Microplastics and Nanoplastics

EDITORIAL

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Towards a geography of plastic fragmentation

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Abstract

Plastic pollution is a growing environmental crisis, with plastic waste accumulating across marine, freshwater, and terrestrial ecosystems. While early research focused on the transport and deposition of plastic debris, recent studies highlight the role of environmental forces in fragmenting plastics into secondary microplastics. However, the spatial variability and drivers of plastic fragmentation remain poorly understood. Here, we introduce the concept of *the geography of plastic fragmentation*, a transdisciplinary framework that integrates natural and social science perspectives to examine the intrinsic (e.g., polymer composition, design, and prior weathering) and extrinsic (e.g., hydrodynamics, climate, land use) controls on fragmentation processes. We propose a research agenda that includes mapping fragmentation hotspots, conducting field experiments across environmental gradients, developing integrative modeling approaches, and leveraging spatial management strategies to mitigate secondary microplastic release. We argue that applying a geographical perspective to plastic fragmentation can help bridge critical knowledge gaps, providing insights into where, when, and how plastics fragment across diverse environments. By synthesizing geomorphological, socio-economic, and policy dimensions, this approach can inform targeted interventions, from product design improvements to waste management reforms. Advancing research on the geography of plastic fragmentation is essential for shaping effective mitigation strategies and guiding sustainable plastic policies in the face of the predicted increase in plastic production and ongoing climate change.

Keywords Microplastic, Secondary microplastic, Macroplastic fragmentation, Plastic breakdown

Plastic fragmentation as an unexplored component of plastic pollution

Plastic pollution has emerged as one of the most pressing environmental challenges of the past two decades [1]. Early research primarily focused on the emission, transport, and deposition of macro- and microplastics in marine environments [e.g., 2–3], later expanding to other settings such as rivers and lakes [e.g., 4–5]. Collectively, these studies have demonstrated that the widespread release and movement of plastic litter have led to its accumulation across virtually all environments worldwide [6].

Recent research suggests that plastics degrade and fragment under natural forces– such as sunlight, water movement, and wind– generating unknown fluxes of secondary microplastics [3, 7–8]. This fragmentation process prolongs and exacerbates the risks associated with plastic pollution [9], particularly given the projected increase in mismanaged plastic waste [10] and the compounding effects of climate change. Addressing these interlinked challenges requires urgent and transdisciplinary efforts from scientists, practitioners, and policymakers to understand, anticipate, and mitigate plastic fragmentation processes [11].

The goal of this special collection is to present the first baseline observations of plastic fragmentation across

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different environments, alongside the methods and conceptual approaches that can guide its systematic exploration. Given the urgent need for collaborative efforts in collecting new observational data, comprehensively understanding the controls of plastic fragmentation across spatial scales, and developing a theoretical framework for interpreting and applying future findings, we propose a geographical perspective.

Geography, as a discipline bridging the environmental and social sciences, is particularly well suited to addressing these transdisciplinary knowledge gaps. By integrating environmental science with socio-economic and policy perspectives, geography has increasingly served as a valuable conceptual and process-oriented framework in plastic pollution research [12–13]. Here, we propose applying this framework to a specific, measurable component of plastic pollution—plastic fragmentation—to provide a holistic theoretical foundation for analysing its controls, conceptualizing its processes, and, most importantly, translating scientific insights into actionable solutions within the human-environment context.

Geography of plastic fragmentation

We define the "geography of plastic fragmentation" as a transdisciplinary field that examines the interplay between intrinsic (human-controlled) factors (e.g., plastic design, production, usage, and the emission of mismanaged plastic waste) and extrinsic (environmental) processes (e.g., UV irradiation, wind intensity, water movement, and biotic interactions) that determine the potential for plastic fragmentation in a given location.

The design of a plastic object directly influences its intrinsic properties, which, in turn, control its fragmentation rate (e.g., polymer composition, shape, and prior weathering) [14]. Alongside production and the emission of mismanaged plastic waste, these factors regulate the presence of plastic in a given region. Extrinsic factors, which vary more significantly at local scales (e.g., river hydrodynamics, climate, land use), influence fragmentation through mechanical and biochemical forces (inspired by [14–16]). Incorporating a geographical perspective into macroplastic fragmentation research provides a valuable framework for analysing existing knowledge gaps, understanding cause-effect relationships, and guiding more effective mitigation strategies. For example, this perspective enables the identification of spatial patterns in the variability of intrinsic and extrinsic controls (Fig. 1A), helping to determine the most suitable methods and approaches for investigating these factors as drivers of plastic fragmentation (Fig. 1B).

A future research agenda for geographically oriented studies on plastic fragmentation could include the following tasks

Mapping

Utilizing existing databases [e.g., 17], remote sensing, and citizen-science approaches to identify and map potential hotspots of plastic fragmentation.

Field experiments across environmental gradients

Designing systematic experiments to compare fragmentation rates under varying environmental conditions—such as river hydromorphology [8] and beach wave energy [18]—to capture the heterogeneity of mechanical and biochemical forces driving plastic fragmentation in aquatic and terrestrial environments.

Integrative modeling approaches

Developing and refining numerical models that integrate energy gradients of specific environments (e.g., water and sediment transport, wind) with socio-economic datasets (e.g., waste generation statistics, landfill locations, local dumping sites) [see 19] to predict future "*hot moments*" (e.g., extreme events occurrence) when stored secondary microplastics and associated contaminants will be released [see 9, 20] and "*hot spots*" [16] where plastic fragmentation is most active.

Policy-relevant case studies

Despite the rapid advancement of computational capabilities, site-specific verification of model predictions remains essential. Future case studies will play a crucial role in assessing the efficacy of local and regional interventions (e.g., plastic bag bans, improved rural waste infrastructure, and road design to limit waste dispersion).

Transdisciplinary collaboration

Collaboration between chemists, ecologists, and public health experts is crucial to measuring not only the mechanical and physical aspects of plastic fragmentation but also the ecological and human health impacts of secondary microplastic release [21].

Product design and extended producer responsibility

A "*plastic footprint*" approach, which quantifies the number of microparticles generated by common plastic items over time in a given environment [see 16], along with the *MicroPlastic Index* (MPI), which measures a polymer's tendency to produce secondary microplastics, could be valuable for future field [8] and laboratory experiments [22]. These insights can inform the development of more sustainable plastic packaging. Policymakers could leverage such data to incentivize the reduction of fragmentation-prone materials (e.g., foils, expanded polystyrene),

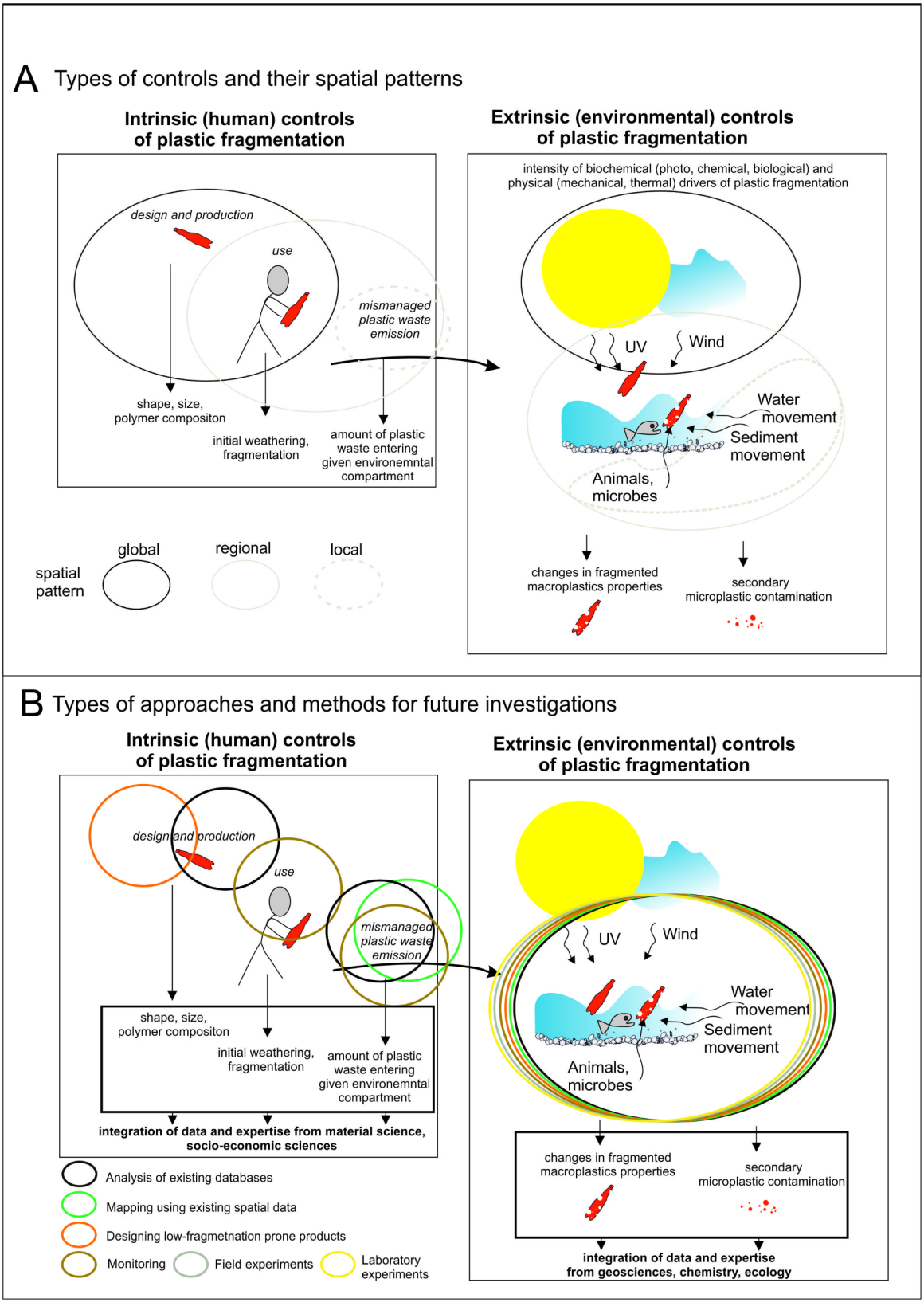

Figure. 1 General conceptualization of a geographical frame for the future investigation of plastic fragmentation.

complementing ongoing efforts to phase out single-use plastics.

Spatial management

Findings from future research should directly inform land management and spatial planning policies to prevent the uncontrolled remobilization of secondary microplastics from contaminated sediments (e.g., river floodplains, artificial reservoirs), particularly in the context of climate change-driven extreme events. Targeted efforts, such as stabilizing eroding banks and removing legacy plastic deposits, could help limit the continued release of aged macroplastics into the environment.

Conclusion

The existing gaps in our understanding of macroplastic fragmentation and secondary microplastic production [23] are not only scientific challenges but also unique opportunities for the field of geography. By synthesizing natural science perspectives—such as geomorphology and sedimentology [e.g., 12, 24–25]—with social science insights into waste management [13], human behaviour, and policy frameworks, geographers can significantly enhance our understanding of where, when, and how plastics break down across different environments. This integrative perspective is crucial for mitigating the long-term impacts of plastic pollution, safeguarding biodiversity, and protecting public health [see 9, 23].

While marine microplastics have received considerable attention, terrestrial and freshwater ecosystems—including agricultural lands, urban settings, and river corridors—are equally critical areas for research and intervention. With plastic production continuing to rise [10], it is imperative to fully grasp the spectrum of fragmentation pathways and develop robust, locally tailored strategies to address plastic fragmentation regionally and globally [23].

We hope that interdisciplinary, geographically informed studies and their resulting practical solutions can help shift the trajectory of the plastic pollution crisis toward a more sustainable future. Our geography of plastic fragmentation concept aims to stimulate future research that adopts an interdisciplinary approach, integrating spatial, socio-economic, and physical factors.

Our topical collection welcomes empirical, methodological, and modeling studies that investigate plastic fragmentation across diverse geographical contexts, aiming to advance a comprehensive understanding of the origins, pathways, and impacts of secondary microplastics.

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ML: conceptualization, preparing original draft and figure, AZ: conceptualization, review and editing of draft and figure.

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Data availability
Not applicable.

Declarations

Competing interests
The authors declare no competing interests.

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