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Trophic transfer of microplastics in zooplanktons towards its speculations on human health: A review

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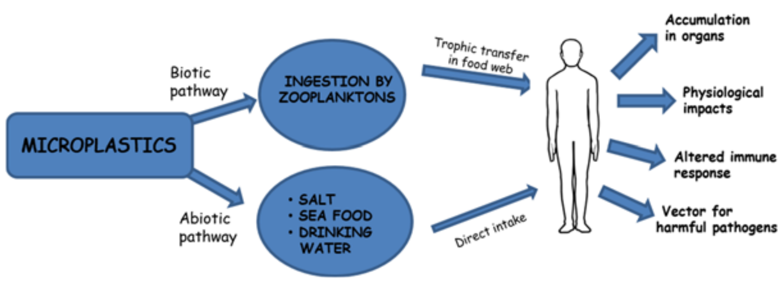
ABSTRACT



Microplastics (MPs) are plastic pieces that are less than 5mm in size and originate either by fragmentation of bigger plastic pieces or are intentionally manufactured. The main sources of marine microplastic pollution are several anthropological activities like fishing industry, aquaculture, coastal tourism, household effluents etc. Various lower trophic level organisms in the marine world have been found to be mistaking microplastics for food. Detrimental effects due to ingested microplastics may arise due to their extremely slow degradability and capacity to act as carriers for organic pollutants; thus contributing to their bio-accumulation. The present review focuses on the various studies that prove uptake of microplastics by zooplanktonic species, its impacts and the potential broader biomedical implications looming over the future of human health.

Keywords: Microplastics; zooplankton; primary consumer; bio-accumulated; ingestion.

INTRODUCTION

Microplastics (MPs) encompass a very heterogeneous assemblage of particles that vary in size, shape, and chemical composition, among other properties.[1,2] MPs have been defined as plastic particles typically less than 5 mm in diameter, which include particles in the nano-size range (1 nm).[3,4] Looking at the huge variety of synthetic plastic materials either manufactured intentionally or resulting due to the breakdown of larger plastic pieces; having diverse chemical compositions and high durability in the natural environment, microplastics are definitely not simple to define.

However, most recently Frias et al., 2019 have given an excellent account of the various scientific groups giving varied definitions of microplastics. In conclusion, they have proposed a descriptively all-inclusive definition as given below.[5]

"Microplastics are any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 µm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water."

Plastics have proven to be a man-made material with the properties of a double edged sword. On one hand it is difficult to imagine our lives without plastic products and at the same time plastic pollution has emerged as the biggest threat to the

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entire ecosystem. This problem arises as a result of no biodegradability of plastics,[6] their fragmentation owing to various environmental factors and their capacity to act as carriers for organic pollutants.[7,8] It shall not be an exaggeration to state that plastic pollution is ubiquitous. Plastic pollution exists in air, in water and on land. However, oceans draw special attention in terms of plastic accumulation and its harmful effects as they are the final reservoir. The most appalling example of persisting plastic waste in oceans is the Great Pacific Garbage Patch. It is a 1.6 million square kilometres of approximately 80 thousand tonnes of floating plastic garbage of which microplastics constitute 94% pieces (in terms of numbers). [9,10]

Not only are these microplastics accumulating in ocean waters at various depths but they have been found to have entered the marine organisms. A range of marine biota like seabirds, crustaceans, mollucs, fish and zooplankton have been found to ingest microplastics.[11-15]

The present review focusses on the uptake of microplastics by zooplankton since planktonic organisms have been used as indicators of ecosystem changes.[16] Zooplankton are taxonomically diverse marine animals that either spend their entire life cycle (holoplankton), and those with larval stages (meroplankton), in the plankton. They are heterotrophic in nutrition and serve as the main food source of various abundant marine animals.[17] Zooplankton plays important role in food web by linking the primary producers to the higher trophic levels by feeding on the phytoplanktons (and even other zooplanktonic organisms). Hence, entry of microplastics at the lower trophic levels in zooplankton may have devastating outcome in the long run for the entire food web and the ecosystem as a whole.

In this review, we aim to evaluate the current knowledge base gleaned by laboratory and field studies in recentmost times regarding ingestion of microplastic by zooplankton. The review also deals with studying the reports of the effects of microplastic bioaccumulation in zooplabktons by various research groups. The review presents a speculative view of the things to come in terms of microplastics affecting human health in the long term.

METHODS

PUBMED, Google Scholar and Researchgate were searched during February to June using a combination of keywords including 'plastic', 'microplastic(s)', 'bio-accumulated', 'ingestion', 'plankton', 'bioavailability', 'toxicity', 'marine' and 'zooplankton'. Various combinations of keywords were used as search title such as : "(microplastics) AND zooplankton[Title]"; (Microplastic)AND (Zooplankton) AND (ingestion); "(microplastics) AND human health" etc. The relevant references were carefully selected for the review process while the spurious hits which did not include the relevant text were ignored.

ZOOPLANKTONS AND THEIR SUSCIPLTIBLITY TO MP UPTAKE

Zooplankton are morphologically and taxonomically among the most diverse as well as abundant aquatic organisms and also occupy key trophic levels in most marine and freshwater environments.[18,19] Zooplankton in marine and freshwater environments exhibit significant diversity of ecological strategies, dominance patterns and effects on ecosystems.[20-23] Based on the developmental stages, zooplanktons are classified as holoplankton (permanent planktonic forms throughout life) e.g. krill, copepods, salps etc., or they may be termed as meroplanktons which are the temporary members such as most larval forms of sea stars, crustaceans, some marine snails, marine worms, sea urchins, most fish, etc.[17,20] Several groups have classified zooplanktons on the basis of their physical attributes like size, length, density etc. A common classification based on size along with common examples is given as below.[21-23]

(i) *picoplankton* : less than 2 micrometers (e.g. Flagellates, protozoa).

(ii) nanoplankton: between 2-20 micrometers, (e.g. Flagellates, ciliates, dinoflagellates)

(iii) *microplankton*: between 20-200 micrometers, (e.g. Protozoan, copepod naupli, larval forms, rotifers)

(iv) *mesoplankton:* between 0.2-20 millimeters, (e.g. Copepods, Mysids, Cladocerans, invertebrate larval forms)

(v) *macroplankton*: between 20-200 millimeters, (e.g. Arrow worms, crustaceans, krills)

(vi) *megaplankton*: over 200 millimeters, (e.g. Coelentrates, tunicates, cephalopods)

Additionally, Figure 1 depicts the heterogeneity in zooplanktons across the various taxonomic groups in the animal kingdom.

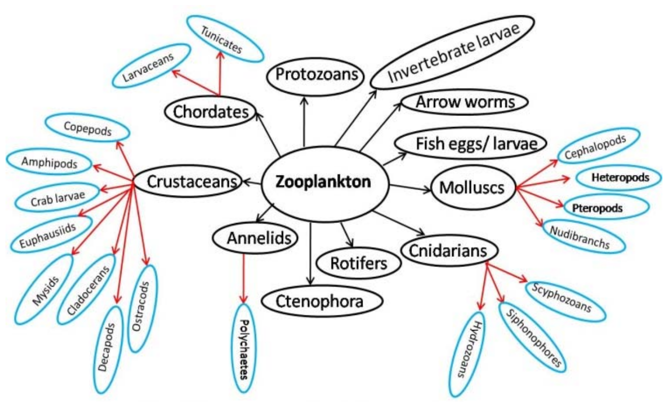

Figure 1. Zooplanktons: a heterogenenous group of organisms across various taxa.

From the above classification it is clear that zooplankton is not only a taxonomically diverse group but it also exhibits diverse feeding strategies comprising of suspension feeding and ambush/raptorial feeding methods.[18,24]

Although a wide range of marine biota have been found to ingest microplastics, zooplankton are particularly susciptible due to the following factors:

(i) Lower trophic level organisms are generally indiscriminate feeders and possess limited ability to differentiate food from plastic particles. Hence, they may directly ingest MPs accidentally due to indiscriminate feeding strategies like filter feeding or due to mistaking microplastics for food. [25-29]

(ii) Low-density MPs such as those composed of polyethylene and polystyrene are quite buoyant and are abundant near the sea surface. Hence, their bioavailability is enhanced to a wide range of planktonic organisms that reside within the euphotic zone. [25,30-32]

(iii) MPs have been reported in diverse shapes like fibres, beads, irregular shaped fragments and sizes even within the micro ranges such as particles as small as 1 micrometer in diameter, and 15 micrometer in length.[29,33]

(iv) MP ingestion in larger zooplanktons may result indirectly through eating natural prey that have themselves consumed microplastics.[15,30]

All these factors in combination put zooplanktons at a greater risk by microplastics pollution and their potential harmful effects.

Possible ways in which MPs may be toxic

Several detrimental effects across many taxa have been reported by various studies as shown in Tables 1 and 2. The potential mechanisms of such harmful effects may be attributed to several factors associated with MPs (as depicted in Figure 2). Firstly, the chemicals which are used in the production of plastics like solvents, plasticizers and surfactants themselves may eventually leach out within the organism after their ingestion and can also contribute to the toxicity. The toxicity hence caused will also depend on the type of plastic compositions and proportions of additives included, such as phthalates, flame-retardants and UV-stabilisers.[34]

Also, the fact that most microplastics have large surface area-to-volume ratio can result in the accumulation of contaminants on their surfaces by processes like adsoption and absorption. Some such chemical contaminants in the marine environment are heavy metals, polychlorinated biphenyls (PCBs) and many more. These chemicals allong with the ones incorporated in the microplastics may leach off into biological tissue and may potentially cause sub-lethal harmful effects in zooplanktons themselves and may also bioaccumulate in the higher trophic levels of the food web.[35]

Additionally, the sheer ingestion of MPs may clog the internal organs of the zooplanktons eventually resulting in physical injury and/or the detrimental effects may be manifested in varied forms such as reduced feeding behaviour, altered gene expression in oxidative defense, energy production and substance extra cellular transportation, increased mortality etc.[32,36-38]

Entry of microplastics in the food web.

Uptake of microplastics by zooplankton in laboratory as well as in field (wild) studies:

A huge amount of scientific studies have shown microplastics uptake by huge variety of zooplanktons either by direct ingestion or indirectly by trophic transfer though the food web.[17,39] Ever since in the 1960s when plastic fragments were first identified in the alimentary canals of sea birds, extensive studies have been conducted in laboratory and in field to assess the various aspects of microplastic uptake and its consequences.[40]

Table 1 summarises a few recent laboratory studies by various groups from across the world on the effects of microplastic uptake by the zooplanktons whereas Table 2 summarises some recent in field studies.

Table 1 highlights various such studies in the recent times investigating the detrimental effects of the microplastics uptake by zooplanktons. Emerging from these laboratory studies (in table 1) is an undisputed fact that MPs pose a great serious threat to not only the lower trophic levels but even to higher trophic levels as well through the food web.

Katija et al. (2017) have shown in their *in situ* experiments that larvaceans can act as biological transport vectors which could effectively move large amounts of microplastics from near-surface waters into the deep sea through the rapid sinking of fecal pellets and discarded houses both containing the trapped microplastics.[41] Setälä et al. (2014) have shown the plastic microparticle transfer via planktonic organisms from one trophic level (mesozooplankton) to a higher level (macrozooplankton).[42] This is a disturbing finding in the light of our discussion regarding the factors mentioned in figure 2.

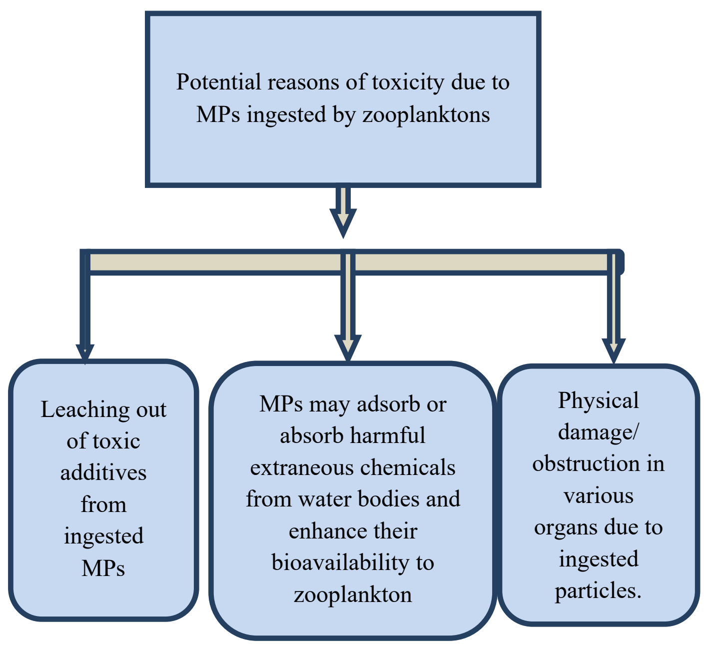

Figure 2. Some possible mechanisms of toxicity by microplastics post-ingestion in zooplanktons.

Table 1. Some most recent laboratory studies by various groups across the world on microplastics uptake and its biological impacts on the zooplanktons.

Reference	**Zooplankton species /Taxa**	**MPs type/ sample source**	**Toxicological/Biological impacts**
Wieczorek et al., 2019	*Salpa fusiformis*	polyethylene and polystyrene microplastics having a biofilm	Microplastic ingestion by salps has minimal impact on the biological pump at present. However, future microplastic concentrations (or in areas such as convergent zones), microplastics may have the potential to lower the efficiency of the biological pump.
Tang et al., 2019	*Daphnia magna*	polystyrene (PS) microbeads concentrations: 0 , 2, 4 and 8 mg L^{-1}	Gene expression data suggest that oxidative defense, energy production and substance extra cellular transportation were significantly regulated by microplastic exposure.
Wang et al., 2019	*Artemia parthenogenetica*	10 mm polystyrene microspheres	Ultrastructural changes on epithelial cells lining of the digestive tract were observed such as fewer and disordered microvilli, increased number of mitochondrion and appearance of autophagosome
Kokalj et al., 2018	*Daphnia magna; Artemia franciscana*	microplastic (MP) derived from two facial cleansers, a plastic bag and polyethylene textile fleece.	All tested microplastics were found inside the guts of *D. magna* and *A. franciscana*. A small mass of particles is sufficient to fill the gut of daphnids. No acute mortality of daphnids and artemias was observed. No delayed lethal effects in a 24 h post-exposure period were found.
Ziajahromi et al., 2017	*Ceriodaphnia dubia.*	microplastic polyester fibers and polyethylene (PE) beads, beads and fibers	Fibers showed greater adverse effects than PE beads with reduced reproductive output observed at concentrations within an order of magnitude of reported environmental levels.
Heindler et al., 2017	*Parvocalanus crassirostris.*	microplastics (PET) and one plasticizer DEHP)	Adults exposed to sub-lethal concentrations of DEHP or microplastics exhibited substantial reductions in egg production, significantly depleted in population size. Results suggest that DEHP may induce reproductive disorders that can be inherited by subsequent generations. Histone 3 (H3) was significantly ($p<0.05$) upregulated in both plastic and DEHP treatments.
Katija et al., 2017	*Bathochordaeus stygius*	Monterey Bay, California. Polyethylene microspheres, or microplastic particles	Giant larvaceans can ingest and package microplastics into sinking aggregates. Our results present a novel biological transport vector that could effectively move large amounts of microplastics from near-surface waters into the deep sea.
Jemec et al., 2016	*Daphnia magna*	Microplastic fibers (MP) from textile weathering and washing, PET textile microfibers	Exposure to these fibers results in increased mortality of daphnids. The uptake and effects of PET textile MP on *D. magna* are presented here for the first time.
Rehse et al., 2016	*Daphnia magna*	1-µm and 100-µm polyethylene particles	Ingestion of 1-µm particles led to immobilisation increasing with dose and time.
Cole et al., 2015	*Calanus helgolandicus*	polystyrene beads	Microplastics impede feeding in copepods. Prolonged exposure to polystyrene microplastics significantly decreased reproductive output. Microplastic-exposed copepods suffer energetic depletion over time
Setälä et al., 2014	Mysid shrimps, copepods, cladocerans, rotifers, polychaete larvae and ciliates	fluorescent polystyrene microspheres of 10um;	Experiments showed ingestion of microspheres in all taxa studied. ; This study shows for the first time the potential of plastic microparticle transfer via planktonic organisms from one trophic level (mesozooplankton) to a higher level (macrozooplankton).

Many fields studies as discussed in table 2 have shown that quite a significant number of zooplankton species have ingested microplastics irrespective of the geographical area studied. Desforges et al. (2015) have shown the first evidence indicating that species at lower trophic levels of the marine food web are mistaking plastic for food.[29] Several of the organisms that were investigated in these studies are keystone species in the ecosystems, thus their populations are crucial to the functioning of these ecosystems. This observation is a confirmation of our

Table 2. Some most recent studies (in field) by various groups across the world on microplastics uptake and its repercussions on zooplanktons.

Reference	Zooplankton species /Taxa	MPs type/ sample source	Results/ conclusion
Collicutt et al., 2019	Juvenile Chinook salmon (*Oncorhynchus tshawytscha*)	East coast of Vancouver Island	In all sample types >90% of microplastics were fibrous in nature compared to fragments, films or pellets. Predominantly microplastic fibres were found inside majority of samples.
Courtene-Jones et al., 2019	*Ophiomusium lymani*, *Hymenaster pellucidus*	Deep sea sample from North East Atlantic	45% of the organisms examined had ingested microplastics, of which fibres were most prevalent (95%).
Figueiredo et al., 2018	copepod, fish-larvae and arrow worms	Guanabara Bay water sample	Although, high microplastic abundance was observed but high zooplankton: microplastic ratios also prevailed.
Li et al., 2018	mussels	8 locations around the U.K. coastal environment, supermarket	Coastal mussels sampled from around the United Kingdom all contain microplastics. Supermarket bought mussels for human consumption also all contain microplastics.
Steer et al., 2017	wild fish larvae	The western English Channel	2.9% of fish larvae had ingested microplastics, of which 66% were blue fibres. With distance from the coast, larval fish density increased significantly ($P < 0.05$), while waterborne microplastic concentrations ($P < 0.01$) and incidence of ingestion decreased.
Katija et al., 2017	*Bathochordaeus stygius*	Monterey Bay, California. Polyethylene microspheres, or microplastic particles	Giant larvaceans can ingest and package microplastics into sinking aggregates. Our results present a novel biological transport vector that could effectively move large amounts of microplastics from near-surface waters into the deep sea.
Li et al., 2016	*Mytilus edulis*	22 sites coastlines of China	Microplastics uptake identified in *Mytilus edulis*, most common were fibers. Mussels could be used as a potential bioindicator of microplastic.
Desforges et al., 2015	*Neocalanus cristatus* and *Euphausia pacifia*	Northeast Pacific Ocean	The ingested particle size was greater in euphausiids (816 ± 108 μm) than in copepods. This study is the first evidence indicating that species at lower trophic levels of the marine food web are mistaking plastic for food.

confounded fears regarding the indeterminate consequences of entry of microplastics in the food web. Evidences of microplatics ingested by organisms have been found even in deep sea sample from North East Atlantic.[43] Many of these filed studies have also pointed out that the majority of the microplastic type found ingested is fibre.[43-46] Moreover, stuides have shown that the fibre form of microplastics is found to be more harmful than others such as beads and irregular fragments. It is speculated that the fibre form may influence gut passage time and hence the severity of the consequential biological effects[47]. Hoever, It has been established by all these studies that microplastic pollution is already adversely affecting the aquatic life in different taxonomic groups.[38,48-53] A lot more concerted studies and serious efforts have to be taken to quantify the magnitude of the ill effects and their potential to threaten the very survival of zooplankton taxa along with higher trophic level organisms. Alarmingly, Li et al., 2018 studied various locations around the U.K. coastal environment and certain supermarkets. They found that not only coastal mussels sampled from around the United Kingdom all had uptaken microplastics but supermarket bought mussels for human consumption also all contained microplastics. This finding gives evidence of the potential catastrophic impacts of microplastic pollution.

Although, a few studies have also shown that things have not reached alarming levels at present. Figueiredo et al., 2018 have shown that in Guanabara Bay water samples high microplastic abundance was observed. However, high zooplankton: microplastic ratios also prevailed and hence presently the situation is not critical.[54] However, if the microplastic pollution increses unabated, the detrimental effects may manifest like in other places.

Potential detrimental impacts of microplastics in aquatic ecosystems on human health

Microplastics may enter humans via biotic or abiotic pathway. The exposure to microplastics might happen via trophic transfer by consuming organisms that have already ingested microplastics. The potential bioaccumulation and biomagnification of microplastics in the food web may lead eventually to various detrimental effects on human health as highlighted in figure 3. Alternatively, humans may also be exposed to microplastics via abiotic factors like salt, minerals and drinking water sourced from lakes or sea polluted by microplastics.

These possibilities have been corroborated by various recent reports of commercial sea food, salt and packaged drinking water samples being contaminated with microplastics. It is obvious that we humans are ingesting microplastics from the aquatic components.[55, 56]

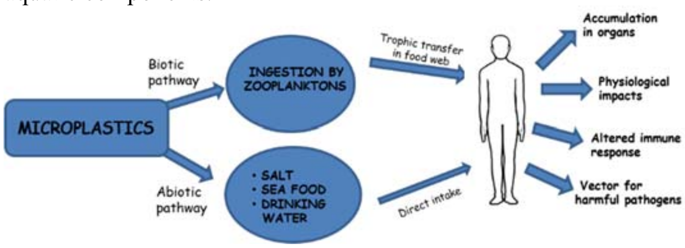

Figure 3. Potential sources and impacts of microplastics exposure on human health.

Although no clinical data is currently available on the toxicological effects of exposure to microplastics in humans, quite a few studies hint towards potential harmful impacts of microplastics in model systems in laboratory. Uptake of microplastics at cellular level in the mammalian system has been observed by Hodges et al. (1995) in their study.[57]

They have provided confirmatory evidence for the uptake and translocation of polystyrene latex microparticles (nonspecifically absorbed and nonbiodegradable) across the mucosal barrier, primarily in the villous tissues adjacent to the Peyer's patch regions in rat. In another study, Wright and Kelly have assessed the various hazards of potential exposure of microplastics on humans and also informs about the comprehension regarding the microplastics uptake, internalization and its potential impacts on human health.[58]

All these findings point towards the need of critically examining the current levels of microplastic pollution, to find ways to minimize the exposure and strict implementation of public policies to ensure the survival of the entire food web in future. Concerted efforts at global level are required to combat this impending disaster that threatens us with dire consequences for our survival.

Conclusion

Our review highlights the existing and expanding problem of microplastic pollution in water bodies and trophic transfer of microplastics through zooplankton taxa that are very foundation of the aquatic ecosystem to higher organisms.

Since zooplanktons are lower trophic level organisms, any threat to them can have serious and far-reaching effects. With this idea, recentmost laboratory and in field research studies in have been analysed. The studies clearly show that uptake of microplastics by zooplankton taxa exist and is detrimental to the organisms.

We have also analysed various studies on entry of microplastics in humans and their potential impacts. We conclude that there is an urgent need to assess the magnitude of potential outcomes of microplastic uptake by trophic levels, particularly humans. Also, the future risks of increasing microplastics levels on the world's ecosystems need to be critically studied so that control measures can be put into force before it is too late.

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