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MICROPLASTIC POLLUTION AND ITS ECOLOGICAL IMPACT ON FRESHWATER AND MARINE FAUNA

[*1]Zohra Farid, [2]Sidra Munir, [3]Sidra Naz, [4]Parwasha Mubarik, [5]Zakir Ullah, [6]Inayat Ullah

*[*1]Master of Zoology, PMAS Arid agriculture university Rawalpindi*
[2]BS Zoology, University of The Punjab Lahore
[3]Master Zoology, PMAS Arid Agriculture University Rawalpindi
[4]Master of Biology, PMAS Arid Agriculture University Rawalpindi
[5]Master Zoology, Islamia College, Peshawar
[6]Master Plant Biodiversity, University of Peshawar

[*1]zohra.farid1122@gmail.com, [2]sidramunir609@gmail.com, [3]Snaz88461@gmail.com, [4]mubarikparwasha@gmail.com, [5]zullah660@gamil.com, [6]inayatkohli18@gmail.com

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Corresponding Author:
Zohra Farid
zohra.farid1122@gmail.com

Abstract

Microplastic contamination is one of the most important environmental issues affecting freshwater and marine areas globally today. Because of the ever-increasing global production of plastic and its environmental durability, microplastics are found in rivers, lakes, estuaries, seas and deep-sea sediments. These particles typically are defined as plastic fragments smaller than 5 mm and derive from primary sources including synthetic fibers and cosmetic microbeads and secondary sources such as the disintegration of larger plastic waste. Microplastics are a serious threat to aquatic biodiversity and environmental health due to their small size, persistence and affinity to absorb toxic compounds. This review aims to provide an overview of the current understanding of the sources, distribution, ecological effects and mechanisms of action of microplastic pollution in freshwater and marine species and to identify major research gaps and future directions. A systematic literature research process was applied to produce a comprehensive and lucid synthesis of the available material. Peer-reviewed research published between 2004 and 2024 was searched in major scientific databases using preset search strategies and inclusion criteria. Pertinent data were collected and analyzed using thematic narrative synthesis, and the methodological quality of the included literature was appraised. These findings demonstrate the ubiquity of microplastics in the aquatic environment and the ingestion of microplastics by various trophic levels of organisms including fish, seabirds, zooplankton, benthic invertebrates and marine mammals. Exposure to microplastics has been associated with a number of deleterious biological effects including reduced feeding efficiency, oxidative stress, inflammatory responses, immunological impairment, alterations in behavior, reduced reproduction and tissue damage . Heavy metals and persistent organic pollutants can also transport and bioaccumulate microplastics throughout the aquatic food web. Moreover, the evidence of trophic transfer suggests that higher-level consumers are more likely to be exposed to microplastics, raising ecological problems in freshwater and marine ecosystems.

Despite the fast growing research, there are still significant hurdles because of the lack of freshwater habitats compared to marine ecosystems, unreliable sampling techniques and lack of long-term ecological studies.The analysis concludes by underscoring that microplastic contamination is a complex and growing ecological problem that deserves cooperation between research, government, and regulation. Future research needs to focus on standardized monitoring procedures, ecologically relevant exposure assessments, long-term ecological studies and integrated approaches to reduce plastic inputs and protect aquatic biodiversity. Interdisciplinary collaboration and evidence-based policymaking will be crucial for ensuring the sustainability of freshwater and marine ecosystems, as well as for alleviating the long-term environmental consequences of microplastic pollution.

Keywords: Microplastics; Freshwater pollution; Marine pollution; Trophic transfer; Aquatic fauna; Ecotoxicology; Plastic ingestion; Bioaccumulation.

Introduction

Plastics are among the most ubiquitous materials in the modern world, with global production rising from 311 million tonnes in 2014 to a projected 1,800 million tonnes by 2050 (Gallo et al., 2018). Their versatility, low cost and resistance to degradation have made them ubiquitous in nearly every sector of the global economy, but these same properties have also made plastics one of the most persistent and pervasive pollutants of the twenty-first century. As plastic debris accumulates in the environment, it is gradually degraded into smaller pieces by ultraviolet radiation, mechanical abrasion, and weathering, leading to what are now broadly referred to as "microplastics," or plastic particles <5 mm in their greatest dimension (Cauwenberghe et al., 2015). The term was first introduced by Thompson et al. in 2004 to define plastic debris of 20 µm size range, but was later extended to the current 5 mm cutoff in 2009 (Cauwenberghe et al., 2015).

Microplastics are usually classified into two groups based on their source. Primary microplastics are produced at microscopic sizes to be used in products such as cosmetic microbeads, industrial abrasives and synthetic textile fibres; indeed, a single synthetic garment can release up to 1,900 fibres per washing cycle (Cauwenberghe et al., 2015). Secondary microplastics are produced by the breakdown of larger plastic items in the environment. It is estimated that the European Union alone releases approximately 75,000–300,000 tons of microplastics per year from the breakdown of plastics (Kannan & Vimalkumar, 2021), and it has been predicted that the amount of microplastics in some oceanic sections will double by 2030 (Hale et al., 2020). The total volumes are huge, with an estimated 4.8–12.7 million metric tonnes of plastic waste entering the ocean in 2010 (Jambeck et al., 2015) and the input of plastics to the ocean predicted to increase 2.6-fold by 2040 in a business as usual scenario (Wayman & Niemann, 2021).

The ecological consequences of this contamination are serious and far-reaching. Microplastics are now found in aquatic environments including all five major ocean gyre surface waters, polar regions, deep-sea sediments, and lakes and rivers (Gallo et al., 2018). Their size is comparable to the prey of many filter feeders, detritivores and predators, and they are readily eaten by a wide range of organisms, including zooplankton and benthic invertebrates, fish, seabirds and marine mammals (Cole et al., 2013; Horton et al., 2017). Laboratory studies have demonstrated that microplastic exposure can result in feeding suppression, lower energy reserves, changes in behaviour, oxidative stress, immune dysregulation and reproductive impairment in species such as the blue mussel, the lugworm, and various freshwater and marine fish (Ghosh, 2024; Subaramaniyam et al., 2023; Wagner et al., 2014). In particular, particles smaller than 10 µm may translocate from the gut into surrounding tissues as demonstrated in M. edulis where they can elicit inflammatory responses and histological change (Hasegawa & Nakaoka, 2021; Wagner et al., 2014). Feeding Antarctic krill has also been shown to fragment microplastics into even smaller particles, which may increase the hazards experienced by their predators (Hasegawa & Nakaoka, 2021).

Microplastics are not just inert physical contaminants. Microplastics have high surface area-to-volume ratio and can sorb and concentrate hydrophobic pollutants including persistent organic pollutants, polycyclic aromatic hydrocarbons and heavy metals which can be desorbed in the guts of the ingesting organisms leading to bioaccumulation of contaminants along food webs (Duis & Coors, 2016; McNeish et al., 2018). Trophic transfer has been documented in several experimental systems, including the transfer of polystyrene microspheres from mussels to shore crabs and from mysids to fish, where ingestion through prey was shown to far exceed direct uptake from the water column (Duis & Coors, 2016; Hasegawa & Nakaoka, 2021). These results highlight that microplastic pollution is not only a question of physical contamination but also a vector for chemical exposure, with consequences that propagate across trophic levels.

Despite the rapidly growing body of literature, there are still important disparities. A review of 440 marine and 106 freshwater studies revealed that 40.5% of marine research examined plastic–biota interactions, while only 33% of freshwater studies did the same (Blettler et al., 2018), and other analyses suggest that as little as 13% of all microplastic research focuses on freshwater systems (Jaikumar et al., 2022). This knowledge gap is important since freshwater environments are important pathways of plastic transfer from land to the ocean and freshwater fauna occupy important positions in aquatic food webs . Despite the rapid increase in the number of publications on microplastic ecotoxicology during the last decade, from one paper each in 2014 and 2015 to 145 papers in 2020 alone (Osman et al., 2023), there is no universally agreed definition for the lower size limit of microplastics, no standardized sampling or analytical protocol, and insufficient empirical data to understand fully long-term ecological consequences at the population, community, and ecosystem levels.

This review makes an effort to summarize the current state of knowledge on microplastic pollution in freshwater and marine environments, with a focus on its ecological effects on aquatic fauna. Specifically, the paper (i) describes sources, distribution and characteristics of microplastics in aquatic systems; (ii) reviews reported biological and ecological impacts on freshwater and marine fauna at different trophic levels; (iii) discusses mechanisms of toxicity, including the role of microplastics as vectors for contaminant transfer; and (iv) highlights important knowledge gaps and priorities for future research and management. This review, integrating recent findings, aims to be a comprehensive resource for ecotoxicologists, conservation biologists, and policy makers aiming to understand and mitigate one of the defining pollution challenges of our time.

Literature Review

Definition, Origin and Global Context of Microplastic Pollution

Microplastics are defined operationally as plastic particles smaller than 5 mm in their longest dimension, a size range that overlaps with the prey of many aquatic organisms and therefore raises particular ecological concern (Cauwenberghe et al., 2015). In this definition two sub categories are distinguished: small microplastics (SMPs, <1 mm) and large microplastics (LMPs, 1–5 mm)(Cauwenberghe et al., 2015). The term itself was first used in the peer-reviewed literature in 2004 when Thompson et al. identified µm-sized plastic debris in subtidal, estuarine and sandy sediments across multiple UK sites, rapidly followed by reports from Singapore, India and Sweden that demonstrated the global nature of the distribution (Cauwenberghe et al., 2015). Polymers degrade very slowly by photo-oxidation in combination with microbial degradation, which means plastic debris persists in the marine environment. Plastic debris was thought to persist for centuries to millennia, but the combined action of these processes can greatly reduce this lifetime of plastic marine debris (Wayman & Niemann, 2021). The problem's extent is defined by the global production of synthetic polymers from 1.5 million tonnes in the 1950s to an estimated 359 million tonnes per year (Hasegawa & Nakaoka, 2021; Osman et al., 2023). Plastics represent more than 75% of marine waste materials by count due to their rigidity and non-biodegradable nature, and the Mediterranean Sea is one of the most polluted water bodies, receiving inputs from countries such as Turkey, Spain, Italy, Egypt and France (Osman et al., 2023).

Sources of Primary and Secondary Microplastics

Microplastics are conventionally classified as primary and secondary, based on their source. Primary microplastics are deliberately produced to be microscopic in size and they are used in cosmetics, exfoliating cleansers, facial scrubs, medicines, detergents, paints, and personal-care products (Duis & Coors, 2016; Osman et al., 2023). Secondary microplastics, on the other hand, are formed unintentionally from the weathering, fragmentation and degradation of larger plastic items such as packaging, bottles, fishing gear and synthetic textiles (Osman et al., 2023). Based on quantitative estimates, the abrasion and fragmentation of larger plastic items is likely to be a more important source of the environmental microplastic load than primary microplastics originating from personal care products (Duis & Coors, 2016).

Fibres, fragments, granules, films and styrofoam particles are the most common particle types found in aquatic habitats, while polyethylene, polypropylene and polystyrene are the most common polymers (Duis & Coors, 2016). Once released, plastic material can be transported by wind, washed from land to surface waters during rainfall and stormwater run-off, or carried by large rivers towards the ocean. It has been estimated that between 70 % and 80 % of marine plastics reach the sea via riverine conduits (Horton et al., 2017). Microplastic loads in water bodies are mainly contributed by land-based sources (urban litter, sewage sludge, tyre wear, construction materials and personal-care products) accounting for about 80–90 %, while ocean-based sources, such as abandoned fishing gear and maritime activities, make up the remaining 10–20 % (Osman et al., 2023).

Distribution in Marine and Freshwater Environments

All major marine compartments now have microplastics recorded in them. Van Cauwenberghe et al. (2015) found that up to 2,000 particles m-2 have been observed in sediments at depths of 5,000 m in the deep ocean. Sampling bias has been shown by Cole et al. (2013) where concentrations were 100,000 times higher in an 80 µm mesh compared to a 450 µm mesh in Swedish coastal waters, with a maximum recorded concentration of 102,000 microplastics m^{-3} near a polyethylene production facility (Cole et al., 2013). These results suggest that historical surveys with larger mesh sizes may have severely underestimated microplastic loads in the water column.

Microplastics are also present in freshwater systems such as rivers, lakes, estuaries and wetlands (Horton et al., 2017). The average abundances in the neuston in the Laurentian Great Lakes were found to be 43,000 items km -2, with hotspots near metropolitan areas (Wagner et al., 2014). Wagner et al. (2014) found that Lake Huron's shorelines contained 0–34 plastic fragments m^{-2}, while sediments in Lake Erie and Lake St. Clair contained 0.2–8 items m^{-2}. However, despite these observations, the literature on freshwater remains disproportionately small, with a comprehensive bibliometric analysis showing that 87 % of the papers on plastic pollution are related to marine environments and only 13 % to freshwater, with annual growth rates of publications of about 41 papers year-1 for marine vs only 7 papers year-1 for freshwater (Blettler et al., 2018). In fact, the freshwater microplastic literature is so limited that a number of authors conclude that "data on MP uptake by freshwater invertebrates and fish is very limited" at the time of their review (Wagner et al., 2014).

Ingestion by Aquatic Fauna

Within aquatic systems, microplastics are ingested by organisms ranging from protozoans to marine mammals, with particle size, shape, density and colour being the main factors controlling particle uptake (Duis & Coors, 2016). Pelagic filter feeders preferentially feed on low-density (buoyant) microplastics, whereas high-density particles sink to the sediments and are ingested by benthic deposit feeders (Duis & Coors, 2016).

The smallest creatures in the web of water food, zooplankton, are especially at risk. Cole et al. (2013) showed that 13 out of 15 zooplankton taxa from the NE Atlantic were able to ingest polystyrene spheres in the size range 7.3–30.6 μm, including copepods, bivalve larvae and decapod larvae, and verified the uptake of 1.7 μm and 3.8 μm particles with coherent anti-Stokes Raman scattering microscopy by Temora longicornis . In copepods, microplastic beads were generally ingested by filter feeding and egested within hours in faecal pellets, although in the absence of food some Calanus helgolandicus individuals retained microplastics in their intestinal tracts for as long as seven days (Cole et al., 2013). Very small microplastics (0.4–3.8 μm) were observed to accumulate between the filamental hairs of the antennules, furca and swimming legs, with potential consequences for locomotion, mechanoreception and predator avoidance (Cole et al., 2013). Daphnia magna water fleas have likewise been found to ingest microplastics (0.02 and 1 mm) rapidly and particles can cross the gut epithelium and accumulate in lipid storage droplets (Wagner et al., 2014). In freshwater fish, microplastics have been found in 12 % of digestive tracts of gudgeon caught in 11 French streams, whereas all other freshwater invertebrates, including annelids, amphipods, ostracods and gastropods, have been documented to ingest microplastics in laboratory studies (Wagner et al., 2014).

In a study of three tributaries of Lake Michigan, McNeish and colleagues categorized fish into functional feeding groups and found that microplastic abundance in fish was positively related to trophic fraction ($r^2 = 0.050$, $P = 0.032$), despite no correlation between microplastic concentrations in fish and surface waters (McNeish et al., 2018). Invasive round goby had the highest concentrations of microplastics in its digestive tissues (~20 particles fish^{-1}) and a positive correlation between microplastic load and body length ($r^2 = 0.393$, $P = 0.010$), indicating bioaccumulation with age (McNeish et al., 2018).

Biological, Cellular and Physiological Effects

Microplastics exposure causes a variety of organism-level effects in aquatic animals. Cole et al. (2013) showed that exposure to 7.3 µm polystyrene beads at ≥4,000 mL-1 significantly reduced the algal ingestion rate of Centropages typicus in a dose dependent, logarithmic relationship ($R^2 = 0.70$, $P \leq 0.05$) with saturation observed above 5,000 beads mL-1. Such reductions in feeding can have serious consequences, particularly for species with limited lipid reserves such as Centropages and Acartia, leading to reduced fecundity, suppressed growth or increased mortality (Cole et al., 2013).

In fish, microplastics are usually detected in the liver, kidney, gills and gut, and they provoke oxidative stress by disturbing the balance between reactive oxygen species and antioxidant defenses (Subaramaniyam et al., 2023). Subaramaniyam et al. (2023) showed that microplastics exposure in zebrafish led to an increase in pro-inflammatory cytokines, TNF-α, IFN-γ, IL-2, IL-6, IL-8 and IL-1β, while anti-inflammatory factors, IL-4 and IL-10 decreased significantly; the NF-κB pathway involved in this process led to oxidative stress, apoptosis and NLRP3 inflammasome activation. Coexposures with heavy metals such as copper further aggravated oxidative stress and lipid peroxidation by inhibition of the activities of catalase and glutathione peroxidase (Subaramaniyam et al., 2023). Microplastics have been shown to induce ROS generation, DNA damage, mitochondrial dysfunction, behavioural changes (e.g. feeding and swimming) and histological changes in the gill and hepatic tissues in different fish species studied (Subaramaniyam et al., 2023).

In waterborne exposures, the minimum concentrations of microplastics that caused adverse effects on marine organisms were about 104 times higher than the maximum concentrations found in marine waters. In sediment-living lugworms, however, effective concentrations were higher than the average concentrations in subtidal sediments, but within the upper range of values reported in beach sediments (Duis & Coors, 2016). A meta-synthesis of the microplastic research from 2014–2020 indicates that the publication output in this area has increased from just one paper in 2014 and one in 2015 to 145 papers on remediation alone in 2020, reflecting the rapidly growing interest in the biological effects of these contaminants (Osman et al., 2023).

Trophic Transfer and Microplastics as Vectors for Contaminants

Organisms can ingest microplastics directly from the water column, but these particles can also be transferred through the food web, and several studies have now shown that trophic transfer can exceed direct ingestion. Hasegawa and Nakaoka (2021) studied a mysid–fish prey–predator system in northern Japan and found fish consumed 8–11 times more polyethylene beads in number and 3–5 times more in mass when exposed via prey compared to exposure via the water column only. Importantly, a large proportion of the beads consumed by mysids were fragmented (34 % after correcting for procedural blanks), and the median size of the fragments recovered from fish that had consumed exposed mysids was 6.61 µm, well below the 10 µm threshold at which particles are known to translocate from the gut lumen to other tissues such as the circulatory system (Hasegawa & Nakaoka, 2021; Wagner et al., 2014). McNeish et al. (2018) cite an earlier trophic-transfer study, which demonstrated that mussels could transfer microplastics to shore crabs, with concentrations of microplastics reaching up to 163,111 particles mL−1 of haemolymph (equivalent to 0.24 % of the load retained in mussels). Trophic transfer between meso- and macrozooplankton has also been observed (Wagner et al., 2014).

Smaller plastic fragments are more likely to sorb hydrophobic compounds, including persistent organic pollutants and polycyclic aromatic hydrocarbons . The sorbed chemicals may be in equilibrium with surrounding seawater at low risk but toxicity may become relevant under specific exposure conditions (Wayman & Niemann, 2021). In zooplankton, plastics in faecal pellets may be excreted and become buoyant again, or sink to the seafloor, changing the vertical flux of organic material and the dynamics of carbon sequestration (Wayman & Niemann, 2021).

Synthesis: A Persistent and Under-studied Contaminant

The weight of evidence is now that microplastics are ubiquitous in marine and freshwater systems , that they are ingested at multiple trophic levels and cause a range of cellular and physiological insults from oxidative stress to reproductive impairment and that they can be transferred through food webs in forms small enough to translocate into tissues . But important gaps remain: freshwater microplastic pollution publication output lags the marine field by a factor of about five (Blettler et al., 2018), standard operating procedures for sampling are still lacking (Horton et al., 2017), and empirical data on chronic, environmentally realistic exposures are sparse (Wagner et al., 2014). Addressing these limitations is necessary to predict the long-term ecological consequences of microplastic contamination on freshwater and marine fauna.

Methodology

Research Design

This study adopted a systematic literature review approach to synthesise the current state of knowledge on microplastic pollution and its ecological impacts on freshwater and marine fauna. Although no original empirical experiments were performed, the structured protocol was designed to minimise the risk of selection bias, enhance reproducibility and provide a transparent audit trail of the evidence underpinning every claim in the review. The methodology adhered in principle to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, an approach that has been adopted by several recent syntheses of the microplastic-pollution literature (Horton et al., 2017; Wagner et al., 2014).

Literature Search Strategy

A structured search of the peer-reviewed English-language literature was undertaken across three principal bibliographic databases: Scopus, Web of Science (core collection) and PubMed. To capture grey literature and recent preprints that may not yet have been indexed in subscription databases, supplementary searches were performed in Google Scholar and ResearchGate. References were also located through hand-searching the reference lists of key authoritative reviews identified in the early stages of the search (Blettler et al., 2018; Horton et al., 2017; Wagner et al., 2014) . The search was restricted to publications released between January 2004, the year in which microplastics were first formally discussed in the scientific literature, and December 2024, ensuring full coverage of the field's emergence and subsequent expansion (Cauwenberghe et al., 2015).

Search Terms and Boolean Combinations

Search strings were built using controlled vocabulary and free-text keywords organized in four thematic blocks linked by the Boolean operators "AND" and "OR". The first block contained the pollutant ("microplastic*" OR "micro-plastic*" OR "plastic debris" OR "plastic fragment*" OR "microbead*" OR "nanoplastic*"). The second one identified the environmental compartment ("freshwater" OR "river*" OR "lake*" OR "stream*" OR "marine" OR "ocean*" OR "sea*" OR "estuar*" OR "coastal" OR "sediment*" OR "water column"). The third specified the biological recipients ("fauna" OR "fauna" OR "biota" OR "zooplankton" OR "fish" OR "invertebrate*" OR "benthos" OR "mussel" OR "crustacean*" OR "trophic" OR "food web"). The fourth one was related to the impact dimension ("ingestion" OR "uptake" OR "toxicity" OR "ecotoxicol*" OR "oxidative stress" OR "bioconcentration" OR "trophic transfer" OR "vector" OR "biomarker*"). Wildcard truncation and phrase search quotation marks were used consistently across databases.

Inclusion and Exclusion Criteria

Studies were eligible if they met all of the following criteria: (i) studied plastic particles <5 mm in their largest dimension, per the operational definition adopted in this field (Cauwenberghe et al., 2015); (ii) focused on freshwater, marine or estuarine environments, in situ or controlled laboratory exposures relevant to natural conditions; (iii) reported at least one ecological endpoint such as ingestion, bioaccumulation, trophic transfer, oxidative stress, histopathology, reproductive impairment or behavioural alteration; and (iv) provided sufficient methodological detail to allow quality appraisal. Studies were excluded if they: (i) were published in a language other than English with no sufficient translation; (ii) reported solely on macroplastics (>5 mm) or solely on chemical characterisation with no biological context; (iii) were conference abstracts without full text articles; or (iv) duplicated previously published data sets.

Screening and Selection Process

All records obtained from database searches were imported into the reference manager Zotero, where duplicates were removed automatically and subsequently manually. Screening was conducted in two phases. Titles and abstracts of stage 1 were screened against inclusion criteria and any records that clearly failed on any criterion were excluded. Stage 2 involved obtaining the full text of the remaining records and re-assessing them. Reviewers recorded reasons for exclusion at each stage following PRISMA guidance. The final selection of studies included peer-reviewed primary research articles, authoritative reviews and meta-analyses that described mechanisms, observations or analytical methods relevant to the objectives of the review.

Quality Assessment

The methodological quality of each included primary study was assessed using a structured checklist assessing (i) clarity of the microplastic definition used; (ii) adequacy of the sampling or exposure design for the research question; (iii) reporting of polymer type, particle size distribution and concentration; (iv) inclusion of appropriate negative and positive controls; and (v) transparency in limits of detection, contamination-prevention procedures and statistical analysis . Each domain was rated on a three-point categorical scale and each study was given an overall quality grade. The breadth and recency of literature covered, internal consistency and the extent to which conclusions were supported by the cited primary literature were separately appraised at review level (Blettler et al., 2018; Horton et al., 2017).

Data Extraction and Synthesis

For each study included, we used a standardized data-extraction form to record: bibliographic information, location and system of the study (freshwater, marine or estuarine), target taxa, polymer type, particle size, exposure concentrations or environmental abundances, biological endpoints measured and principal findings. Where several studies reported compatible quantitative data, results were tabulated for visual comparison. A narrative (qualitative) synthesis was then performed, with findings organised thematically under the headings used in the Literature Review and Discussion sections of this paper. The available studies could not be quantitatively meta-analyzed due to the methodological heterogeneity, e.g. differences in particle characteristics, exposure routes, species and biological endpoints, a limitation that has been recognized in previous syntheses of this field (Osman et al., 2023; Wagner et al., 2014).

Ethical Considerations

All the evidence in this review was obtained from publicly available peer-reviewed publications so no ethics approval or live-animal experimentation was necessary. Secondary data from earlier reviews were incorporated as per normal academic citation practice and all attempts have been made to acknowledge the original sources of all figures, statistics and conclusions reported in this paper.

Results

Bibliometric Landscape

The systematic search yielded a literature dominated by marine focused work and characterised by accelerating publication output over the last decade. 87 % of the global body of plastic-pollution research is related to marine systems compared to only 13 % of the research related to freshwater environments. The annual growth rates of publications are ~41 papers year-1 for marine and only ~7 papers year-1 for freshwater (Blettler et al., 2018). The subject has grown from 1 paper in 2014 and 1 paper in 2015 to 145 papers on microplastic remediation alone in 2020 (Osman et al., 2023), which confirms that microplastic ecotoxicology has become a key topic in aquatic pollution research.

Particle Types, Polymers and Distribution

The most dominant shape classes across the included literature were fibres, fragments, granules, films and styrofoam particles while the most frequently recorded polymers were polyethylene, polypropylene and polystyrene (Duis & Coors, 2016). One synthetic garment has been reported to release up to 1,900 fibres during a single wash cycle (Cauwenberghe et al., 2015). In the marine environment, deep-sea sediments at 5,000 m depth contained up to 2,000 particles m^{-2} (Cauwenberghe et al., 2015), while a coastal monitoring study found a ~100,000-fold higher capture rate with an 80 µm mesh (max 102,000 microplastics m^{-3} near a polyethylene production facility) compared to sampling at 450 µm (Cole et al., 2013). Comparable trends were seen in freshwater settings with the Laurentian Great Lakes neuston averaging 43,000 items km−2, Lake Huron shorelines 0–34 fragments m−2, and the sediments of Lakes Erie and St. Clair 0.2–8 items m−2 (Wagner et al., 2014). Globally, it is estimated that 70–80 % of marine plastic reaches the sea through rivers and that land-based sources contribute ~80–90 % of aquatic microplastic loads with ocean-based sources contributing ~10–20 % (Horton et al., 2017; Osman et al., 2023).

Ingestion Across Taxa

Uptake of microplastic was detected in the entire spectrum of aquatic fauna. Cole et al. (2013) reported ingestion by 13 of 15 northeast-Atlantic taxa of zooplankton (copepods, bivalve larvae and decapod larvae) at polystyrene bead sizes of 7.3–30.6 µm, with uptake of 1.7 µm and 3.8 µm particles confirmed in Temora longicornis by coherent anti-Stokes Raman scattering microscopy. Particles of 0.4–3.8 µm accumulated on the antennules, furca and swimming legs of exposed zooplankton (Cole et al., 2013). Freshwater invertebrates (including Daphnia magna) rapidly ingested particles of 0.02–1 mm, translocating them across the gut epithelium into lipid storage droplets (Wagner et al. , 2014). Among fish, 12 %

of gudgeon collected from 11 French streams contained microplastics (Wagner et al., 2014), and a study of three Lake Michigan tributaries found microplastics in surface-feeding fish, with invasive round goby having the highest tissue concentrations (~20 particles $fish^{-1}$) and a significant positive relationship between body length and particle load (r^2 = 0.393, P = 0.010) (McNeish et al., 2018). In all fish, the abundance of microplastics was positively correlated with the trophic fraction (r^2 = 0.050, P = 0.032) (McNeish et al., 2018).

Cellular and Physiological Effects

The evidence reviewed consistently associates microplastic exposure with oxidative stress, inflammation and histological injury in fish. In zebrafish, microplastics increased TNF-α, IFN-γ, IL-2, IL-6, IL-8 and IL-1β, but decreased IL-4 and IL-10. This was mediated via the NF-κB pathway, inducing oxidative stress, apoptosis and NLRP3 inflammasome activation (Subaramaniyam et al., 2023). The combined exposure with copper aggravated lipid peroxidation by inhibition of catalase and glutathione peroxidase activities (Subaramaniyam et al., 2023). For the marine copepod Centropages typicus, the algal ingestion rate was reduced in a logarithmic and dose-dependent manner following exposure to 7.3 µm polystyrene beads (R2 = 0.70, P ≤ 0.05), with effects becoming significant at ≥4,000 beads mL-1 and saturation apparent at >5,000 beads mL-1 (Cole et al., 2013). Calanus helgolandicus held on to microplastics for up to 7 days when no food was available (Cole et al., 2013). Waterborne exposure studies found lowest observed effect concentrations about 10^4-fold higher than maximum ambient marine water concentrations, while sediment-dwelling lugworms were affected in the upper range of values found in beach sediments (Duis & Coors, 2016).

Trophic Transfer and Contaminant Vector Function

The trophic transfer was quantified in several experimental systems . For instance, in mysid–fish prey–predator experiments from northern Japan, fish ingested 8–11 times more polyethylene beads by number and 3–5 times more by mass via prey exposure than directly from the water column (Hasegawa & Nakaoka, 2021). Mysids fragmented 34 % of the ingested beads (after subtracting procedural blanks), with fragments recovered from fish having a median size of 6.61 µm, well below the 10 µm threshold for gut-to-tissue translocation (Hasegawa & Nakaoka, 2021; Wagner et al., 2014). Microplastics transferred from mussels to shore crabs reached up to 163,111 particles mL^{-1} of haemolymph, equivalent to 0.24 % of the load retained in mussels (McNeish et al., 2018). Furthermore, pH-induced stress has been shown to cause a rapid passive release of microplastics from mussels to the surrounding water column (Wayman & Niemann, 2021).

Discussion

The present review synthesises a large and rapidly growing literature on microplastic pollution. While the evidence base is now sufficiently robust to identify recurring patterns of effect, its interpretation is constrained by two systemic features of the field: a pronounced asymmetry between marine and freshwater research effort, and a lack of methodological standardisation across studies.

The bibliometric imbalance is striking: 87% of the global plastic-pollution literature deals with marine systems, while only 13% concerns freshwater, with annual publication growth rates of ~41 papers $year^{-1}$ for marine research versus only ~7 papers $year^{-1}$ for freshwater (Blettler et al., 2018). This discrepancy is important because up to 70–80 % of marine plastics are estimated to enter the ocean through riverine conduits (Horton et al., 2017), and because land-based sources account for ~80–90 % of the total microplastic load entering aquatic systems, while ocean-based sources account for the complementary 10–20 % (Osman et al., 2023). Freshwater environments thus play a crucial role in the transport pathway from terrestrial sources to the global ocean, and the rivers, lakes and wetlands that are home to riverine and lacustrine fauna remain under-represented in current ecological risk assessments (Wagner et al., 2014). Meanwhile, the exponential growth in the total publication volume from one paper in 2014 to 145 papers in 2020 on remediation alone (Osman et al., 2023), confirms that microplastic ecotoxicology has been mainstreamed into the environmental agenda.

A second interpretive challenge is methodological diversity. The variation in microplastic concentrations in Swedish coastal waters by five orders of magnitude depending on the sampling mesh used (from 1–100 particles m-3 with a 450 µm mesh to a maximum of 102,000 particles m-3 with an 80 µm mesh; Cole et al., 2013) suggests that much of the apparent variation between published abundances may be artefactual. Concerns of a similar nature exist with size class definitions and inter-laboratory limits of detection. The absence of a standardised protocol for freshwater sampling, repeatedly highlighted (Horton et al.,2017;Wagner et al.,2014), hinders cross-system comparison until harmonised procedures become routine. The abundances reported in this review must therefore be interpreted with appropriate caution.

Biologically, the collected results consistently show that microplastic ingestion is not a phenomenon of a single species or a single compartment. Uptake in 13 of 15 zooplankton taxa from the northeast Atlantic was documented for particle sizes of 7.3–30.6 µm (Cole et al., 2013), while freshwater studies have reported ingestion by zooplankton, bivalves, annelids and amphipods, with 12% of individual gudgeon from 11 French streams being contaminated, and invasive round gobies from Lake Michigan tributaries carrying the highest tissue burden (~20 particles $fish^{-1}$) (McNeish et al., 2018; Wagner et al., 2014). The finding that the abundance of microplastics in freshwater fish was positively correlated with trophic fraction (r^2 = 0.050, P = 0.032) and that body length was a strong predictor of body burden in the round goby (r^2 =

0.393, P = 0.010) (McNeish et al., 2018) is consistent with the hypothesis of cumulative exposure through feeding. The low explanatory power of functional-feeding-group membership, however, indicates that species-specific biology and habitat use modulate uptake (McNeish et al., 2018), highlighting the importance of trait-based rather than solely trophic-level interpretations of exposure. Sublethal physiological effects show a consistent pattern across taxa. The experimental logarithmic, dose-dependent decline in algal ingestion rate of Centropages typicus at ≥4,000 beads mL^{-1} (R^2 = 0.70, $P \leq 0.05$) (Cole et al., 2013) indicates a strong behavioural impairment but should be viewed in conjunction with the finding that the lowest observed effect concentrations for waterborne exposure were about 10^4-fold higher than maximum ambient marine water concentrations (Duis & Coors, 2016). Ecologically relevant exposures are therefore likely to be below standard waterborne effect thresholds while sediment-dwelling lugworms are already experiencing exposure in the upper range of values recorded in beach sediments (Duis & Coors, 2016). Combined exposures with other stressors, as exemplified by the synergistic effect of copper and microplastics on oxidative-stress markers and on cytokines TNF-α, IFN-γ, IL-2, IL-6, IL-8 and IL-1β in zebrafish (Subaramaniyam et al., 2023), suggest that the natural toxicological situation is likely worse than predicted by single-stressor laboratory studies.

One of the most important findings reviewed here is trophic transfer. Hasegawa and Nakaoka found that fish consumed 8–11 times more polyethylene beads by number and 3–5 times more by mass via mysids than directly from the water column. Mysids fragmented 34 % of the beads they ingested, and the fragments reached a median size of 6.61 µm, below the threshold for gut-to-tissue translocation of 10 µm (Hasegawa & Nakaoka, 2021; Wagner et al., 2014). In parallel experiments, microplastic concentrations of up to 163,111 particles mL-1 in shore-crab haemolymph after mussel-feeding (~0.24 % of the prey burden, McNeish et al., 2018) were documented. Thus, microplastics do not behave as inert contaminants but rather as dynamic particles that are physically altered during trophic passage, often becoming smaller and more bioavailable precisely because they are processed by prey (Hasegawa & Nakaoka, 2021; Wayman & Niemann, 2021). This has direct implications for animals at higher trophic levels including humans, where the relevance of seafood-borne microplastic exposure has been noted in several reviews (Kannan & Vimalkumar, 2021).

Finally, the role of microplastics as vectors for the transport of sorbed hydrophobic pollutants such as persistent organic pollutants and polycyclic aromatic hydrocarbons adds an additional layer of ecological risk (Duis & Coors, 2016; Wayman & Niemann, 2021). While sorbed chemicals are often at quasi-equilibrium with surrounding seawater at low hazard, dynamic environmental gradients experienced in real food webs may allow localised desorption into gut tissues, especially for small high-surface area fragments (Wayman & Niemann, 2021). The combination of direct ingestion, trophic transfer, fragmentation during feeding and the chemical-vector function make microplastic pollution especially complex and ecological risk assessments based on a single dimension of exposure likely underestimate it (Osman et al., 2023; Wayman & Niemann, 2021).

There are some constraints to the present inferences. Ecologically realistic exposures remain scarce, the freshwater evidence base is about five times smaller than the marine literature (Blettler et al., 2018), and the long-term population-, community- and ecosystem-level consequences of chronic microplastic contamination are still largely unknown. Future research should prioritise standardised freshwater sampling protocols, in situ exposure assessments at environmentally relevant concentrations and resolution of the marine–freshwater research divide that currently skews the literature.

Conclusion

This review synthesizes a large and rapidly growing body of evidence that microplastic pollution has become a hallmark of modern aquatic ecosystems, with measurable effects on organisms ranging from zooplankton to predatory fish. Microplastics have now been documented in surface waters, sediments and biota in marine and freshwater systems, with global production of synthetic polymers reaching ~359 million tonnes annually and a single synthetic garment releasing up to 1,900 fibres per wash (Cauwenberghe et al., 2015; Osman et al., 2023). These particles are ingested over a broad range of taxa: 13 of 15 zooplankton taxa in the northeast Atlantic have been shown to consume polystyrene beads (Cole et al., 2013), 12 % of freshwater gudgeon from 11 French streams were contaminated (Wagner et al., 2014) and invasive round gobies in the Great Lakes showed a clear relation between body length and microplastic burden (McNeish et al., 2018).

Sublethal effects are not species specific but consistent across taxonomic groups. Copepods showed a log-dose dependent reduction in algal ingestion rate at exposure concentrations ≥ 4,000 beads mL^{-1} (Cole et al., 2013), and zebrafish showed significant elevations of pro-inflammatory cytokines along with oxidative stress under combined microplastic and copper exposure (Subaramaniyam et al., 2023). At the same time, the lowest effect concentrations tested for waterborne exposure are still about 10^4 times higher than ambient concentrations in the marine environment, and sediment dwelling organisms already are exposed to concentrations in the upper ranges of those measured in beach sediments, indicating that environmentally relevant effects are more likely to be mediated via sediments, biofilms and trophic pathways rather than simply via water (Duis & Coors 2016).

Perhaps the most ecologically important finding reviewed here is on trophic transfer. Fish that ate mysids had 8–11 times more polyethylene beads by number and 3–5 times more by mass than fish exposed directly via the water column (Hasegawa & Nakaoka, 2021); mysids degraded 34% of ingested beads to small enough pieces (median 6.61 µm) to cross the gut wall and enter tissues (Hasegawa & Nakaoka, 2021; Wagner et al., 2014). Similar transfer has been seen from mussels to shore crabs, with concentrations of up to 163,111 particles mL-1 found in haemolymph (McNeish et al., 2018). These findings show that microplastics are not inert, but are continually reconfigured through trophic transfer, becoming increasingly bioavailable at each stage.

But the current knowledge base is still patchy and limited. Freshwater systems represent only 13 % of the literature, and grow at about one-fifth the rate of marine research, despite comprising the dominant 70–80 % of the land-to-ocean transport pathway and ~80–90 % of total microplastic inputs (Blettler et al., 2018; Horton et al., 2017; Osman et al., 2023). There are no standardized sampling protocols and population-, community- and ecosystem-level consequences of chronic exposure are poorly quantified.

Future research should therefore focus on harmonised freshwater monitoring, ecologically realistic chronic exposures, trophic-level ecological risk assessment and an evaluation of microplastics as vectors for sorbed pollutants across food webs. The recent surge in publications (from 1 paper in 2014 to 145 in 2020 (Osman et al., 2023)) exemplifies the extent of scientific engagement, but also underscores the immediate need to convert this descriptive evidence base into predictive, management-relevant knowledge to protect freshwater and marine fauna.

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