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Plastic pollution: When do we know enough?

Alice A. Horton

National Oceanography Centre, European Way, Southampton SO14 3ZH, UK

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ABSTRACT

Plastic pollution is one of today's great environmental challenges. Research addressing the issue of plastic pollution is growing, improving our predictions of risk, and informing the development of long-term solutions and mitigations. Nonetheless, sufficient evidence already exists to show that immediate and widespread action must be taken to reduce plastic release to the environment, and thus limit future harm. Given the cross-sector and multi-stakeholder approach that will be required to address plastic pollution, it is essential that contrasting opinions and misconceptions are tackled with respect to the status of knowledge, relative importance of plastics as an environmental stressor, and measures to reduce or mitigate harm from plastics in the environment. This perspective article lays out some key considerations and recommendations for moving forward with respect to both research and action.

1. Introduction

Plastics are nowadays essential across many aspects of modern life, for applications including, but not limited to, healthcare, technology, construction and performance clothing. Plastics have significant beneficial properties that are difficult to obtain using other materials, for example depending on the polymer type, it is possible to heat, sterilise and manipulate plastics while maintaining their structural properties. Furthermore, they can replace otherwise unsustainable products derived from animals, such as ivory, tortoiseshell or fur. Due to their low weight, plastics also produce fewer carbon emissions during transport than alternative materials such as glass (Humbert et al., 2009; Miller, 2020). Nonetheless, their cheap and disposable nature often leads them to be used and discarded unnecessarily. Never have the conflicting advantages and disadvantages of plastics been more apparent than during the COVID-19 pandemic, during which time plastic-based PPE and packaging have helped to prevent the spread of the virus, while simultaneously leading to a measurable increase in related plastic debris in the environment (de Sousa, 2020).

Despite widespread awareness that excessive use and mismanagement of plastics is leading to global contamination and environmental damage, plastic production continues to soar. Cumulatively, more plastics were produced between the years 2005 and 2017 than in the previous 50 years (Geyer et al., 2017) (Fig. 1). Globally, waste management systems are struggling to cope with the resulting influx of waste, and it was estimated that in 2016 alone, up to 23 million tonnes of plastics entered aquatic ecosystems (Borrelle et al., 2020). Even with ambitious reduction targets, by 2030 this amount is predicted to double (Borrelle et al., 2020), with a predicted increase of 300–400% by 2050 (Geyer et al., 2017).

We know plastics to be persistent and pervasive throughout the environment, from the deepest parts of the ocean to the tops of the highest and most remote mountains (Allen et al., 2019; Chiba et al., 2018). We have information on the sources, degradation and transport of plastics, and a variety of research has been carried out to investigate the ecotoxicological and wider ecological consequences of plastic ingestion and entanglement (Senko et al., 2020; Galloway et al., 2017). This knowledge is well-publicised in the media and wider public communications. In the eyes of the general public, therefore, it would be easy to think that we know everything with respect to plastic pollution.

However, despite the existing knowledge on plastics, there is plenty that we do not yet know. Even within the last five years we have identified sources of microplastics (1 μm–5 mm) to the environment that are not novel, but had not previously been considered, for example road paints (Horton et al., 2017) and tyre wear particles (Knight et al., 2020; Kole et al., 2017). Other potentially significant sources such as artificial sports pitches, the day-to-day wear of shoe soles, and plastics used in construction (accounting for around 20% European plastic consumption (PlasticsEurope, 2020)), have been almost completely overlooked. We are also discovering that plastics are not inert as previously thought, as they commonly leach toxic plasticiser chemicals, aggregate with other materials and form chemical and biological associations. In addition to microplastics, nanoplastics (<1 μm) are likely prevalent, with their small size allowing for translocation through biological membranes and

E-mail address: alihort@noc.ac.uk.

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tissues, and a high surface area to volume ratio leading to increased associations with chemicals, overall making them potentially more hazardous than larger sized plastics. Despite these concerns, based on available analytical techniques, nanoplastics are currently very difficult to detect within environmental samples. These uncertainties make one wonder what we might still be missing. The question of whether we know 'enough' about plastic pollution can be considered within two distinct themes: research and action. These two themes will be explored in detail in the following sections.

2. When do we know enough to stop researching plastics?

While knowledge of plastic pollution has grown in recent years, there are still many unknowns regarding the distribution, fate and toxicity of plastics within the environment. The complexity of plastics as materials, with thousands of combinations of polymer types and chemical additives, confounds our understanding of how these materials behave and degrade. Plastics are lost to the environment either during use or at the end of life, but both the locations and volumes of these losses are difficult to pinpoint. Fate and transport are dependent on various interacting factors including plastic characteristics, source location and environmental conditions. Temporal (e.g. seasonal) variability adds to this complexity, having a significant influence on plastic inputs and transport (Balthazar-Silva et al., 2020). Furthermore, much of the plastic we believe to be in the environment, as a result of waste mismanagement, cannot be accounted for. This is certainly not because all the plastics have disappeared, but is likely because they have thus far evaded the spatial and analytical limits of our research. It is worth noting that much of our knowledge on global plastic stocks and flows to date is derived from model estimates. For models to produce accurate outputs relies on the input of sufficient real-world data, meaning that where data are limited, these model predictions are subject to significant uncertainty. Greater volumes of field-collected data will continue to improve model predictions in coming years.

Organism responses to plastics are complex, and dependent on the characteristics of the plastic item (chemical structure and additives, size, shape, age), the extent and route of exposure, and the species, life stage, and traits of the organism. Environmental conditions can also play a large role in organism and ecosystem responses to plastics as a result of combined stressors, such as ocean acidification, warming, or wider contamination (Horton and Barnes, 2020). With the known persistence of plastics there is the potential for long-term exposure at sub-lethal concentrations, leading to bioaccumulation, and chronic health or population effects. Given the lack of consistency and consensus on effects across species and experimental conditions, and almost infinite combinations of exposure possibilities, we therefore cannot say that we yet understand the long-term environmental implications or ecological effects of microplastics, especially in the context of multiple varied stressors.

Ongoing research on plastics, especially when pre-emptive (i.e. testing of materials under development, or testing ecological hazard under possible future contamination scenarios), will afford us the knowledge to prevent the creation of new issues. Blindly removing plastics can lead to regrettable substitutions, i.e. materials which in principle may seem better, but could cause equal or worse environmental consequences. This may be the case, for example, for some biodegradable polymers (Zhu and Wang, 2020; Zimmermann et al., 2020). These usually do not have the same strength and stability as conventional polymers, and therefore are not effective substitutes for many products (Shen et al., 2020). Furthermore, these can contaminate recycling streams and may not fully degrade within the natural environment (often designed instead to degrade under industrial composting conditions) (Alaerts et al., 2018; Napper and Thompson, 2019). It is therefore crucial that we do not simply replace plastics with alternative materials without sufficient research into their suitability and sustainability.

3. Debate on the relative importance of plastics research

To some, the rapid profusion of plastics research in recent years has led to the opinion that plastic research is a fad, with interest soon to pass. It has also been suggested that the current attention on plastics is

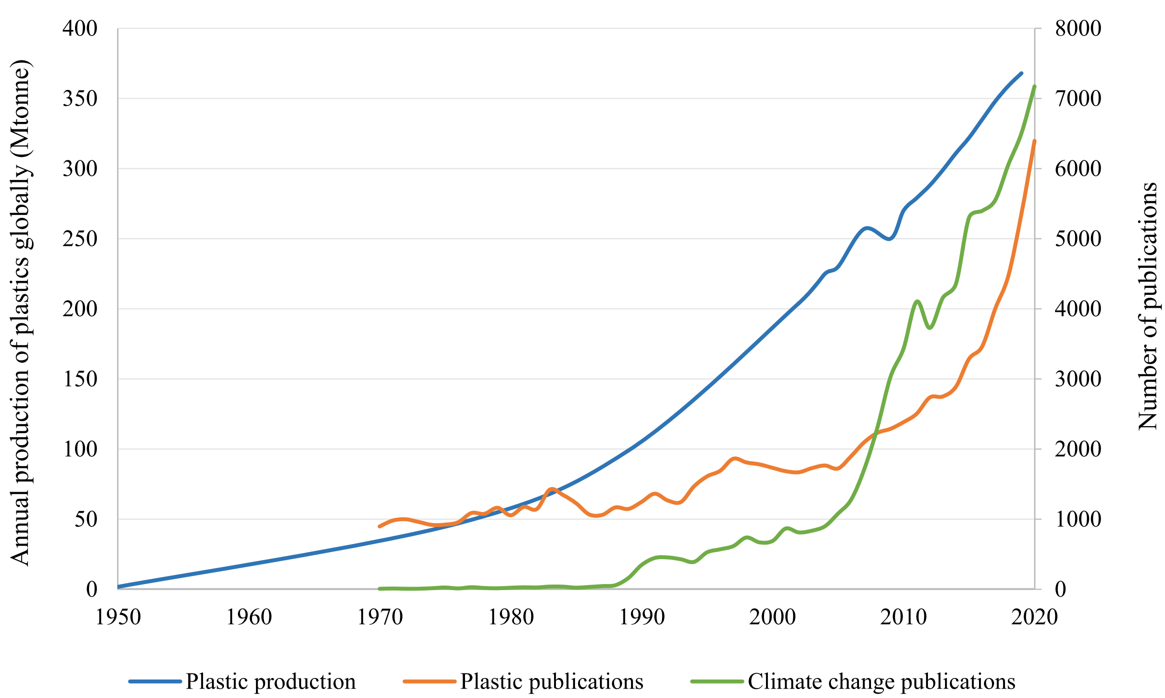

Fig. 1. Volume of global plastic production since 1950, compared to the number of publications on plastics and, separately, climate change. Data on plastic production is market data from PlasticsEurope (PlasticsEurope, 2020), data on publications was collected from Web of Science in July 2021 based on available data between 1970 and 2020. Searches were carried out for each topic separately and search terms were as follows: TITLE: ((plastic* OR microplastic* OR nanoplastic*) NOT (plasticity OR plastically)); TITLE: ('climate change' OR 'global warming').

overshadowing issues of greater importance, such as climate change (Stafford and Jones, 2019). However, while there is undoubtedly considerable focus on plastics, in reality the research itself does not does not receive proportionally more research effort than climate change (Fig. 1.). The growing public awareness of plastics is partly due to the visibility of the problem; plastic litter is widespread and ugly, it is difficult to ignore. In this way, plastic pollution can be seen as a 'gateway issue', one that enables people to become aware of, and act to reduce, wider environmental problems. It should also be noted that the issues of plastics and climate change are closely interconnected and should not be considered as competing fields of research. Plastic production contributes significantly to greenhouse gas emissions: in 2015 plastic production accounted for 3.8% global CO_2 emissions (Zheng and Suh, 2019) (almost double that of the aviation industry which contributed approximately 2%) and by 2050 will account for a predicted 20% of all global oil consumption (World Economic Forum, 2016). Additionally, the degradation of plastics can release greenhouse gases including methane and ethylene (Royer et al., 2018). Therefore, improved controls on plastic production, use and waste management can directly or indirectly lead to a reduction in the release of greenhouse gases.

Others will argue that plastic is not a serious problem – it has been in the environment for decades, and while there are some animal mortalities, we have not seen populations collapsing as a result. However, this perspective does not account for the rapidly increasing volumes entering the environment, combined with the longevity of the plastics already present. The timescale of environmental contamination to date is less than a human generation and does not represent the multigenerational timescales that may be required to see chronic effects in many organisms. While generally the global risk to aquatic ecosystems is currently believed to be low (Everaert et al., 2020), growing data on hazard and exposure has shown that risk is possible in some locations, for example where sensitive organisms inhabit regions where plastics (especially microplastics) accumulate (Adam et al., 2019; Besseling et al., 2019). Considering that microplastics will likely continue to increase in abundance (mass and number) in coming years, as a result of the breakdown of existing and new debris, this risk is likely to increase.

We have a long way to go before we can confidently say that we truly know enough to understand the long-term implications of current and future environmental plastic contamination. It is therefore crucial that research efforts continue, to provide us with the knowledge we need to reduce or mitigate any potential future harm.

4. When do we know enough to act?

There is no doubt that despite the aforementioned uncertainties, we already have sufficient knowledge to justify action to reduce plastic leakage into the environment. Even if plastics are not always harmful, there is enough evidence to show that they can be, under a variety of conditions (Besseling et al., 2019). Further concerns stem from possible human health implications of micro- and nanoplastics, especially given our likely high day-to-day exposure. Therefore, even if it is to prevent the *possibility* of harm, that is sufficient reason to implement change.

To this end, the precautionary principle is now being applied with respect to some uses of plastics, especially where plastics are deemed unnecessary, replaceable, or there is an unacceptable risk of release to the environment. For example, plastic bags are now taxed or even entirely phased out in many countries worldwide. Regarding microplastics, microbead bans for personal care products now exist in a variety of countries worldwide, with the European Chemicals Agency (ECHA) going even further to propose a restriction on all intentionally added microplastics (also known as primary microplastics) in any product (ECHA, 2019). The ECHA restriction alone will prevent tens of thousands of tonnes of microplastics entering the environment annually. These are bold and industry-defining moves, based primarily on the likelihood rather than the guarantee of harm. Nonetheless, secondary microplastics (i.e. those shed from larger items) by far dominate the composition of microplastics in the environment, with primary microplastics such as those added to products making up only 1–2% (Boucher and Friot, 2017). Measures to tackle these secondary microplastics will be far more challenging.

It is important to note that change does not come without cost (economic or environmental), and simply replacing or removing plastics is unlikely to be appropriate in many cases. It is recognised that globally, plastics have enormous benefits: they are cheap, durable, strong materials that are now irreplaceable across many industries. As such, cost-benefit analyses should be considered when deciding on preferred materials and management strategies (ECHA, 2019), recognising that in some instances, it will not be possible, nor desirable to eliminate plastics. Life cycle assessments (LCAs) carried out on plastics in comparison to other materials (for example glass or metal) often find plastics to have the least environmental impact with respect to manufacturing emissions, transport emissions and volume of material needed to produce new products (Miller, 2020). The comparative sustainability of paper and card products, on the other hand, is less clear as their manufacture relies heavily on freshwater resources, land use and produces greater carbon emissions. Nonetheless, compared to plastics they contain fewer additive chemicals and can be more easily recycled (Lewis et al., 2010). While plastics are widely reviled, and indeed their longevity poses a great problem if they enter the environment, in fact the key issue is today's throwaway culture, dominated by single-use items, regardless of material type. By restricting single-use items in general, and encouraging reuse, we will go a long way to not only reducing the issues associated with plastics, but improving resource use and wider environmental quality (Herberz et al., 2020).

Instead of replacing or eliminating plastics, in many instances it may be more favourable to shift towards a system of reduced complexity i.e. using a smaller range of (more recyclable) polymers, such as PET, with fewer additives and colourants, across a greater range of applications. This is desirable where it is possible to maintain key product properties, while simultaneously simplifying plastic composition. Despite it being recognised that reduced complexity of polymer types and composites would facilitate improved waste management, this is not a commonly suggested solution to plastic pollution. However, this would enable easier recycling and greater transparency through the supply chain, both for industry and consumers. Furthermore, as many plastic product formulas are currently commercially confidential, it would be advisable for regulators to mandate that the ingredients of products become publicly available. Currently, researchers are spending time and effort analysing product composition, when this information exists, yet is unavailable (Zimmermann et al., 2019). In the interest of efficiency, cost saving and research progress (for example understanding potential hazard posed by products and their additives), providing accessibility to this information is highly advisable.

5. Looking forward: improved knowledge and effective solutions

To identify and address the key issues and knowledge gaps surrounding plastic pollution, concerted effort is required. Ongoing research into sources and fate of plastics in the environment will help to target the worst offenders: plastics which are the most prolific, informing solutions, mitigations and alternative materials. Cross disciplinary collaborations will be crucial, including biologists, chemists, materials scientists, social scientists, economists and many more. To accurately assess environmental concentrations of plastics, reliable and repeatable methods are essential. It is widely stated amongst plastic researchers that standardised or harmonised methods are desirable, especially for field studies, to improve reporting and interpretation of data, and enable comparison of data between studies. Nonetheless it must also be recognised that different methods may be appropriate in different scenarios, depending on the type of study and the research questions being asked. Further, methods for both sampling and analysis continue to develop and improve. Therefore, any standardisation should not prevent research by those who do not have access to agreed 'standard' facilities, nor inhibit methodological and analytical progression. For example, semi-automated techniques are now available for microplastics in the form of linear plane array and focal plane array FTIR spectroscopy combined with image analysis, methods which were not widely used or available even five years ago (Primpke et al., 2017). This improved speed and automation is enabling the analysis of ever-larger numbers of samples, with greater accuracy, and should be capitalised on. Chemical analysis techniques (such as pyrolysis GC-MS) allowing for similar high throughput of samples are available, yet continue to be optimised, and are likely to be more widely used in coming years (Picó and Barceló, 2020; Dibke et al., 2021).

Considering ecological hazard, future research should focus not only on establishing toxicity thresholds, but determining the effects of plastics and their additives under realistic scenarios and timescales. This requires using environmentally-representative particle types and concentrations, and chronic exposures (Paul-Pont et al., 2018). For example, studies have shown that fibres are the dominant particle type across multiple environmental matrices (Xu et al., 2021; Horton et al., 2018), however these are infrequently used in laboratory testing for particle behaviour or toxicity. Furthermore, the longevity of plastics means than ecosystem exposure will be long-term, yet the majority of exposure studies to date have been acute, in the order of hours or days (de Ruijter et al., 2020). Importantly, toxicity data be should considered in the context of the complex conditions and multiple stressors that will be encountered by organisms in the environment (Horton and Barnes, 2020). Environmental variables are among the most influential factors in influencing microplastic exposure and toxicity, yet are difficult to account for under controlled laboratory conditions. Multi-species outdoor mesocosm studies can go some way to addressing these complexities (O'Brien and Keough, 2013). However, the limitations of any experimental study with respect to representing the real environment must be recognised.

Only with improved data on both environmental abundance (exposure) and the extent and drivers of detrimental effects on organisms and ecosystems (hazard) can we predict likely future risk (Adam et al., 2019; Besseling et al., 2019). However, it is not possible to spend indefinite amounts of time and money investigating all possible permutations of plastic exposure and hazard. Exploiting more-developed research from other fields, plus predictive tools, will help inform and streamline plastics research to achieve the greatest benefit with the least cost. For example, traits-based species sensitivity assessment and predictive modelling can help in determining likely species and ecosystem responses to different stressors (Spurgeon et al., 2020), while relevant fields with comparatively more data, for example engineered nanomaterials, can provide valuable analogues (Hüffer et al., 2017; Rist and Hartmann, 2018). Returning to the question 'when do we know enough to stop researching plastic pollution' the answer is 'not yet, and not any time soon'.

Even while research is ongoing, action to reduce the possible short and long-term harm posed by plastics is essential, and can be achieved through policy, legislation, industrial and social measures. Clean-up operations at a local scale can be beneficial, both in terms of educating the public, temporarily reducing local pollution and, in some instances, simultaneously gathering data on types and abundances of different litter items (Syberg et al., 2020). Large-scale clean-up operations, for example ship-based booms or wheels, can remove larger amounts of debris from the aquatic environment, although have economic costs and environmental implications associated with the use of large vessels and equipment (Cordier and Uehara, 2019). However, despite some benefits, based on the huge volumes of plastics present in the environment, neither of these activities will feasibly lead to any significant reduction of plastic contamination. Instead, measures must target the prevention of release to the environment, improvement of waste management, and reduction of material complexity (using fewer polymer types and chemical additives) where possible. Combined, these actions will enable plastic reuse and effective recycling, recouping valuable materials and reducing the requirement for virgin materials and chemicals in line with circular economy principles (Kümmerer et al., 2020).

It is recognised that system changes will be costly and therefore should not be a knee-jerk reaction to public pressure, but should be targeted and evidence-based. Hasty responses are likely to lead to ill-considered decisions, and greater economic or environmental harm. For example, it has been suggested that a tax on single-use plastic bags in the UK has led to a corresponding increase in the use of thicker reusable plastic bags, which are discarded in the same way regardless, and are likely more environmentally damaging (Environmental Investigation Agency and Greenpeace, 2019). Further, effectiveness of such bans relies on strict regulations, and also the availability of alternatives, both of which are often lacking. For example in Bangladesh, which banned plastic bags in 2002, bags are still widely used (Chowdhury et al., 2021). While evidence-based decision-making is of foremost importance, nonetheless public pressure can be constructive in encouraging producers to more critically consider their use of plastics, and eliminate these where they are not essential. An example is that of microbeads in wash-off personal care products, a non-essential use of plastics, which a number of manufacturers phased out even before legislative bans were enforced. Public actions continue to contribute to reducing plastic losses, with small but effective measures such as reuse of everyday items such as shopping bags and water bottles, alongside efforts to recycle non-reusable items.

For the effective implementation of evidence-based decision-making, science, policy and industry must work together, to enable actions to adapt with the development of scientific knowledge, and vice versa. As a starting point, it makes sense to focus on both 'easy wins' (products that are relatively cheap and simple to adapt or replace) and the most significant polluters (e.g. packaging or vehicle tyres), whereby system overhaul will be enormously challenging, but will lead to the greatest environmental gains. Therefore, considering the question 'when do we know enough to act?', the answer is, unquestionably, now.

CRediT authorship contribution statement

AAH conceived, researched and wrote the manuscript.

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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