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Effects of micro- and nanoplastics on aquatic ecosystems: Current research trends and perspectives

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ABSTRACT

Contamination by bulk plastics and plastic debris is currently the one of the most serious environmental problems in aquatic ecosystems. In particular, small-scale plastic debris such as microplastics and nanoplastics has become leading contributors to the pollution of marine and freshwater ecosystems. Studies are investigating the impacts of micro-and nanoplastics on aquatic organisms and ecosystems worldwide. This review covers 83 studies that investigated the distribution of microplastics and the ecotoxicity of micro- and nanoplastics in marine and freshwater ecosystems. The studies indicated that micro-sized plastics and plastic debris were distributed at various concentrations in aquatic ecosystems around the world. They had various effects on the growth, development, behavior, reproduction, and mortality of aquatic animals. We discuss these studies in detail and suggest directions for future research.

1. Introduction

Plastic pollution is one of the most serious environmental issues worldwide (Dunlap and Scarce, 1991; Mato et al., 2001; Gregory, 2009; Thompson et al., 2009; Rochman et al., 2013), and concerns about plastic pollution are increasing (Goldstein et al., 2013; Gross, 2013; Cózar et al., 2014). Microplastics are plastic particles measuring <5 mm in diameter, as defined by the U.S. National Oceanic and Atmospheric Administration in 2008 (Betts, 2008; Barnes et al., 2009), whereas nanoplastics are generally <100 μm in diameter) (Koelmans et al., 2015; Bergami et al., 2016). They are of concern because of their wide distribution (Cole et al., 2013; Klein et al., 2015) and the enormous variety of uses of plastics (Plastics Europe, 2014). Small bits of plastic debris can be ingested by aquatic organisms (Lee et al., 2013b; Kaposi et al., 2014; Cole and Galloway, 2015; Desforges et al., 2015), accumulating as they travel up the food chain (Cedervall et al., 2012; Rillig, 2012; Mattsson et al., 2014) and finally reaching humans (Bouwmeester et al., 2015). They can cause various adverse effects on organisms, including growth inhibition (Hämer et al., 2014; Au et al., 2015; Cole and Galloway, 2015; Sjollema et al., 2016; Sussarellu et al., 2016), behavioral disorders (Mattsson et al., 2014; Rehse et al., 2016), reproductive dysfunction (Lee et al., 2013b; Besseling et al., 2014; Sussarellu et al., 2016), feeding disorders (Hart, 1991; Wright et al., 2013; Hall et al., 2015; Nasser and Lynch, 2016; Green et al., 2016), reduced viability (Browne et al., 2008; Canesi et al., 2015), and even mortality (Casado et al., 2013; Lee et al., 2013b; Au et al., 2015; Nasser and Lynch, 2016).

Micro-sized plastics are found in marine and freshwater ecosystems worldwide, as shown in Fig. 1 and Table S1. Many of the studies included in this review were conducted in North America and Europe, while several studies were carried out in East Asia, Latin America, Africa, and Oceania. Fig. 1 shows the distribution of studies that measured plastic particles from the surface of the ocean (navy color), on the beach sand (brown color), in deep sea water (dark gray color), and in lake water (light blue color). Microplastic densities varied from 0 to 466,305 microplastics per km^2. Detailed values and sampling dates may be found in Table S1.

In this review article, we summarize 59 studies that examined the ecotoxicity of microplastics and nanoplastics to aquatic organisms, as well as describing the scopes and purposes of the studies. The studies were classified according to whether they examined 1) the sole effects of microplastics on organisms, 2) the complex effects of microplastics in association with other contaminants, 3) the intrinsic toxicities and the trophic transfer of nanoplastics, or 4) the differences in toxicity between microplastics and nanoplastics. The 59 studies include both marine (Fig. 2) and freshwater (Fig. 3) ecosystems. We conclude by suggesting directions for future studies and perspectives to guide them.

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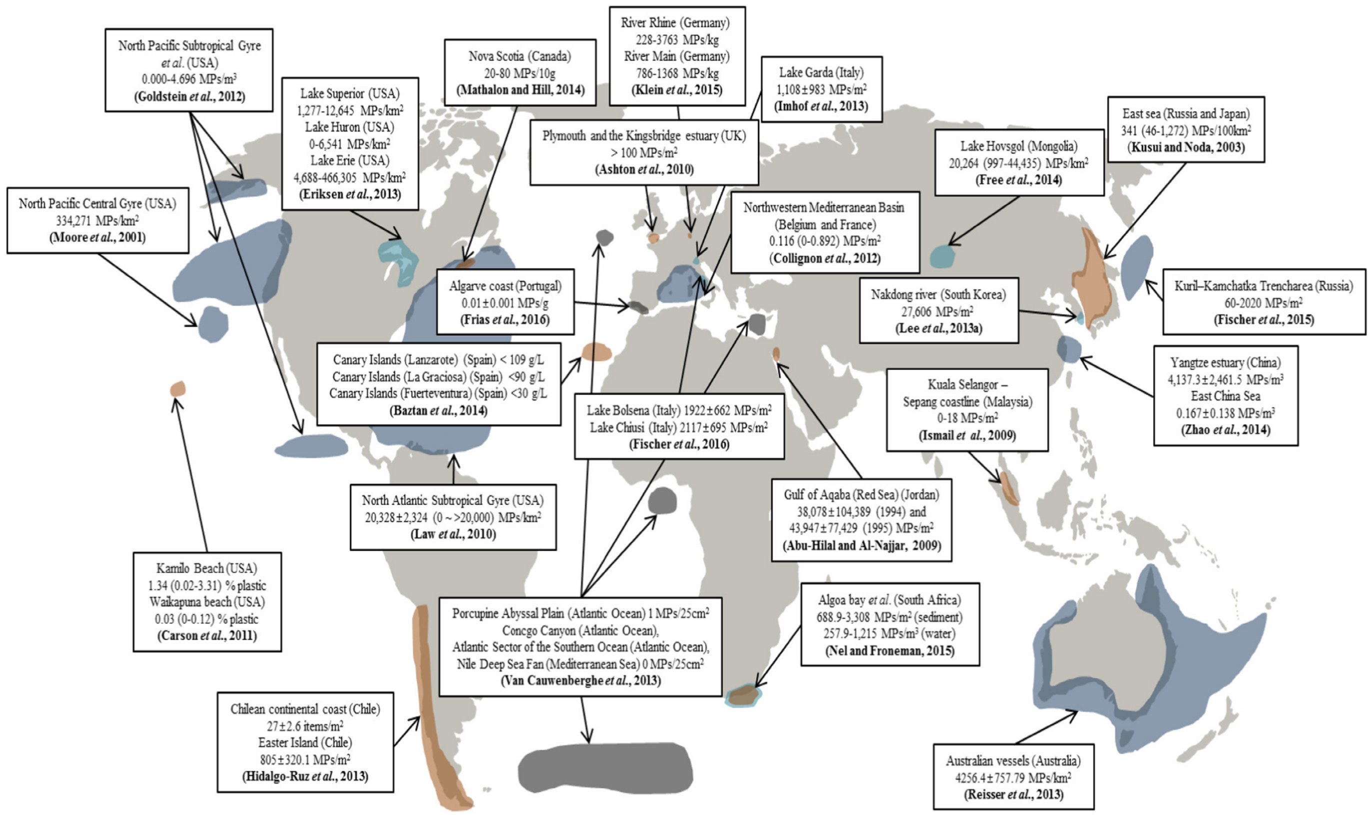

Fig. 1. Studies that measured the concentrations and distributions of micro-sized plastics in ocean surface water (navy), beach sand (brown), deep sea water (dark gray), and lake water (light blue) worldwide. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Effects of microplastics in aquatic environments

2.1. Intrinsic toxicity of micro-sized plastics

The toxic effects of micro-sized plastics have been studied and investigated since the late 1980s and early 1990s. Studies on the toxicities of several microplastics of varying sizes and characteristics and their lethal or sub-lethal effects have been assessed using aquatic organisms including algae, ciliates, invertebrates, crustaceans, and fish, as shown in Table S2. In two of the earliest studies, Hart (1991) assessed the effects of polystyrene (PS) divinylbenzene microspheres on the feeding, clearance rate, and ciliated band lengths of *Strongylocentrotus purpuratus*, *Strongylocentrotus droebachiensis*, *Stylasterias forreri*, *Ophiopholis aculeata*, and *Parastichopus californicus*, and Bolton and Havenhand (1998) analyzed the effects of two sizes (3 and 10 μm) of polymer (ficoll) on the feeding performance of *Galeolaria caespitosa* larvae.

This research was followed by several studies on the ecotoxicity of micro-sized plastics. Browne et al. (2008) analyzed the effects of fluorescent PS microspheres of various sizes on the uptake, translocation, and cell viability of *Mytilus edulis*, a model marine organism. The use of these fluorescent particles allowed visual analysis of microplastics. The study showed that smaller particles may accumulate more easily in organisms and that short-term exposure did not cause significant biological effects, although the authors suggested that long-term exposure studies and analysis of the effects of chronic exposure were necessary. Graham and Thompson (2009) used sea cucumbers (Echinodermata), including *Thyonella gemmata, Holothuria floridana, Holothuria grisea*, and *Cucumaria frondosa*, to investigate the ingestion of various types of plastic debris, including poly(vinyl) chloride (PVC) fragments, nylon fragments, and PVC pellets, collected from sediments during short-term (20–25 h) exposure. They reported that polychlorinated biphenyls (PCBs) attached to the surface of plastics could cause adverse effects and could transfer from the plastic consumers to their predators, including humans, through trophic chains.

Recently, more advanced studies using high-level analytical equipment and in-depth analysis have been conducted. Von Moos et al. (2012) analyzed various indicators of exposure to high-density polyethylene (HDPE) particles in *M. edulis*, including condition index, uptake, lysosomal membrane stability, lipofuscin, neutral lipids, and histological diagnosis. Despite the relatively short-term exposure (96 h), ingested microplastics (0–80 μm) caused significant adverse effects on the tissue and cells of *M. edulis*. Cole et al. (2013) exposed 14 marine species to fluorescently labeled PS (7.3–30.6 μm) for 1 and 24 h and analyzed the uptake rate of microplastics by different species. They used coherent anti-Stokes Raman scattering (CARS) microscopy to observe the microplastics adhered to the surface of copepods. In another study, Wright et al. (2013) exposed *Arenicola marina* to 0% and 5% (*w*/w) and 0%, 0.5%, 1%, and 5% (*w*/w) of clean and chemically inert unplasticized polyvinylchloride (130 μm) in an acute test (48 h) and a chronic test (4 weeks), respectively. They investigated feeding activity, gut residence, and egestion in the acute test and feeding activity, immunity, and energy reserves in the chronic test. The data confirmed a decrease of the number of casts, the number of egestion events, and the total energy reserves after exposure to polyvinylchloride. The study proved that microplastics can cause physical effects on organisms in marine ecosystems and emphasized the need to reconsider how plastics are discarded.

In another study, Hämer et al. (2014) examined both acute (3 d) and chronic (6–7 weeks) exposure to three different fluorescent plastics (10 μm of dyed green aqueous fluorescent PS particles, 0–100 μm of blue fluorescent PS granules, and orange fluorescent polyacrylic wool plastic fibers) in the marine isopod *Idotea emarginata*. Hämer et al. fed