmetric stretching vibration (νas) of methylene (CH₂).

FIGURE 4 PS MPs originate from PS foam containers. A, Raman spectra of PS foam containers and PS MPs, with a wavenumber range of 100 cm⁻¹ to 3200 cm⁻¹ and excitation wavelength at 785 nm to mitigate fluorescence signals. B, FTIR spectra of PS and PS MPs, with detection of the same characteristic peaks from 500 cm⁻¹ to 4000 cm⁻¹. C, XRD pattern of PS and PS MPs, with detection of the same characteristic peaks from 5° to 80°. D, C 1s XPS spectra of PS and PS MPs, with detection of the same characteristic peaks from 280 eV to 295 eV.
respectively.\(^2\) Moreover, XRD is a tool for the investigation of the fine structure of matter because the crystal diffracts X-rays and the manner of the diffraction can reveal the structure of the crystal.\(^3\) We used XRD to explore the crystallization of PS MPs and the original PS foam containers. The XRD pattern of PS MPs is nearly identical to that of PS foam containers, as seen in Figure 4C. In addition, XPS is a commonly used spectroscopy technique in areas of materials science and chemistry to assess surface chemistry, bonding structure, and composition of surfaces and interfaces in materials.\(^4\) The XPS data also support the above characterization results, confirming that the material of PS MPs matches the original PS foam containers (Figure 4D). The characterizations of other MPs and original victuals packaging materials are shown in supplemental materials, demonstrating that the observed MPs indeed originate from corresponding plastic packaging materials (Figures S6-S9).

2.4 Intuitive observation of microplastics

The above chemical characterization and analysis have demonstrated that the MPs indeed originate from corresponding plastic packaging materials. Scanning electron microscopy/energy dispersive X-ray spectrometry (SEM/EDS) is a widely applied elemental microanalysis method, which can assist us to more intuitively observe MPs of various shapes and sizes.\(^5\) In order to reveal the distribution of the elements, EDS mapping has been performed with the silicon wafer as a substrate to avoid other carbon sources except for PS foam containers. It is clearly seen that micron- and submicron-sized PS MPs correspond to the distribution of C elements (red) and other areas correspond to the distribution of Si elements (green), indicating that PS MPs are released from PS foam containers (Figure 5A-C). AFM is an advanced technology for observing the surface structure of matter with high resolution and precision.\(^6\) As shown in Figure 5D, AFM image of the PS MPs determines the morphology of released MPs, and their surface is wrinkled, which can be attributed to the inherent property of the PS foam containers. In order to observe the morphology of PS MPs more intuitively, we used the polarized light microscope (Figure 5E,F). With polarized light, the MPs are readily discernible, and it is revealed that released MPs are heterogeneous.

Similarly, other commercial victuals packaging materials can also release MPs of various shapes and sizes during daily usage (Figure 6 and Figures S2-S5). As may easily be imagined, humans are exposed to MPs when they eat food packaged in plastic. The ingestion of MPs may have negative effects on the gut microbiome, which helps the host to perform a variety of physiological and biochemical functions.\(^7\) Another potential risk that has been intensively discussed but not yet sufficiently investigated and understood is the transfer of MPs to cells and tissue through the digestive tract, which can cause inflammatory lesions.\(^8\) Up to now, the effects of consuming MPs on human health are still unknown. In the future, the possibility of uptake and accumulation of MPs
in the human body and the subsequent negative physiological effects merit in-depth investigation.

3 | CONCLUSION

In conclusion, represented by PS foam containers, through the combination of various appropriate physical (eg, microscope) and chemical (eg, spectroscopy) characterization and analysis, we proved that commercial victuals packaging materials can release MPs during daily usage, which is indeed a matter worthy of public concern. Although the impacts of MPs on ecosystems and human health are still under discussion, it would be better to not use PS foam containers for holding hot food and to minimize the long-term use of petrochemical-based plastics when in direct contact with hot water or food if possible.

Because of the huge potential risks of MPs, it is an urgent need for the development of more efficient ways to alleviate the problem of MPs. The problem of MPs, in the final analysis, is still the problem of petrochemical-based plastics. There is no denying that tackling the plastic problem necessitates significant cooperation between sciences, engineering, technology, materials design, humanities, human behavior, policy, regulation, economics, and business. Although it is anything but a low-hanging fruit, scientists are trying their best to deal with the problem of petrochemical-based plastic. Besides controlling the release of plastic waste and improving plastic recycling rates,36–39 developing sustainable alternatives for plastic replacement is a promising way, which can pull the plug on MPs release. The good news is that many biodegradable polymers (eg, bio-based polymer polylactic acid, microbial synthetic polymer polyhydroxyalkanoates, etc.) and emerging various forms of sustainable bulk materials based on renewable resources (eg, cellulose nanofiber) have been developed, which are potential substitutes for petrochemical-based plastics.40–48 After
continuous exploration and development, these sustainable alternatives may be the key to solve the problem of MPs in the future.

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CONFLICT OF INTEREST
The authors declare no conflict of interest. [Correction added on 10 June 2021, after first online publication: Conflict of Interest section has been added.]

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of this article.

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