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Application of nuclear techniques to environmental plastics research

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ABSTRACT

Plastic pollution is ubiquitous in aquatic environments and its potential impacts to wildlife and humans present a growing global concern. Despite recent efforts in understanding environmental impacts associated with plastic pollution, considerable uncertainties still exist regarding the true risks of nano- and micro-sized plastics (< 5 mm). The challenges faced in this field largely relate to the methodological and analytical limitations associated with studying plastic debris at low (environmentally relevant) concentrations. The present paper highlights how radiotracing techniques that are commonly applied to trace the fate and behaviour of chemicals and particles in various systems, can contribute towards addressing several important and outstanding questions in environmental plastic pollution research. Specifically, we discuss the use of radiolabeled microplastics and/or chemicals for 1) determining sorption/desorption kinetics of a range of contaminants to different types of plastics under varying conditions, 2) understanding the influence of microplastics on contaminant and nutrient bioaccumulation in aquatic organisms, and 3) assessing biokinetics, biodistribution, trophic transfer and potential biological impacts of microplastic at realistic concentrations. Radiotracer techniques are uniquely suited for this research because of their sensitivity, accuracy and capacity to measure relevant parameters over time. Obtaining precise and timely information on the fate of plastic particles and co-contaminants in wildlife has widespread applications towards effective monitoring programmes and environmental management strategies.

1. Introduction

The global proliferation of plastic pollution over the last 60 years, and awareness of its magnitude, has triggered broad public and scientific concern regarding its potential threat to wildlife (Borrelle et al., 2017; Eriksen et al., 2014) and humans through seafood consumption (Barboza et al., 2018; Rochman et al., 2015; Seltenrich, 2015). Research programmes across the world have consequently been directed at understanding and characterising the risks of plastic pollution in freshwater and marine systems (e.g., GESAMP, 2015; NOAA, 2008; UNEP, 2016). In these studies, the visible impacts of macroplastics (> 250 mm) described are clear (e.g., entanglement, ingestion), but consequences associated with smaller nano- and micro-sized plastics (< 5 mm) are much less obvious. This has led to some controversy on the relative importance of small plastic particles to cause effects in wildlife at environmental concentrations, and a push for improved ecotoxicity research to achieve accurate and reliable risk assessments (Burton, 2017; Connors et al., 2017; Hale, 2018; Koelmans et al., 2017; Kramm et al., 2018).

Recent models estimated that over 5.2 trillion micro-sized plastic particles (0.33–200 mm) weighing 66,140 tonnes are floating in the ocean (Eriksen et al., 2014). As a result, microplastics have been

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identified in many aquatic organisms, and linked to a range of biological effects (reviewed by Avio et al., 2017; Bouwmeester et al., 2015; Eerkes-Medrano et al., 2015; Ivar Do Sul and Costa, 2014; Wright et al., 2013a). Reported effects include reduced feeding (Besseling et al., 2013; Cole et al., 2015; Wright et al., 2013b), swimming activity (Chen et al., 2017; Gambardella et al., 2017) and assimilation efficiency (Blarer and Burkhardt-Holm, 2016), altered size (Au et al., 2015; Besseling et al., 2013; Redondo-Hasselerharm et al., 2018), impaired reproduction (Au et al., 2015; Sussarellu et al., 2016) and tissue damage (Lei et al., 2018). Several studies have also found that exposure to microplastic particles influenced the accumulation of co-contaminants (Avio et al., 2015; Besseling et al., 2013; Browne et al., 2013; Chua et al., 2014) and present a potential risk for trophic transfer of both plastics and associated contaminants (Au et al., 2017; Carbery et al., 2018; Chae et al., 2018; Farrell and Nelson, 2013; Setälä et al., 2014). Contrary to these studies, several others have found no apparent effects of plastics on a range of organisms (Bruck and Ford, 2018; Santana et al., 2018; Weber et al., 2018), which highlights the need to better understand the discrepancies between studies, including differences in species sensitivity and experimental design.

Despite reported impacts, uncertainties remain regarding the effects associated with nano- and microplastics under ecologically relevant conditions. This primarily stems from the difficulties associated with quantifying low concentrations of small particles and the challenges involved in characterising plastic polymers (Avio et al., 2017; Lenz et al., 2016; Rocha-Santos and Duarte, 2015; Silva et al., 2018). To date, the majority of environmental surveys have focused on particles between 0.3 and 5 mm (Eriksen et al., 2013; Kovač Viršek et al., 2016; Morét-Ferguson et al., 2010), and few studies have considered smaller sized particles because of the difficulties associated with sampling and sorting small particles (Conkle et al., 2018). Most commonly, plastic particles are quantified and characterised by visual assessment, as this is the simplest and cheapest method available (Hidalgo-Ruz et al., 2012). However, this method was found to commonly misidentify plastics for organic particles or vice versa, and consequently inaccurately estimate plastic concentrations when compared to spectroscopic identification (Lenz et al., 2015; Song et al., 2015). Because of these challenges and uncertainties, the majority of laboratory studies investigating the effects of microplastics have used concentrations several orders of magnitude higher than what is typically found in the environment, and likely overstate the effects of plastics under realistic conditions (Lenz et al., 2016).

Recent publications have challenged the initial overstatements of plastic effects reported due to experimental exposures of organisms to unrealistically high concentrations (Burton, 2017; Koelmans et al., 2017; Ogonowski et al., 2018). There is a general consensus in recent reviews that current research needs to better manage and understand the environmental impacts of microplastics (Au et al., 2017; Conkle et al., 2018; Connors et al., 2017; Duis and Coors, 2016; Wagner et al., 2014). Suggested improvements include: (1) establishing standardised methods for sampling, quantifying and characterising nano- and microplastics, (2) increasing environmental relevance in laboratory testing by considering realistic plastic particle concentrations, a range of plastic types and sizes, as well as the influence of weathering, biofouling, and abiotic factors to the plastic behaviour, (3) determining the potential role of plastic particles as vectors of contaminants and the risks associated with metals and trace organic compounds sorbed to them, as well as (4) determining the biological effects of plastic particles at different levels of biological organisation. Considering the methodological challenges and remaining uncertainties surrounding the environmental effects of microplastic and nanoplastic pollution, it seems clear that new technical approaches are required to advance this area of research. In this perspective article, we aim at highlighting the benefits of radiotracer techniques, and describing how these tools can contribute towards advancing environmental plastic pollution research.

2. Future perspectives: applications of radiotracer techniques to environmental plastics studies

2.1. Radiotracer techniques

Radiotracer techniques consist of measuring the behaviour and fate of radionuclides or labeled compounds within a given system (reviewed by Kratz and Lieser, 2013). This can be achieved using several types of detectors, including scintillation counters, gas-filled detectors and semiconductor detectors that measure the radiation emitted by the tracers. The distribution of radiotracers within a sample can also be visualised using imaging techniques, including autoradiography, positron emission tomography (PET imaging) and single photon emission computed tomography (SPECT). As such, radiodetectors can be used to qualitatively or quantitatively measure tracers on both a spatial and/or temporal scale. These techniques are well recognised as being highly sensitive, accurate, and relatively rapid compared to other analytical methods, and therefore have a broad range of applications in several fields, including life sciences, chemistry and industrial research (Kratz and Lieser, 2013).

Another important advantage of radiotracing methods is the ability, in some cases, to monitor the fate of radiotracers *in vivo*, in a non-destructive manner. This can be done using *in vivo* gamma counting, which allows repeated non-invasive measurements of radioactivity to be measured in real time that can be used to determine uptake, assimilation and elimination kinetics in a range of organisms (Reinfelder et al., 1998a). Non-invasive imaging tools, such as PET and SPECT imaging, can also be used to monitor radiotracers in live organisms over time (Decristoforo et al., 2017). *In vivo* methods not only reduce the processing time but also reduce the biological variability and the number of organisms required compared to experiments where destructive sampling is required to obtain temporal data (e.g., mass spectrometry based analysis of contaminants extracted from tissue samples or whole animals) (Cresswell et al., 2017).

In ecological and ecotoxicity studies, radioactive isotopes of organic and inorganic chemicals are commonly used to assess the fate and transfer of trace elements and compounds between different environmental components (e.g., water, soil, biota), and to quantitatively assess rates of uptake and depuration, assimilation efficiencies, biological half-lives, routes of uptake and biodistribution of chemicals in biota (Cresswell et al., 2015; Danis et al., 2005; Lanctôt et al., 2017; Metian et al., 2009; Wang and Fisher, 1996). Radiotracers can also be used to study biochemical processes, for examples photosynthesis using $^{14}CO_2$ (Maleva et al., 2013; Prasad et al., 2011), calcification using ^{45}Ca (Houlbrèque et al., 2012; Malone and Dodd, 1967) and the metabolism of radiolabeled molecules (Sprankle et al., 1975; Thomas and White, 1989).

2.2. Application to environmental plastics research

Given their high sensitivity and broad applications, laboratory-based radiotracer techniques can provide critical new information on microplastic interactions and biological impacts within the aquatic environment. Specifically, these tools have the potential to help fill important knowledge gaps that include: 1) the sorption and desorption kinetics of trace pollutants to microplastics (Fig. 1a), 2) the evaluation of the biokinetics, biodistribution and potential biological impacts, and trophic transfer of small plastic particles in biota (Fig. 1b), and 3) the influence of microplastics on bioaccumulation and bioavailability of co-contaminants and essential elements to aquatic organisms (Fig. 1c). By efficiently contributing critical information about such fundamental questions, these tools can help address unresolved questions about the ability of microplastics to bioaccumulate (i.e., translocate across epithelial membranes and enter tissues or circulatory system), their role as vectors of chemical transfer, and subsequently, their potential to accumulate through food webs under typical relevant exposure