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Sources of nanoplastic and microplastic pollution which are hidden in plain sight

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Perspective

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Abstract

Plastic pollution is pervasive in our environment, with impacts seen across ecosystems and taxa. While plastic has become an integral part of our daily lives, not all of it is readily apparent, making it challenging to effectively reduce plastic pollution. A hidden source of plastic pollution is plastic-based printing, which is used on a wide range of items including single-use products like plastic food containers and multi-use plastic items like credit cards. This also includes items that we would not consider to be sources of plastic pollution such as glass bottles with surface printing. The widespread use of this printing, therefore, results in even non-plastic items contributing to plastic pollution, potentially contaminating recycling streams and exacerbating nano- and microplastic (NMP) dispersion. Given the challenges of remediating NMP plastic pollution once it has entered the environment, prevention becomes paramount. With significant efforts underway to reduce plastic production, it is important to take a holistic approach to redesigning objects and materials to avoid false solutions, which will continue to contribute to ecosystem degradation and planetary boundary transgressions. To make meaningful progress and avoid ineffective solutions, it is imperative to consider all sources of plastic pollution, including those concealed within apparently non-plastic objects.

Impact statement

Plastic particles are ubiquitous in our environment, with their impacts seen across ecosystems and taxa. There is an increasing urgency to stem the tide of plastic pollution; however, a holistic approach is needed to eliminate unnecessary sources of plastic pollution, along with the redesign of objects and materials. It encompasses identifying and acknowledging all sources of plastic pollution large and small, including those concealed within seemingly non-plastic items. Embracing such a comprehensive strategy is crucial to prevent regrettable substitutions that perpetuate the transgression of planetary boundaries. This transformation may be intricate and lengthy, but the unsustainable nature of the status quo is increasingly evident. To make meaningful progress and avoid ineffective solutions, it is imperative to consider all sources of plastic pollution, including those concealed within apparently non-plastic objects.

Introduction

Plastic, across its entire life cycle, poses a threat to both human and environmental health, and contributes to the disturbance of the processes that underpin the stability and resilience of the Earth system on which humanity depends (Persson et al., 2022; Richardson et al., 2023). Awareness around the environmental impacts of large plastics began in the 1970s; however, it is only since the early 2000s (Thompson et al., 2004) that nano- and microplastics (NMPs) (Cunningham and Sigwart, 2019) have received great attention, evident from both the scientific literature with the number of published articles increasing exponentially, and in the popular press. While there is attention on, and consequently public awareness, of microplastic pollution from washing synthetic clothing (De Falco et al., 2019) and from the general wear of vehicle tyres (Knight et al., 2020), or the breakdown of single-use food packaging on beaches after a long voyage at sea (Ryan et al., 2021), there is less awareness of other items which we use every day being a source. The presence of these plastic particles have been reported for all ecosystem compartments, as well as evidence to show that this form of anthropogenic contamination poses a serious threat to all ecosystems and biota, across all taxa and trophic levels, and having individual- to ecosystem-level impacts (Du et al., 2021; Dissanayake et al., 2022; Morrison et al., 2022). While the body of evidence around the interactions and effects of plastic pollution on the environment continues to grow, research into the complex multi-factorial nature of plastic contamination (particle size, polymer type, associated chemicals, species-specific effects, environmental condition interactions etc.) is still in its relative infancy. But one thing remains clear – there is a pressing need to reduce the levels of plastic pollution, both large and small, entering the environment and we should be using every available opportunity to do this.

Primary NMPs (Frias and Nash, 2019), such as microbeads and particles used in consumer products and industrial abrasives, glitter and preproduction pellets (nurdles), can be controlled through bans (Rochman et al., 2015) and can have strict regulations imposed to control release to the environment. Such strict controls cannot be placed on secondary NMPs as they evolve from the breakdown/fragmentation of larger plastic items (Weinstein et al., 2016; Dawson et al., 2018; Hernandez et al., 2019; Porter et al., 2019; Liu et al., 2020; Po et al., 2020; Rambacher et al., 2023) during natural wear and tear resulting from usage, and during their post-use fate. Whether this is fragmentation in the environment after leakage due to mismanagement, or following managed disposal in landfill (Silva et al., 2021; Kabir et al., 2023) or recycling (Suzuki et al., 2022; Brown et al., 2023), it is becoming increasingly evident that we need to reduce the burden plastic pollution has on the planet. This can be achieved by reducing the production of plastics, especially unnecessary plastics. In instances where plastic is still required, improvements to product design to increase the durability and end-of-life management will aid in minimising the levels of potential plastic pollution. With a focus on phasing out single-use plastics and replacing them with multi-use items, we not only need to not lose sight of the fact that products made of plastic will still be a source of NMPs, but possibly more importantly, be aware that some products which we would not consider as either single-use or even plastic contribute to NMP pollution. Examples include metal water bottles and cardboard food containers, due to the use of plastics in the application of printed labels, decorations and branding.

Forgotten sources of nano- and microplastic pollution

It is most often impossible to identify the original plastic object that secondary NMPs originated from. Fibres may be attributed to clothing, soft furnishings and other textiles. Conversely, the extensive usage of hard plastics in a range of applications, from medicine to transportation, means that determining the potential origin of fragments found in the environment is a near impossible task due to the lack of distinguishing features. When the source cannot be identified due to the lack of identifiable characteristics, it not only makes it harder to take action to reduce it at the source (e.g. through product bans), but it also removes any sense of personal responsibility. Microbeads and glitter are recognisable examples of primary microplastics produced for a certain purpose. Glitter in particular can be used in several applications. Although the specific use may not be possible to ascertain, it has most likely been for aesthetic purposes and its end of life fate almost certainly will be one of pollution (Green et al., 2021; Perosa et al., 2021).

A more surreptitious and widespread potential source of secondary NMPs, which is overlooked, is the printing and labelling on items that we surround ourselves with daily. Coloured pigments combined with synthetic polymers (e.g. acrylic, epoxy resin and vinyl ester) are frequently used in a range of printing techniques for the application of solid colours or graphics and text on a diverse range of everyday items. Halftone printing, a technique that simulates varying shades and tones in an image by using dots of different sizes and spacing to create the illusion of continuous tones, is used widely due to its versatility, especially when paired with synthetic polymers. The characteristics of this printing method makes the microplastics that originate from these sources distinctive, and stand out from the vast background of indistinguishable plastic fragments. Their presence in different environmental matrices clearly demonstrates that this application of plastics is a significant source of NMPs, previously hidden in plain sight.

In food packaging, plastic-based halftone printing is utilised to enhance the aesthetic appeal of product labels and packaging designs and can be applied to the food-contact packaging material that will be of a material best-suited to functional requirements. For example, the adhesive labels of plastic chilled food containers consist of a synthetic polymer backing with a plastic-based print finish (Figure 1A). This promotes durability to endure a range of environmental conditions the product may encounter, such as condensation and abrasion during transportation and storage, and a level of resilience that paper-based labels would not offer.

This method of printing is also used on items that are considered to be multi-use, such as plastic bank/credit cards and loyalty/store cards (Lindgreen et al., 2018; Murti et al., 2022). The body of the card can range in polymer type with multiple layers depending on the desired properties dictated by function, with the halftone pattern printed on with plastic-based inks (Figure 1B,C). The use of plastic-based halftone printing in credit card manufacturing allows the creation of visually striking designs (Figure 1B), and the meticulous crafting also achieves protection against counterfeiting. These properties are highly advantageous and attractive to banks and credit card companies that consider these features essential.

Non-plastic items, of variable lifespans, are also a potential source of NMPs from plastic-based printing. Examples include patterns/logos printed directly or indirectly on metal drink bottles and glass beverage bottles, and labels on paper-based egg cartons (Figure 1D,E). In some jurisdictions there has been a lot of attention drawn to plastic price look-up (PLU) code labels, which are used on loose fresh produce, due to their potential to contaminate organic waste. However, paper-based or biodegradable stickers have not come under such scrutiny despite the fact that they may also carry a NMP contamination risk as a result of the plastic-based printing used (Figure 1F). Another printing technique, which is a source of NMPs, is laser printer toner, which contains plastic nanoparticles, pigments and other additives. Upon heating, the thermoplastic particles soften, fusing to the paper. The use of plastic provides the high durability of the printed material.

During everyday use, fragments can be shed from these plastic surfaces, entering the environment unnoticed. Bank/credit cards and loyalty/store cards show visual signs of wear, due to the gradual release of plastic fragments from their printed surface. Similarly, other multi-use items such as metal water bottles, with printed embellishments, experience a change in their surface integrity over time with the loss of these printed designs. Both items may also contribute to environmental NMP indirectly via wastewater treatment plants (Figure 2), for example, when bottles are washed or clothes whose pockets have carried cards or wallets release the particles that they have been gathering. These fragments, once released, will continue to proliferate through the environment and be found far from their source (Figure 2).

Printed plastic surfaces also alter the pollution potential of the objects they are on. For example, a glass beverage bottle that has been discarded in the environment or repurposed carries with it potential NMP pollution. Recycling processes are not immune to this issue, as the recycling stream may become contaminated with these printing polymers. Paper-based PLU stickers may biodegrade in compost, but they leave behind a plastic fingerprint in the form of the surface printing (Figure 1F). Paper and cardboard recycling is contaminated by the printing materials or labels like those used on

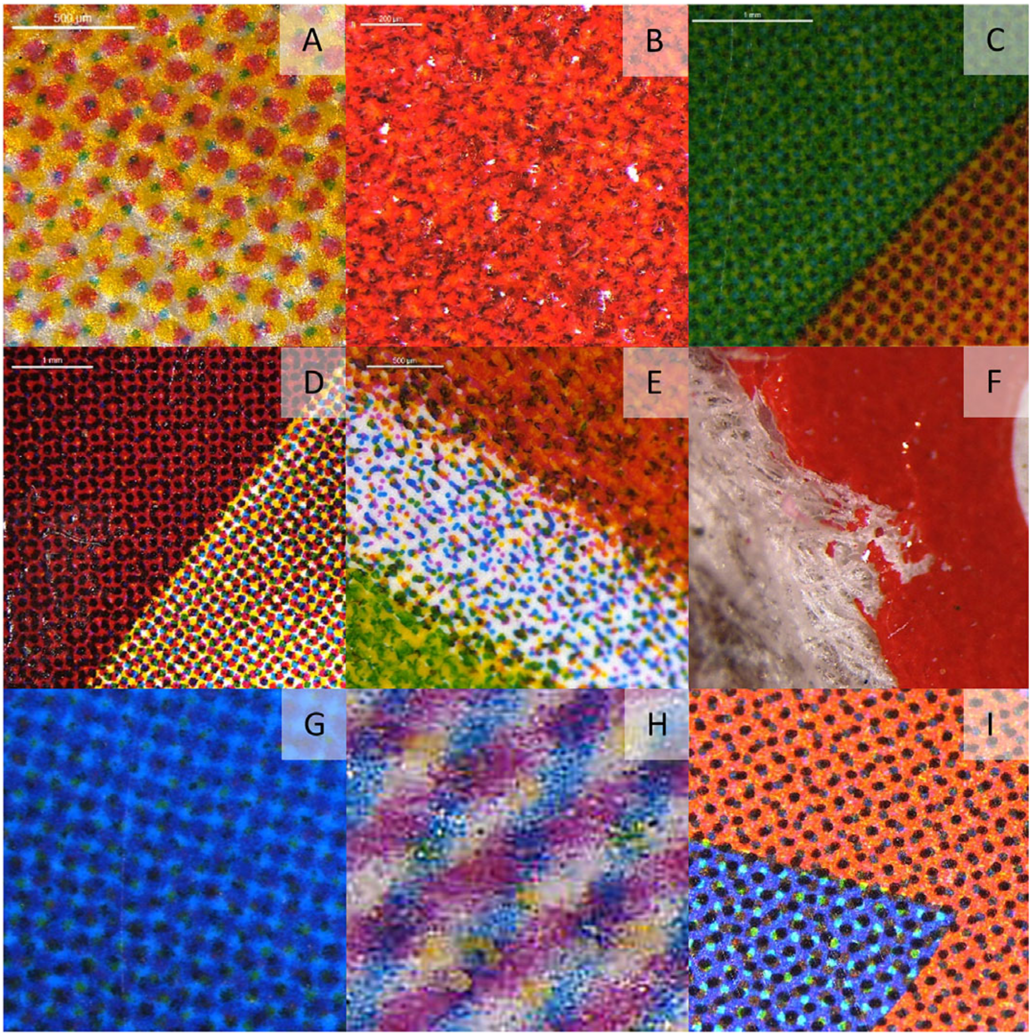

Figure 1. Examples of everyday items with plastic-based printing: (A) ice cream container – acrylic; (B) credit card – acrylic; (C) loyalty card – acrylic; (D) cardboard egg carton – acrylic; (E) metal water bottle – acrylic; (F) paper banana sticker – vinyl ester; (G) cardboard business card – epoxy resin; (H) laser printing on paper – epoxy resin and (I) cardboard box – vinyl ester.

cardboard egg cartons (Figure 1D), and other printed items (Figure 1G–I). These print-associated plastics can contaminate both the recycled materials and the solid and liquid waste resulting from the recycling process itself. Although there is currently a lack of regulations governing NMP levels in discharges, unlike other chemical and microbial contaminants, the lack of knowledge around other potential sources may hamper the control of key sources to the environment.

Life cycle assessments (LCAs) provide a powerful tool for evaluating the environmental impacts of products throughout their entire lifespan, utilising a systems thinking approach. However, it is widely recognised by both the scientific and industrial communities that they possess limitations when it comes to plastics. Some of the key limitations of LCA for plastics include data availability and quality, boundary setting, substitution effects, multi-functionality, indirect environmental impacts, the dynamic nature of plastics, temporal and geographical variability, social and economic factors, cumulative effects and complex end-of-life scenarios (Pellengahr et al., 2023). The continuous shedding of plastic particles from plastic items is an important parameter currently lacking from LCAs and will play an important role in addressing plastic pollution and promoting sustainability. Equally these parameters should be included for non-plastic items which incorporate plastic-based printing as they represent a significant range of products with high usage, therefore having the potential to contribute to plastic pollution across all ecosystems.

Making change that is better, not just different

Preventing primary NMP pollution is undoubtedly a more manageable task when compared to the herculean challenge of containing secondary NMP leakage into the environment, or remediating that which is already there. Currently there are no strategies to remove NMPs from waste management systems and environmental matrices. Throughout history, humans have frequently been faced with apparent unforeseen repercussions from the use of chemicals in a variety of applications, often employed to replace existing substances or practices. Plastics, across their full life cycle, are no exception and epitomise the unpredictable outcomes associated with synthetic materials.

The move towards encouraging multi-use items, like drinking bottles, is invaluable in reducing the use of plastic and creation of plastic waste. However, they are likely to still contribute to NMPs due to colour and decorations applied by polymer printing, which

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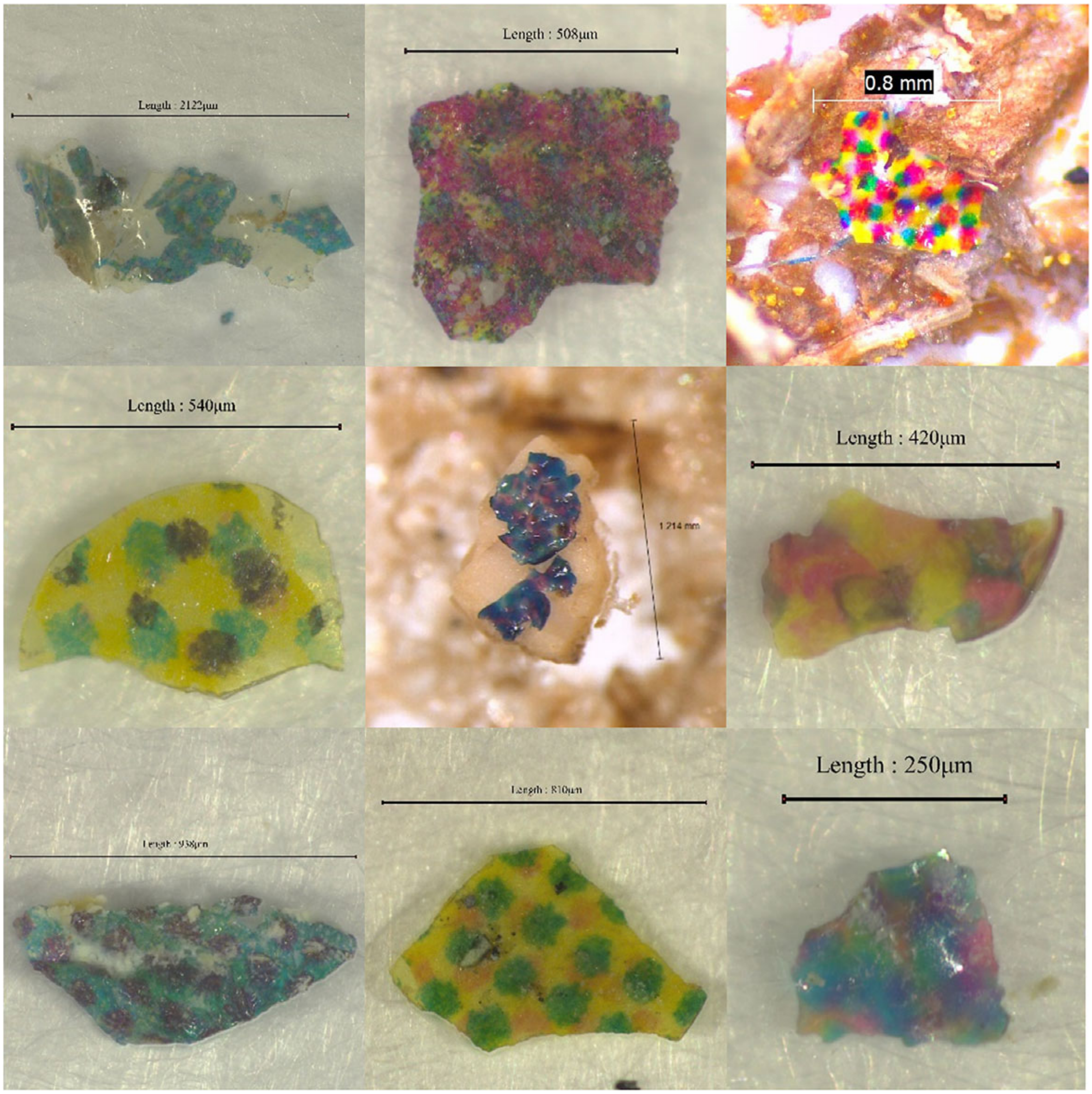

Figure 2. Examples of different microplastic fragments with halftone printing isolated from environmental matrices, including biosolids, compost, wastewater and seawater.

highlights the need to scrutinise all aspects of alternative designs. By taking a holistic approach when redesigning objects, whether they are traditionally seen as plastic or not, and by including these concealed sources in LCAs, we can achieve a more comprehensive understanding of a product's genuine environmental impact. This enables us to make more informed decisions regarding design, sustainable use, reuse and disposal. When complete elimination is unattainable, we should prioritise better and more sustainable alternatives. Tackling the challenge of these less noticeable sources may represent a significant opportunity for green chemistry to have a pivotal impact. Although it is challenging to estimate the contribution this use of plastic makes to the levels of NMPs in our environment, if you consider that a single credit card has the potential to release a minimum of 370 microplastics (9.24×10^9 nanoplastics) from its surface printing, and a lacquered 700 ml steel drink bottle an order of magnitude more, it gives an indication of the scale of the NMP smog that we leave in our wake. Therefore, in addressing these sources, it will make a significant difference if you consider how many of these items there are in circulation. Using materials for these applications that pose no threat to the environment where elimination is not an option could act as a safeguard against the potential consequences of these previously unaccounted NMPs.

Conclusions and possible future perspectives

The upper limits of six of the nine key environmental processes and systems that humanity needs to function within to avoid a catastrophic environmental change and impact, have already been exceeded (Richardson et al., 2023). Adhering to planetary boundaries is crucial for addressing global challenges such as climate change, biodiversity loss and ecosystem degradation. It is essential to adopt a more sustainable and responsible approach to development and resource management to ensure the well-being of current and future generations. While plastics offer many benefits in terms of convenience and functionality, their production, use and disposal have significant environmental impacts. These all contribute to the transgression of several planetary boundaries (Persson et al., 2022) from climate change to biosphere integrity due to biodiversity loss.

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Reducing plastic pollution and transitioning to more sustainable materials and practices is an essential part of addressing these environmental challenges and promoting a more sustainable future. It is not only about mitigating the visible impacts of plastic waste but also minimising the release of NMPs into the environment. Critical to this is identifying and acknowledging all sources of NMPs such as plastic-based printing, particularly on items not considered as plastic. The ubiquity of NMPs in different environmental matrices is due to the wide array of sources. Although some of these transition points before discharge to the environment (e.g. composting facilities) may allow focused remediation, there are currently no viable solutions. Attention must therefore be given to the upstream phase of the items' life cycle, with a focus on product design to achieve the greatest impact and reduce environmental harm from NMPs. Embracing a holistic approach to redesigning objects and materials can help ensure that we do not repeat past mistakes with regrettable substitutions, inadvertently continuing to contribute to the transgression of planetary boundaries and that our actions align with a more sustainable and responsible path forward. This transition may be a long and complex process, but it is becoming increasingly evident that the business-as-usual is not sustainable. To do this effectively, without false solutions, it is important that all sources of plastic pollution, including those hidden within apparently non-plastic items, are considered during product design.

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