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Shaping a dynamic open platform for the holistic assessment of micro- and nano-plastic emissions from plastic products

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The widespread use of plastics and their improper disposal have released a large number of micro- and nano-plastics (MNPs) into various environmental media. Although the release of MNPs from individual plastic products has been widely reported, there is a lack of a holistic assessment framework to determine the overall release of plastic products to soil, water, and air during their life cycle. Therefore, based on big data, neural network algorithms, and material flows, a new open platform for the comprehensive assessment of the release of MNPs from plastic products will be developed. The proposed emission inventory platform consists of three main modules: a global polymer product production dataset, an assessment of the emission processes, influencing factors, and emission factors of MNPs, and an emission inventory of MNP releases to the environment. The global data on polymer production, use, and waste disposal, and collate data on the degradation behavior of different plastic types under various environmental conditions will be collected. Next, big data analysis will be applied to train the patterns of MNP production and emissions, and algorithms such as neural networks will be used to simulate the complex processes and mechanisms of MNP emissions. Finally, a comprehensive emission inventory model will be established. The proposed dynamic MNPs emission assessment platform integrates material flow analysis and experimentally validated release kinetics. Utilizing machine learning techniques and laboratory and field datasets, the platform can derive dynamic, environment-specific emission factors to support specific emission estimates, source prioritization, and targeted emission reduction strategies.

Environmental significance

The release of micro- and nano-plastics (MNPs) into the environment during the production, transportation, use, and disposal of plastic products presents a significant environmental challenge. This study proposes an open and dynamic platform for the comprehensive assessment of MNP emissions from plastic products, considering multiple factors such as production processes, environmental pathways, and release mechanisms. The framework provides valuable insights into the distribution, release dynamics, and accumulation of MNPs, enabling the identification of high-risk plastic products and regions. The platform promotes a data-driven approach to comprehensively assess MNP pollution and fosters cross-sectoral collaboration to tackle this emerging environmental issue.

1 Introduction

Plastic products have profoundly changed the way people produce and live since their development, owing to their exceptional physicochemical properties and economic feasibility. Plastics, consisting of synthetic organic polymers, are extensively used in various applications, such as water bottles, clothing, food packaging, medical supplies, electronic goods, and construction materials.[1] While plastics bring convenience to society, their ubiquitous has introduced new environmental pressures.[2] A report shows that urban solid waste generation is projected to increase from 2.1 billion tons in 2023 to 3.8 billion tons by 2050. In 2020, the direct costs of global waste management were estimated at $252 billion. Without urgent waste management action, this annual global cost could reach $640.3 billion by 2050.[3] Without urgent waste management action, this annual global cost could reach $640.3 billion by 2050. Due to a lack of environmental awareness and the absence of relevant regulations, a significant amount of

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plastic waste ends up in uncontrolled environments instead of controlled systems such as landfills and incinerators. Plastics possess excellent physicochemical properties and weathering resistance, making them difficult to degrade once they enter the environment.

Another concern centers on the fact that plastic products can release micro- and nano-plastics (MNPs), considered emerging contaminants, during production, usage, and especially in the environment after discarding. Typically, plastic particles smaller than 5 mm and larger than 1 μm are considered microplastics (MPs), while particle sizes smaller than 1 μm are classified as nanoplastics (NPs).[4,5] MNPs have also been found to be ubiquitous across the world's oceans and detected in a variety of marine organisms, including fish,[6] shellfish,[7] and birds.[8] Even more concerning is that MNPs can enter the human body through the food chain.[9] Recent studies have identified MNPs in the human colon[10] and even in the placenta.[11] The sources of MNPs are so widespread that it is reasonable to assume that the entire life cycle of plastics is accompanied by the release of MNPs. Notable examples of substantial MNP release during the usage include tires and textiles. Tires release particles into the air through abrasion, with the majority settling on nearby soil and water bodies.[12,13] Textile clothing also releases microfibers through abrasion during use, which may even be inhaled into the human body.[14] Particularly concerning is the release of MNPs from clothing during the washing process. Some studies have focused on the effect of washing conditions on microfiber release.[15–17] The management and utilization of plastic waste are related to regional economic conditions. Studies indicate that only 13% of plastics are recycled, and 46% is mismanaged.[18] Beyond consumer plastics and textiles, paints and coatings are increasingly recognized as significant sources of MNPs. Recent studies indicate that weathering, mechanical wear, flaking, or maintenance of painted surfaces can cause polymer-based coating fragments to detach and enter both aquatic and terrestrial environments. Given the global prevalence of coatings, incorporating coating fragments into emission inventories is crucial.[19] Discarded plastic waste in nature can release MNPs into the surrounding environment, with the release process highly dependent on local environmental conditions. Research also shows that MNPs not only release chemicals, but also adsorb and bind to other contaminants in the natural environment, increasing their environmental and health risks.[20–22] Without effective remediation, MNPs in the environment are estimated to reach 10 billion tons by 2040.[23]

Given the environmental and health risks associated with MNPs, there is an increasing need to evaluate the sources, distribution, and centration of MNPs in various natural media. To achieve holistic management of environmental problems arising from MNPs, it is necessary to have a more accurate estimation of the amount of MNPs discharged into the environment. Tsunematsu *et al.*[24] explored the emission inventory of MPs from municipal solid waste incinerators in Japan. Liu *et al.*[25] estimated the global emissions of atmospheric fibrous MPs from indoor sources into the ocean. Zhu *et al.*[26] established a standardized framework for measuring urban plastic pollution emissions, quantified emissions from different sources using activity data and emission factors, and calculated annual plastic emissions in Toronto as an example. Cottom *et al.*[27] combined conceptual models of emission mechanisms with activity data, and incorporated machine learning and probabilistic material flow analysis to develop a global macro-level inventory of plastic pollution emissions. The study found that uncollected waste is the primary source of pollution in the Global South, while indiscriminate littering is the primary source in the Global North. While recent studies have compiled macro-level plastic emissions inventories at the local and global levels, these frameworks typically employ fixed or average emission factors, providing only static estimates. Such approaches fail to analyze emissions at the level of specific plastic products or capture time-varying release behavior related to environmental aging and usage processes. To overcome these limitations, we propose a framework that links material flow pathways to dynamic release kinetics derived from experimental data and machine learning modeling. This platform is designed to remain open and continuously updated, enabling researchers and policymakers to integrate new datasets, generate scenario-specific estimates, and identify products and environments requiring priority for emission reduction.

2 Dynamic inventory platform for MNP emissions from plastic products

The proposed emission inventory platform consists of three main modules, namely a global/regional production dataset of plastic products, an assessment of release processes, influences and emission factors for the release of MNPs, and a holistic assessment of the MNP release into the environment. Establishing a comprehensive plastic product database is a prerequisite. This database will compile the production volumes of various plastic products across industries such as agriculture, packaging, food, apparel, tires, household, personal care products, and medical supplies, alongside the corresponding types of products and materials. Depending on the assessment scope and data availability, global, national, or region-specific data may be selected. The next step is to calculate emission factors for MNPs released from plastic products through various weathering processes.

Researchers have conducted numerous studies on the release pathways of MNPs from various plastic products, identifying four main types of pathways: physical, chemical, biological, and others. For example, Sommer *et al.*[28] found that the environmental aerosols near roads consisted primarily of traffic-related wear particles, accounting for approximately 90%, by analyzing samples from passive samplers along the roadside. Zha *et al.*[29] investigated the dynamic changes and photoaging characteristics of MNPs released from two types of disposable plastic boxes under light and mechanical wear conditions. The results showed that the combined effects of light and wear generated a large number of fragments. The fragmentation behaviour of MPs was mainly related to photo-oxidation, while mechanical wear also played a certain

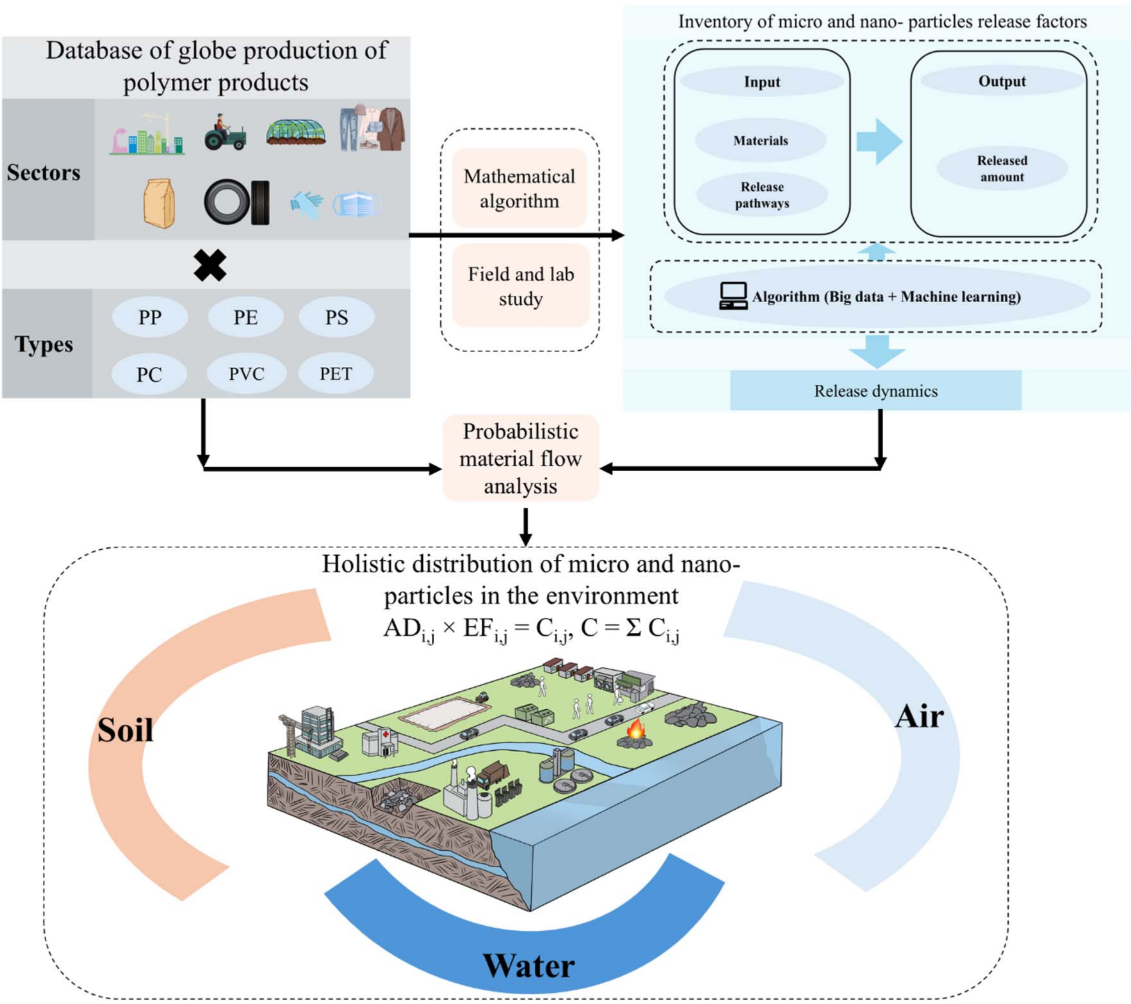

Fig. 1 The framework of the inventory platform for MNP emissions.

promoting role. Wei *et al.*[30] found that during the biodegradation process of degradable plastics, not only do they release hydrolysis products such as acidic monomers and oligomers, but they also release MPs into the environment. In addition, many natural parameters and human interventions impact the release process. Common environmental factors include temperature, humidity or moisture, pH, salinity, *etc.* Human intervention, such as heat treatment and mechanical wear, also needs to be considered. UV irradiation is considered one of the most important environmental factors influencing the transformation and aging of plastics. The unsaturated structures in polymers firstly absorb UV light to form polymer radicals, and then oxygen addition and hydrogen abstraction occur, which finally cause the cleavage of polymer chains.[31,32]

Due to differences in experimental materials, weathering or processing methods, and qualitative and quantitative identification methods, the amount of MNPs released varies significantly, even for the same type of plastic product under similar treatment conditions. For example, since the pandemic, the massive use of personal protective equipment, especially disposable masks, has brought new challenges to the social and the environment. Many studies have investigated the release of MPs from discarded masks after weathering in the natural environment.[33–35] Wang *et al.*[36] examined the release of MPs from disposable masks into the shoreline environment under simulated conditions. They found that after UV weathering, an un-weathered disposable mask released approximately 483 888 MPs into the water under shaking at 300 rpm for 24 hours, compared to 1 566 560 MPs from a UV-weathered mask and 16 001 943 MPs from a UV-weathered mask in a simulated shoreline environment with sand. Chen *et al.*[35] studied the release of MPs under shaking at 120 rpm for 24 hours, finding that a new mask released 183.00 ± 78.42, with values ranging from 159.80 ± 46.14 to 222.17 ± 98.79 MPs. This amount increased to 1246.62 ± 403.50, ranging from 1146.04.67 ± 307.60 to 1478.00 ± 265.80 particles per piece for used masks. Furthermore, they estimated that over 100 billion masks used in China in 2020 released more than 1.2×10^{14} MPs into the environment within 24 hours of being disposed of in water. Ma *et al.*[37] also investigated the release of MPs from masks under different conditions, placing one mask in a flask with 100 mL of water, shaking it vigorously for 3 minutes, and repeating the process up to 10 times. They found that each mask released $1.6–3.8 \times 10^9$ NPs, with MPs larger than 1 μm making up only a small fraction of the particles, with 1.3–4.4 × 10^3 MPs released per mask. Comparing these studies reveals considerable variation in the amount of MPs or NPs released from the masks under different experimental conditions. Therefore, to derive release kinetics, the release factors calculated from individual experiments can be combined with the respective experimental conditions through algorithms or simulations, such as machine learning. It is important to emphasize that in this platform, emission factors are not treated as fixed constants, but rather as dynamic parameters related to environmental conditions. Based on extensive experimental and site data, release kinetics are modeled using machine learning methods to capture the nonlinear relationship between the aging process and the fragmentation rate. Within given environmental parameters and timeframes, the platform can provide effective emission factors as feature values for comparative analysis based on release kinetics.

Once the release kinetics for each plastic product have been established, the total number of MNPs released from the plastic product into the environment can be calculated directly from the global production of plastic products and the corresponding environmental loads in the first module. Specifically, differences in data due to varying release environments are significant and therefore need to be applied in a way that accounts for conditions such as the region studied and the characteristics of the plastic product. The release factors in this module can be trained with a large amount of experimental and field data, which includes information on the plastic's nature, experimental conditions, location, and other relevant factors. The release processes and mechanisms are analyzed through neural networks, artificial intelligence, and other methods to determine the release factors. By associating each dataset with environmental condition metadata—such as temperature, UV radiation, humidity, and hydrodynamic stress—regional and climatic variations are incorporated. These parameters will be used to derive release kinetics related to environmental conditions, enabling the platform to generate region-specific estimates of MNP emissions. When applied, the platform automatically recognizes and matches the corresponding emission factors based on user-provided data, resulting in outputs that closely align with real-world conditions (Fig. 1).

3 Inventory calculation framework and illustrative applications

The complete calculation and evaluation process through this platform can be expressed by the following formula: $\mathrm{AD}_{i,j} \times \mathrm{EF}_{i,j} = C_{i,j}$, $C = \sum C_{i,j}$, where AD indicates the activity data of a plastic product; EF represents the emission factor; C is the final amount of MNPs released; i represents the usage phase, which are during the usage and after the usage, respectively; j represents the environmental media, primarily soil, water, and air.

Taking the disposable mask as an example, the main contribution of MNPs released from masks occurs after usage (au), and the emissions during usage (du) can be ignored, so the $C_{i(\mathrm{du}),j}$ is zero. It has been reported that over 450 billion masks were manufactured globally from January 2020 to March 2021.[38] Here, we assume that after use, 10% are recycled and reused, 10% are incinerated, 70% go to landfills, and the remaining 10% are discarded into nature and eventually reach water bodies. Therefore, $\mathrm{AD}_{\mathrm{du,soil}}$ = 315 billion and $\mathrm{AD}_{\mathrm{du,water}}$ = 45 billion.[39] Combustion emissions are not considered in this example. According to the previous study on MNPs released from disposable masks, the emission factor for $\mathrm{EF}_{\mathrm{au,water}}$ = 10 000 pieces per mask, and $\mathrm{EF}_{\mathrm{au,soil}}$ = 4000 pieces per mask.[40] Thus, $C_{\mathrm{au,water}}$ = 45 billion × 10 000 pieces per mask = 4.50 × 10^{14} pieces per mask per year, $C_{\mathrm{au,soil}}$ = 315 billion × 4000 pieces per mask = 12.60 × 10^{14} pieces per mask per year, C = 1.71 × 10^{15} pieces per mask per year. Another example is tires, focusing on the plastics released during use. It is reported that, during tire wear, 2–5% of particulate matter is released into the air, 45–75% enters the nearby soil, and 25–55% reaches water bodies *via* surface runoff.[41] Assuming tire wear is 1 kg year^{-1} during usage, the emission factors are $\mathrm{EF}_{\mathrm{du,air}}$ = 0.05 kg per tire per year, $\mathrm{EF}_{\mathrm{du,water}}$ = 0.40 kg per tire per year, and $\mathrm{EF}_{\mathrm{du,soil}}$ = 0.55 kg per tire per year.[42] If the annual tire production in 2022 was 2.2 billion, then $C_{\mathrm{du,air}}$ = 2.2 billion × 0.05 kg per tire per year = 1.10 × 10^8 kg year^{-1}, $C_{\mathrm{du,water}}$ = 2.2 billion × 0.4 kg per tire per year = 8.80 × 10^8 kg year^{-1}, and $C_{\mathrm{du,soil}}$ = 2.2 billion × 0.55 kg per tire per year = 12.10 × 10^8 kg year^{-1}, C = 2.20 × 10^9 kg year^{-1}. It is important to note that the examples above represent estimates of MNP release under assumed conditions. In reality, released plastic particles continue to undergo environmental aging and decompose into even smaller MNPs. Therefore, in the proposed platform, the emission factor is treated as a condition-dependent parameter, which can be iteratively applied as sufficient data become available to achieve dynamically updated predictions of MNP concentrations under specific scenarios.

4 Conclusions and outlook

Establishing and enhancing the platform requires cross-sectoral cooperation, involving government, enterprises, research institutions, public interest organizations, and the public. Therefore, this platform is designed to enable open access and collaborative development. Its data structures and core computational tools will be made publicly available to foster community contributions and ensure transparent applications. For instance, researchers can input their latest findings on MNP release from plastic products, including release quantities and corresponding experimental parameters, into the second module to enhance the accuracy of calculated release factors. In addition, experts in algorithm development can update release parameter algorithms according to the latest computational principles, making the derived release dynamics from the 'black box' more transparent. By integrating these contributions, the global platform can provide a continuously updated overview of MNP release levels, pathways, and environmental distributions across diverse plastic products. This platform can identify products with varying MNP release potentials while revealing how specific environmental stressors and natural processes, such as ultraviolet radiation, mechanical abrasion, hydrodynamics, and climatic conditions, drive the generation, migration, and accumulation of MNPs in soil, water, and air. By deciphering emission mechanisms, the platform can provide guidance for regulatory screening, prioritization, and scenario assessments. Ultimately, this framework moves beyond static emission inventories toward a dynamic, evidence-integrated assessment system. Its outputs support the development of pollution mitigation and policy strategies across the entire plastic lifecycle, including source control and product redesign, use-phase interventions (*e.g.*, filtration technologies or wear mitigation measures), and improved end-of-life management and disposal methods. In this way, the platform aims to bridge experimental research and decision-making, thereby contributing to more effective and adaptive responses to MNP pollution.

Author contributions

The manuscript was written with contributions from all authors. All authors have given approval to the final version of the manuscript. Dr Zheng Wang: conceptualization, writing original draft, literature review, data collection. Dr Zhi Chen: conceptualization, review, editing. Dr Baiyu Zhang: conceptualization, review, editing. Dr Qi Feng: data collection and manuscript preparation. Dr Zhikun Chen: data collection and manuscript preparation. Dr Kenneth Lee: conceptualization, review, editing. Dr Chunjiang An: conceptualization, review, editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

All data underlying the results are available as part of the article and no additional source data are required.

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