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Invited Commentary

Microplastics Are Not Important for the Cycling and Bioaccumulation of Organic Pollutants in the Oceans—but Should Microplastics Be Considered POPs Themselves?

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EDITOR'S NOTE:

This is 1 of 15 invited commentaries in the series "Current Understanding of Risks Posed by Microplastics in the Environment." Each peer-reviewed commentary reflects the views and knowledge of international experts in this field and, collectively, inform our current understanding of microplastics fate and effects in the aquatic environment.

ABSTRACT

The role of microplastic particles in the cycling and bioaccumulation of persistent organic pollutants (POPs) is discussed. Five common concepts, sometimes misconceptions, about the role of microplastics are reviewed. While there is ample evidence that microplastics accumulate high concentrations of POPs, this does not result in microplastics being important for the global dispersion of POPs. Similarly, there is scant evidence that microplastics are an important transfer vector of POPs into animals, but possibly for plastic additives (flame retardants). Last, listing microplastics as POPs could help reduce their environmental impact. *Integr Environ Assess Manag* 2017;13:460–465. © 2017 SETAC

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This commentary discusses the current evidence about current prevailing themes on the relationship between marine microplastics and organic pollutants. In this context, microplastics can be defined as particles less than 5 mm in size (Thompson et al. 2004). This plastic debris, mostly from anthropogenic land-based sources, fragments into smaller pieces over time (Jambeck et al. 2015).

DO MICROPLASTICS ACCUMULATE HIGH CONCENTRATIONS OF ORGANIC POLLUTANTS?

The current body of evidence suggests that microplastics accumulate high concentrations of organic pollutants, as microplastics act—as the specific affinity of a given organic pollutant for a polymer dictates its overall enrichment factor (partitioning constant) in the microplastic (Rusina et al. 2007). The specific affinity for various hydrophobic organic contaminants (HOCs) for polymers has been determined in numerous laboratory and field calibrations in which the partitioning constants between passive samplers and water or air were measured (Adams et al. 2007; Rusina et al. 2007; Smedes et al. 2009; Lohmann 2012; Pintado-Herrera et al. 2016; Ziccardi et al. 2016). The polymers most commonly used as passive samplers in field experiments include polyethylene (PE), silicone rubber (SR), and polyoxymethylene (POM) sheets.

There is plenty of field evidence showing that generic plastic debris accumulates organic pollutants (Karapanagioti et al. 2011; Rochman, Hoh, Hentschel et al. 2013; Endo et al. 2013). A prominent example is the so-called "pellet watch" global monitoring program, which relies on plastic pellets collected by volunteers from across the globe (Hirai et al. 2011). In these studies, strong enrichment of HOCs in the polymers, often exceeding 10^6 times relative to their dissolved concentrations, was found.

HOW SIGNIFICANTLY WILL MICROPLASTICS CONTRIBUTE TO THE DISPERSION AND GLOBAL CYCLING OF PERSISTENT ORGANIC POLLUTANTS?

It has become common knowledge that microplastics are present around the globe and have been found in all ocean gyres, coastal seas, and beaches (Jambeck et al. 2015; van Sebille et al. 2015). It should therefore be no surprise that the concept of microplastics as being important for the global dispersion of organic pollutants, in particular persistent organic pollutants (POPs), a subgroup of persistent HOCs,

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has been suggested. Yet, numerous studies have refuted that idea (Zarfl and Matthies 2010; Gouin et al. 2011; Koelmans et al. 2016; Ziccardi et al. 2016). There is simply not enough microplastic and plastic debris present in the oceans to outcompete the partitioning of POPs to water and natural organic matter (such as phytoplankton). In the analysis by Koelman et al. (2016) of a strongly hydrophobic organic chemical (concentrated 10^7 times by microplastic from water), ocean water nonetheless contained 99% of the HOC, followed by dissolved organic carbon, DOC, and colloids (0.4% each); microplastics captured approximately 10^{-4}% of the total mass present in the oceans.

In addition, diffusion of HOCs in and out of microplastics is slow. The time for various dissolved PCBs to reach equilibrium with a 50 μm or 500 μm PE sheet ranges from days to decades (Lohmann and Muir 2010; Endo et al. 2013). Thus, the release of these contaminants from the microplastic present in the remote ocean will be strongly retarded (Endo et al. 2013; Bakir et al. 2014b) and only add a small contribution relative to already present POPs at any given place and time. Results by Zarfl and Matthies (2010) also implied that microplastics are not an efficient transport vector of HOCs in comparison to long range transport by ocean or atmosphere, except for very high log K_{ow} chemicals, which have otherwise limited transport potential in air and water.

Last, a comparison of microplastic particle density in the Pacific Ocean as detected by the Sea Education Association (SEA) (Kara Lavender Law, Sea Education Association, Woods Hole, Massachusetts, personal communication) and measured concentrations of PCBs in surface seawater in the region (Zhang and Lohmann 2010) revealed little correlation between both.

TO WHAT EXTENT DO MICROPLASTICS CONTRIBUTE TO THE BIOACCUMULATION AND FOOD WEB TRANSFER OF POPS?

There has been a long-standing assumption in many articles and studies that microplastics are efficient carriers of organic pollutants into biota and the food web (Teuten et al. 2009; Rochman, Hoh, Kurobe et al. 2013; Chua et al. 2014; Batel et al. 2016; Wardrop et al. 2016). Such arguments have been based on the notion that microplastics enrich various POPs (correct, see above), coupled with the assumption that inside an animal, these pollutants are stripped off or leach out of the microplastic and are consequently taken up by the organism (Teuten et al. 2007; Bakir et al. 2014a). It is worth recalling that chemicals diffuse to achieve the same chemical activity in the environment, be that water, microplastic, or biota (Schwarzenbach et al. 2003). Just because microplastics display greater concentrations of POPs than present in water does not mean that there is a greater tendency for these pollutants to diffuse out of the plastic particles. The potential importance of microplastics as carriers of POPs into animals remains a strong theme in discussion on microplastics. Although, seemingly corroborated by empirical evidence (Teuten et al. 2009), it requires deeper examination. This will be addressed in more detail below using the 3 scenarios outlined in Figure 1, in which a) a naturally contaminated fish ingests a naturally contaminated microplastic (e.g., both collected in the wild), b) a clean fish consumes a contaminated microplastic particle (e.g., in laboratory experiments), and c) a reverse set-up, where a contaminated fish consumes a pollutant-free microplastic particle. Examples from the literature supporting these different scenarios are listed in Table 1. At a very basic level, equilibrium partitioning can be used to define simple expectations on how organic pollutants will move in a bioaccumulation experiment.

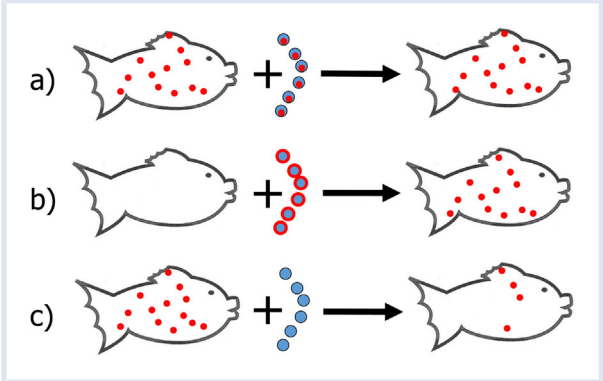

Figure 1. Three different hypothetical bioaccumulation experiments with fish, microplastics (blue circles), and organic contaminants (red).

Scenario A

As outlined in scenario A (Figure 1), a fish ingests pieces of microplastic 'naturally' containing POPs already, simply from occurring in the environment. The presence of POPs in the fish, and a microplastic residing in the same environment, are driven by the contaminants' chemical activity and ought to be the same in both fish and microplastic particles. The ingestion of the microplastic by the fish does not change the contaminant burden by the fish or the microplastic, as they are both already in equilibrium (Gouin et al. 2011). This should be the most prevalent interaction of biota, microplastics, and POPs in the natural environment, as animals are constantly taking up POPs from the environment via their diet and respiration. There are neither clean (i.e., POPs-free) oceans nor animals present, which means that they will bioaccumulate POPs regardless of whether they ingest microplastics or not.

In the South Atlantic Ocean, there was generally no correlation between HOCs in microplastics and amphipods (Rochman et al. 2014). Of the targeted HOCs (bisphenol A [BPA], alkylphenols, alkylphenol ethoxylates, PCBs, and polybrominated diphenyl ethers [PBDEs]), only PBDEs displayed increased body burdens in regions where more microplastics were present. The presence of PBDEs in tissues could be due to the presence of small microplastic particles during the extraction (see below). Another good example of scenario a is a recent study in which birds and the microplastics in their gut were analyzed for PCBs (Herzke et al. 2016). The authors concluded that the presence of PCBs in the fulmars due to the ingestion of plastics was negligible relative to the uptake of PCBs via their prey.

Table 1. Bioaccumulation studies involving microplastics and HOCs

Studied biota	Targeted HOCs	Effect on HOC concentration in biota	Reference
Scenario A: Clean biota and contaminated microplastic			
Streaked shearwater (*Calonectris leucomelas*)	PCBs	PCBs from microplastics were outcompeted by PCBs from natural diet in chicks	Teuten et al. 2009
Lugworm (*Arenicola marina*)	PAHs, PBDEs, triclosan, nonylphenyl	Increased HOCs in lugworms exposed to spiked plastic particles (5% wet wt) in sediment	Teuten et al. 2009
Lugworm (*A. marina*)	PCBs	Increased PCB at lowest polystyrene dose of 0.074% by 1.1−1.5 times	Besseling et al. 2013
Japanese medeka (*Oryzias latipes*)	PAHs, PCBs, PBDEs	Increase in PBDEs, PCB 28, and chrysene in fish fed field-contaminated microplastics	Rochman et al. 2013
Zebrafish (*Danio rerio*)	Benzo[*a*]pyrene	Evidence of transfer of Benzo(*a*)pyrene into zebrafish from microplastic	Batel et al. 2016
Amphipods (*Allorchestes compressa*)	PBDEs	Microplastic exposure decreased PBDEs in exposed amphipods	Chua et al. 2014
Scenario B: Field-contaminated animals and field-contaminated microplastic			
Mussel (*Mytilus galloprovincialis*)	HBCD	Increase in HBCD observed in mussels with Styrofoam	Jang et al. 2016
Northern fulmar (*Fulmarus glacialis*)	PCBs	No evidence for PCB uptake from microplastic	Herzke et al. 2016
Short-tailed shearwaters (*Puffinus tenuirostris*)	PBDEs	PBDEs 183 and 209 present in 3 birds, but not their prey	Tanaka et al. 2013
Myctophids	Bisphenol A, alkylphenols, alkylphenol ethoxylates, PCBs, PBDEs	No correlation between HOCs in fish and microplastic abundance, except for BDEs 183–209	Rochman et al. 2014
Scenario C: Contaminated animal and clean microplastic			
Rainbow trout (*Oncorhynchus mykiss*)	PCBs	No decrease of PCB observed	Rummel et al. 2016

PAHs = polycyclic aromatic hydrocarbons; PBDEs = polybrominated diphenlyethers; PCBs = polychlorinated biphenyls; HBCD = hexabromocyclododecane; HOCs = hydrophobic organic contaminants.

Similar conclusions were reached earlier by Gouin et al. (2011) based on theoretical considerations derived from a bioaccumulation food web model. Last, Koelmans et al. (2016) also concluded that there is no experimental or theoretical evidence for an important role of microplastics in the transfer of POPs into animals.

Scenario B

This scenario consists of exposing clean animals from a reference site to microplastics containing a high concentration of POPs, either from laboratory dosing or from microplastics exposed to contaminants at urban and/or industrialized sites. Most reported bioaccumulation studies with microplastics are based on this scenario, such as the ingestion of PBDE-spiked particles by amphipods in the laboratory (Chua et al. 2014). Interestingly, the experiment actually resulted in decreased PBDE bioaccumulation uptake relative to control animals. Other experiments used field-contaminated microplastic particles. For example, Teuten et al. (2009) described the feeding of microplastics—naturally contaminated by PCBs from Tokyo Bay—to shearwater chicks hidden in a fish diet. Initially, some uptake of lower chlorinated PCBs was observed, but the PCBs ingested from the birds' prey fish outweighed the birds' body burden over time (Teuten et al. 2009).

In general, an efficient transfer of POPs from the microplastic to the animals is observed. This is due to the experimental design and shows that microplastic can be used as a vector for POPs into animals. It does not demonstrate, however, that this pathway is relevant in the

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Table 2. Criteria for inclusion of compounds to the Stockholm Convention on POPs

Categories	Criteria	Evidence for microplastic	Examples
Persistence	$t_{1/2}$ (H_2O) >2 mo, $t_{1/2}$ (soil or sediment) >6 mo	Long half-life of e.g., PET	Ioakeimidis et al. 2016
Bioaccumulation	BCF >5000, log K_{ow} >5 or high bioaccumulation in species	Transfer in food chain and predators	Batel et al. 2016
Long-range transport	Measurable levels of concern, LRT data, or properties	Presence in remote ocean locations	Eriksen et al. 2014
Adverse effects	Evidence of adverse effects, toxicity, or ecotoxicological data	Histological changes in cells in blue mussels; decrease in fecundity in marine copepods	von Moos et al. 2012; Lee et al. 2013

BCF = bioconcentration factor; LRT = long range transport; PET = polyethylene terephthalate; POPs = persistent organic pollutants.

field. As noted above, animals in the wild are typically as "contaminated" with respect to POPs as the microplastic particles they might consume. The conclusion that microplastics is not an important transfer process was also reached in a study in which lugworms were exposed to sediments enriched with field-contaminated polystyrene particles (Besseling et al. 2013). The observed increase in PCB bioaccumulation (1.1–1.5 times relative to controls) was only observed at low concentrations of polystyrene particles.

Scenario C

This scenario is the reverse of scenario B in which a POP-contaminated fish is fed clean microplastic particles to determine if this will lower its body burden with respect to the POP. The idea is based on research that olestra, a nondigestible fat, can be used to remove POPs from contaminated animals (Moser and McLachlan 1999). Gouin et al. (2011) included this concept in their bioaccumulation model, suggesting that the ingestion of clean microplastic could indeed cause a decreased body burden in animals. Recently, Rummel et al. (2016) did not observe a significant decrease in bioaccumulation of PCBs in rainbow trout made to ingest clean microplastics.

DO MICROPLASTICS TRANSFER OTHER ORGANIC CONTAMINANTS INTO BIOTA?

As discussed above, there is little evidence that microplastics play a major role in the bioaccumulation of POPs when compared to the role of diet in nature. As already discussed by Teuten et al. (2009) and Gouin et al. (2011), microplastics could become an important pathway for polymer additives that otherwise would not be easily transferred into the marine environment. In particular, Teuten et al. (2009) suggested research should focus on the release of phenolic additive-derived chemicals (i.e., alkylphenols and BPA) from microplastics in the food web. Yet neither a modeling study by Koelmans et al. (2014) nor the field study by Rochman et al. (2014) found evidence that the ingestion of microplastics is relevant for the uptake of these compounds by biota.

Several recent studies highlighted that certain chemicals, likely originating from plastic particles, can indeed be transferred into animals. The presence of highly brominated BDEs 183 and 209 in seabirds was linked to their ingestion of marine plastics (Tanaka et al. 2013). The birds' prey items had no detectable BDE 183 and 209 concentrations, but these contaminants were observed in both the birds and ingested plastic debris particles. Similarly, the presence of hexabromocyclododecanes (HBCDs) in Styrofoam and blue mussels from coastal South Korea were linked (Jang et al. 2016). Elevated concentrations and a α–γHBCD ratio closer to that of Styrofoam were detected in mussels colonizing Styrofoam buoys, when compared to mussels collected from other substrates and regions along the coast. Overall, strong evidence was presented for a direct pathway of HBCD from the Styrofoam buoy into the mussel, including the detection of Styrofoam particles in the mussels themselves.

Because there is good evidence that brominated compounds can be metabolized in animals (Stapleton et al. 2004), the presence of several low solubility brominated compounds (highly brominated BDEs, HBCD) in biota, linked to the ingestion of microplastics, seems surprising at first. Yet, it might actually indicate that these compounds are not properly dissolved in the animals, but rather part of nanoplastic particles dispersed within the animals' tissue and organs.

SHOULD MICROPLASTICS BE CONSIDERED POPS?

Although the preceding discussion highlighted that microplastics in the oceans do little to affect the presence and transfer of most organic pollutants at this point, there is still plenty of evidence that microplastics are harmful and their impact should be minimized, as far as possible. This be could be seen as a contribution toward a sustainable use of resources.

One approach would be to consider classifying microplastics as potential pollutants under the Stockholm Convention on POPs (UNEP 2001). Four criteria, namely persistence, bioaccumulation, long-range transport, and adverse effects (Table 2), must be met for a compound to be listed as a POP. There is strong evidence that microplastics are persistent, as a result of their industrial polymer properties and additives (Gewert et al. 2015), and that they undergo long-range transport, as documented by their widespread presence in remote oceans (Law et al. 2010; van Sebille et al. 2015). Several ecotoxicological studies highlight adverse effects,

although these experiments are often performed at unrealistically high doses of microplastic exposure. The classical concept of bioaccumulation and biomagnification on a molecular level is not met, but there is evidence that microplastics are present in top predators and are transferred up the food chain.

In summary, there is little evidence that marine microplastics affect the global transport or bioaccumulation of POPs in the oceans. In terms of bioaccumulation, experimental designs can be manipulated to show that microplastics are a vector of POPs into organisms in the laboratory. Yet, there is scant evidence from field studies that the ingestion of microplastics affects the bioaccumulation of POPs. Although there are some studies that show several low-solubility compounds increase in animals that have ingested more microplastic pieces, this might, in fact, be from the presence of micro- and nanoplastic particles in those animals. Just because microplastics are not relevant for the transport of POPs does not take away from their potential for detrimental impacts on the environment. A possibility to address these concerns could be to consider marine (micro)plastics as POPs and rely on the Stockholm Convention to reduce their sources.

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