



• Systemic Review

Microplastics Exposure Routes and Toxicity Studies to Ecosystems: An Overview

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Microplastics (MPs) are now ubiquitous in global ecosystem, therefore all biota is at risk of exposure and potential toxicity. In this study, we presented an overview of information based on literature concerning exposure to MPs and the toxicity of such exposure. Currently, four major routes of exposure have been identified including entanglement, contact, ingestion and inhalation. Humans maybe the most exposed organism because they are at the peak of the food chain. Toxicology effect to marine and freshwater organisms are classified based on exposure dosage as either high (mortality, decreased reproductive output, organ damage) or low (changes in behavior with time). On plants, reports have shown that MPs exposure can affect negatively the growth and depending on exposure concentration and types of MPs and oxidative activities. However, effects on plants maybe short-term and transient. Although, toxicity studies regarding human are still ongoing as per reports, plants and animals are still scantly studied. Animal toxicity studies have widely used *D. magna* as model specie. MPs pollution may have a knock-on effect on trophic structure and functioning of ecosystems by affecting the base of the food chain. We concluded by identifying the gap in knowledge and give recommendations for future research.

Keywords: Air, Soil, Water, Food, Human health, Toxicity, Exposure, Micropollutants

INTRODUCTION

Plastic products with tremendous consumption are ubiquitous in our daily lives and the annual production of plastics is drastically increasing [1]. It is now expected to reach 33 billion tonnes by 2050 [2] with plastic waste in the environment projected to reach 67.8 million metric tons by the same year [3]. The pollution of plastic cum microplastics (MPs) from degradation in the environment is currently a hot issue attracting the global attention of many scientists, governmental and non-governmental organization and the public media [3-7]. Although few studies have investigated the chemical behavior and toxicity of MPs in the natural environment, studies focusing on its toxicity in tandem with toxic chemicals to ecosystems are scarce [1,4,8]. There are many toxicology reports that MPs are harmful to ecosystems. Terrestrial organisms such as

earthworms, soil collembolans, and other animals, as well as plants have been affected by MPs [1,4,9-13]. Also, aquatic organisms such fish, sandhoppers, sea turtle, crustacean and mussel have also been affected by MPs [14-15]. In addition, humans are exposed to MPs via trophic transfer or by direct ingestion, contact and inhalation and plausible effects include lung inflammation and genotoxicity may occur [1,3,16,17]. Aside from the innate toxicity of MPs, they can carry different toxic chemicals such as heavy metals and organic pollutant by adsorption process, and double the effect of such pollutants [1,8,18].

Succinctly, plastic products are made up of mixtures of polymers, fillers, and multiple additives to improve its usability. Also, there are other chemicals including unreacted monomers, starting substances and non-intentionally added substances (NIAS; impurities, side or breakdown products) that are also present in plastic. However, most of these chemicals are not covalently bound to the polymer, so they can be released at all stages of the plastics' life cycle via migration to liquids or solids or via volatilization [1]. Therefore, plastic materials are an important source of human exposure to chemicals.

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The well-known examples are the plastic monomer bisphenol A (BPA) and phthalate esters used as plasticizers [19]. More route of attachment of environmental chemicals to plastics is through formed biofilm on the microplastic surface and hydrophobic adsorption (for adsorption and desorption mechanism see ref. [1]).

According to the recent studies around toxicities of plastics and their chemical releases, more analyses of the dangers of MP pollution to terrestrial biodiversity are required because the abundance, composition and physicochemical surface properties of particulate material follow typical patterns in terrestrial and continental environments [20, 21]. Recently Verla et al. presented a comprehensive review of the interaction between MP and toxic chemicals as well as the implications of such interaction to ecosystems [1]. In their review, they reported that twelve metals - aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), titanium (Ti), and zinc (Zn); one halogen - bromine (Br); and fifteen groups of organic pollutants - polycyclic aromatic hydrocarbons (PAHs), Polychlorinated biphenyls (PCBs), dichloro-diphenyl-trichloroethane (DDTs), hexachlorocyclohexane (HCHs), chlordane, mirex, hexachlorobenzene, hopanes, polybrominated diphenyl ether (PBDEs), perfluorinated compound/acid (PFC/PFA), aliphatic hydrocarbons, BPA, nonylphenols (NPs) and octylphenols (OPs) have generally been quantified from different locations globally up till now. These chemicals are ubiquitous just as MPs and are abundant in areas of high anthropogenic activities [1]. Further, they can adversely affect human health with potential carcinogenic, teratogenic and mutagenic

effects [22]. The study aimed at presenting a summary of studies conducted on exposure and toxicities of MPs to man and environment. Understanding the route of exposure to MPs may help preventing lethal effects they may pose to biota.

EXPOSURE ROUTE TO MICROPLASTICS

MPs are ubiquitous in the environment since they have been found in all components of the ecosystems [4]. Therefore, biota interact each other either from the soil, water or air. Sizes, density, abundance, shape, and color of MPs control its bio-availability [1] and therefore its toxicological effect. In the last five years, research have focused on the transfer and the effects of MPs through the food chain. Diverse species are currently being investigated to find out more susceptible species to MPs exposure [23]. Cunningham and Sigwart presented a meta-analysis of experimental exposure studies (number of studies = 128) on marine and freshwater species to MPs [24]. Exposure impact of MPs was classified as either high (decreased reproductive output, damage to organ and mortality) when dosage is greater than 100 MPs/L for water and greater 100 MPs/kg for sediment and low (transient behavioral changes such as increased respiration, reduced feeding, and reduced energy) when dosage is ≤ 100 MPs/L for water and ≤ 100 MPs/kg for sediment. The threshold for a cut-off between the two classes was selected based on the highest recorded environmental surface water concentrations [25]. Although concentrations of MPs can vary with time, the threshold of 100 MPs/L is intended to represent the highest values of MPs reported at a given time [24]. Therefore, different cut-off size will

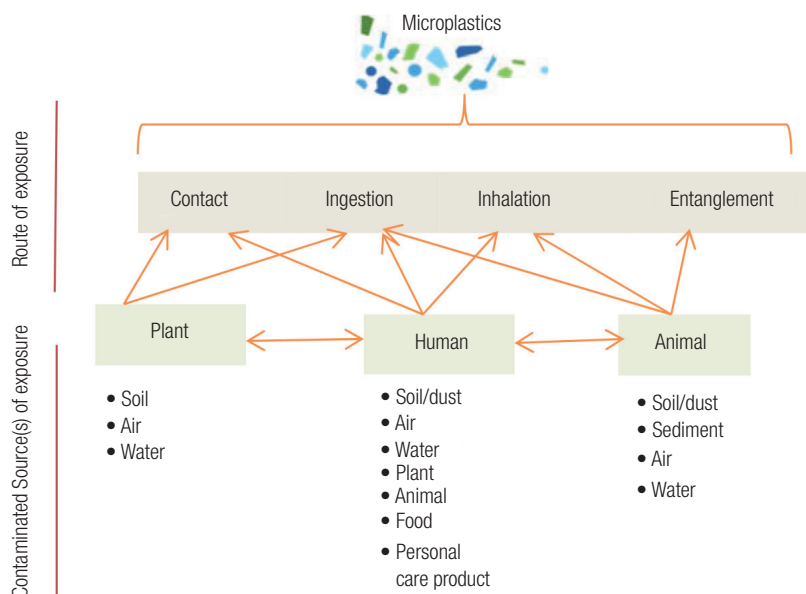


Figure 1. Summary of exposure route to environmental microplastics (MPs)

lead to different values, since number concentration of MPs is size-dependent. However, many species either by selective targeting of plastic items, or accidental ingestion by filtration or predation are exposed directly to MPs [26]. Based on current information, all categories of exposure fall under the four major routes to MPs: entanglement, contact, ingestion and inhalation (Figure 1). Entanglement and contact are similar, but this study regarded them as different based on the mode of exposure. Contact involves attachment and/or penetration through skin pores while entanglement is defined when MPs remain attached/packed on the surface/body of the organism, which can cause the organism to sink if in water.

Plant

Plants are exposed to MPs through contact (from MPs fallout or through contaminated water or irrigation water) and ingestion by uptake through the rhizosphere in the plastic-soil matrix. Contact exposure was reported for aquatic plant e.g. Duckweed (*lemma minor*) and moss plant (*Sphagnum palustre* L). MPs made of polyethylene (PE) are adhering to whole *L. minor* colonies by exposing to 50,000 MPs/mL of size dimension of 10–45 µm [27]. Capozzi et. al. [79] also made similar observation for polystyrene (PS) on *S. palustre* L in freshwater. Overall, prolong exposure to the treatment showed increasing adherence to MPs in water by aquatic plant [27,79], thus they can be used for monitoring MPs contamination of freshwater environments.

Recent studies have also suggested that plants which are exposed to MPs in the soil matrix have the potential to uptake them [4]. Studies have shown nanoplastics (<100 nm) and MPs (0.2 µm) can uptake by a plant [28,29,80,82]. This is hypothetically possible because small-sized MPs can bypass plant cell wall and membrane barriers or block cell pores [4,18,82].

Animal

The exposure route of animals, including marine and soil organisms, to MPs is by entanglement and ingestion [1,15]. One of the major reasons why some marine organisms get entangled or ingest MPs is due to the formation of biofilm on the microplastic surface [1]. Biofilm forming processes on virgin microplastic particles begin within seconds of the first contact with ambient water [1,30].

The number of marine species reported to have interacted with plastic debris has increased over time with current counts over 1,000, while about 800 of these have shown interaction with MPs [31]. Previous reports showed that by ingestion 220 species were contaminated and through entanglement 580 species were contaminated and these organisms include ma-

rine mammals, fish, invertebrates and fish-eating birds [1,32,33]. However, soil animals such as nematodes, collembolan, oligochaeta (e.g. earthworms) and isopods are also known to interact within different ways and ingest soil plastic debris [1].

Land or terrestrial animals are mainly herbivorous, e.g. goat, cow, etc., and they may be exposed indirectly by consuming MP-contaminated plant and/or directly from consuming contaminated animal feed or water. Carnivores, e.g. lion, tiger, etc., may then be exposed through food-chain process or trophic transfer by consuming or feeding on herbivores tissues and bio-system. The food chain exposure processes are also often exhibited in the aquatic ecosystem, for example, whale or sharks feeding on smaller marine animals may have ingested MPs or amphipod *Gammarus duebeni* eating PE laden *L. minor* [27]. Generally, data on the presence of MPs in freshwater macroinvertebrates are scarce, as most studies have focused on fish and birds [34].

Human

The routes of exposure of humans to MPs are diverse. The summary and mechanism of exposure are presented in Figure 1. The ingestion may be by oral route which involves consumption of contaminated water, food products (honey and beverages), through use of personal care products (toothpaste, face wash, scrubs, soap; also dermal route), marine product (food chain), plant (food chain), contact (dermal) from soil, water or fallout of airborne MPs, from particulate fallout from air during open meal and inhalation.

Humans may also be directly exposed to MPs through the actual ingestion of these particles from drinking water, honey, beers and table salt [35-38]. MPs have been found in drinking water sources but in low concentrations [40,78]. Analysis of beer samples in Germany reported about 2 to 79 fibers/L and from 12 to 109 fragments/L [36]. Recently, Karami et al. analyzed different salt brands (n = 17) from 8 countries for MP-like particles and observed that the salts were predominantly contaminated by fragments of polypropylene (PP) and PE [37]. Through salt consumption, it was estimated that at most 37 particles per individual were ingested [1]. Although, these routes of exposure to MPs through consumption of salts pose no/negligible health risks as concluded by researchers [38,39]. Another route of direct ingestion of MPs is from atmospheric fallout of indoor airborne MPs during open meals [3]. Cantarino et al. demonstrated this exposure route in their study and extrapolated that humans may ingest MPs which ranged from 13,731 to 68,415 particles per year from this scenario [4,41].

MPs can also be ingested indirectly through personal care

products such as toothpaste, face wash, scrubs and soap [42,43]. There are reports of MPs present in diverse personal care products. Results from a recent study showed that 50 % of the face wash products and 67 % of the facial scrubs studied mainly contained microbeads [44]. These microbeads can cause skin aging and dark spots on the skin by letting in bacteria through the tiny rips formed. Kaur explained that tiny rips in the skin may occur from exposing the skin to microbeads in personal care products [44]. Microbeads can also injure the cornea when it gets stuck in under the eyelid from face washing. There are many reports of the presence of MPs in toothpaste products [45]. MPs in toothpaste can lead to gingivitis and bleeding with prolonged exposure when trapped between gum [44].

The food chain exposure process is based on human consuming MPs contaminated aquatic organisms, animals or plants, which in turn may have consumed the plastic through MP loaded water or the feeding from other organisms. There are many studies which reported the presence MPs in various organisms from the lowest levels of food chain such as zooplanktonic organisms to the highest levels in both invertebrates (Crustacea, mollusks) and vertebrates (fish) [1,15,46-48]. Güven et al. studying the Mediterranean coast (Turkey) for MPs in fishes, reported a total of 1,822 and 1,337 MP particles were recovered from stomachs and intestines respectively [49]. Furthermore, it was also reported MPs reached 92.3% of the total number of plastic items (meso-/micro- plastics) in fishes collected from coastal and freshwater in China [37]. MPs have also been recently found in the livers of fish fed plastic particles [39]. It was estimated that a top European shellfish consumer will consume 11,000 plastic particles annually by the aforementioned route [1]. Another aspect of food chain exposure is by consuming contaminated plants. Previous reports have demonstrated the potentiality of plant bioaccumulating MPs and from extrapolations, they may consume about 80 g daily [4].

Dermal exposure may occur when humans interact with water or soil contaminated with MPs or from contact with particulate MPs. Contact (dermal) exposure will be through skin pores penetration. Exposure by this means is based on individual susceptibility as human skin pores vary by individual. Very small synthetic fibers (<25 μm) can penetrate skin pores which is as small as 40–80 μm , but they will be bypassed the stratum corneum [4,51-53].

Humans may also be exposed to MPs through inhalation. This is only possible when the MPs become airborne [4,6]. Few studies have reported the presence of MPs in indoor and outdoor air [4]. For MPs to be inhalable, it must have a size

that can allow it reaches the respiratory system and not conform to the criteria of fiber provided by World Health Organization (WHO), i.e. must have a length more than 5 μm , with a diameter less than 3 μm , and a length-to-diameter ratio more than 3:1 [54]. Recently, Vianello et al. observed from their simulated experiment using a breathing thermal manikin (BTM) that over 24 h, humans may inhale airborne MPs up to 272 particles from inhaling indoor air [55]. Although using BTM cannot truly replicate the complexity of the branching airways of the human lung, the findings from the study still expose the high potential exposure route through inhalation [5].

TOXICITY STUDIES ON MICROPLASTICS

Chemicals can be adsorbed to MPs surfaces and may pose threat biota post-ingestion. The precise mechanisms by which MPs adsorb toxic chemicals in the environment is yet to be understood fully, although the plausible mechanism involves: hydrophobic adsorption, biofilm and plastic additives [1]. MPs, therefore, serve as a carrier for toxic chemicals such as heavy metals and organic pollutants in the environmental matrix. Toxicity studies of MPs to marine and terrestrial animals have been well conducted whereas plants are scarcely studied and recently started gaining increasing attention while no reports yet concerning humans.

Plants

The effects of MPs on soil-plant and water-plant systems have started gaining increasing attention recently. MPs in soil matrix can affect the soil properties including soil aggregation, bulk density and water holding capacity and may also affects water properties such as total dissolved and suspended solids, electrical conductivity, pH and dissolved oxygen [3,5-6,56]. Plants are usually exposed to MPs from the soil matrix and the effect or toxicity they have maybe dependent on plant, type, shape, size and concentration of MPs [1,4]. Studies conducted so far have focused on vegetative and reproductive growth as well as chlorophyll contents of plants. These studies are summarized in Table 1. In soil-plant systems, most studies have adopted an approach of comparing the outcome of single and combined exposure. Reports so far have shown that MPs exposure can affect negatively, depending on exposure concentration and types, on the growth and varying effects on oxidative activities of plants. However, effects maybe short-term and transient.

Animals

Although using animal as biomarker are commonly used for

Table 1. Summary of toxicological studies of microplastics (MPs) exposure on plants

Matrix studied	MPs type	Treatment	Plant studied	Plant part	Result	Conclusion	References
Soil	Bio and LDPE	1 % with and without earthworm	wheat (<i>Triticum aestivum</i>)	Above-ground	Bio-affected above ground biomass negatively reducing plant height, number of tillers, fruits and causing thinner stem during the growth process while LDPE showed no clear effect in comparison with control.	Earthworm had a positive effect on the wheat growth and chiefly alleviated the impairments made by plastic residues increasing total biomass by 26.2% after 4 months. However, both Bio and LDPE significantly affected the total biomass.	[13]
	Synthetic fibre, Bio-PLA and HDPE	0.001% w/w, 0.1 % w/w and 0.1 % w/w respectively.	perennial ryegrass (<i>Lolium perenne</i>)	Below-ground	Significant decrease in below-ground biomass	The study provided evidence that MPs manufactured of HDPE, PLA, and synthetic fibers can affect the development of <i>L. perenne</i> health	[56]
				Above-ground	Shoot height was reduced especially for synthetic fibre and Bio-PLA. Increased chlorophyll a and b contents compared to control.		
	LDPE, PP and PS	0.5 % w/w (LDPE, PP, PS respectively), 1 % w/w (for LDPE+PP, LDPE+PS, PP+PS respectively) and 1.5 % w/w (LDPE+PP+PS)	Juvenile Lime Tree (<i>Citrus aurantium</i>)	Below-ground	Seed germination was reduced especially for synthetic fibre and Bio-PLA. Increased root biomass compared to control except bio-PLA	Showed more negative effects compared to control by reducing height, number of branches, leaf number and area. Highest negative effect shown by LDPE while least by LDPE+PP+PS	C. aurantium generally showed high tolerance (>70%) to the different treatment groups. Despite the observed toxicity symptoms as the decrease in total plant biomass, there was no unfavorable impact on the relative growth rate (RGR) of the tree.
Above-ground							
Green fluorescent Microspheres	103 to 107 Particles/mL	vascular plant (<i>Lepidium sativum</i>)	Below-ground	Reduced germination after 8 hours of exposure with no significant differences after 24 hours from the control	Increasing exposure concentration, size and time reduces germinating rate and chlorophyll contents.	[80]	
Sediment	PS	10 % dry weight	<i>M. spicatum</i> <i>Elodea</i> sp.	Above-ground	Shoot length reduced with increasing concentration	All effects occurred at higher than environmentally realistic concentrations, suggesting no immediate implications for ecological risks.	[81]
Water	PE Microbeads	0, 10, 50, and 100 mg /L	duckweed (<i>L. minor</i>)	Root	Significant decrease in root length with increasing concentration	Overall, results showed that specific leaf growth rate and content of photosynthetic pigments in duckweed leaves are not negatively affected by polyethylene microbeads. However, investigated particles significantly affected the root growth	[58]
	PE	50,000 MPs/mL	duckweed (<i>L. minor</i>)	Leaves	After seven days treatment caused less than 10% inhibition in comparison to control (<8%) with no significant effect. Furthermore, photosynthetic pigment concentration (chlorophyll a and b) was not significantly affected compared to controls	Over seven days PE MPs did not affect photosynthetic efficiency and plant growth. However, 30-day chronic exposure showed some negative effect on root and leaves.	[27]
				Root	Root length increased with time from 24 to 168 hours with no significant differences from the control		
PS-MPs	5 µm with 10, 50 and 100 mg/L	Vicia faba	Whole plant	Reduced growth with varying effect on enzyme activities such as catalase (CAT) (decreased significantly), superoxide dismutase (SOD) and peroxidase (POD) (both increased significantly).	Showed mild genotoxic effects on the plant and most probably block cell connections or cell wall pores for transport of nutrients.	[82]	

*Bio: Biodegradable; PLA: polylactic acid, HDPE: high density polyethylene, PP: polypropylene, PS: polystyrene, LDPE: low density polyethylene.

neuro- and genotoxicity, this review focused more on the studies that related toxicity to sorption of toxic chemical by MPs [59-64]. Many animals collected from both marine and terrestrial ecosystems have shown to ingest MPs [1,15,18]. Therefore, studying the role of MPs in the toxicity of chemical contaminants cannot be underemphasized. A review of toxicity studies on animals by MPs-toxic chemical interaction has been conducted recently [65]. Most studies have used *Daphnia magna* (a small planktonic crustacean belonging to the subclass Phyllopoda; adult length is usually 1.5–5.0 mm) as a model specie.

Outcome comparison of single and combined effects of MPs approach has been commonly adopted across studies. For example, Rehse et al. using *D. magna* reported that the half maximal effective concentration (EC_{50}) for the immobilization of BPA did not differ significantly from when the organism is treated with both BPA and polyamides (PA) [66]. Furthermore, Horton et al. reported that the immobilization and toxicity of pesticide (dimethoate and deltamethrin) by *D. magna* was not affected when polystyrene (PS) was introduced [67]. Using the same organism, similar observation was also made for the immobilization of phenanthrene alone and with irregular PE MPs [68]. For predatory performance of *Pomatoschistus microps*, Fonte et al. reported an increase in EC_{50} due to combined exposure effects to cefalexin and PE spheres [69]. Davarpanah and Guilhermino showed that the EC_{10} (maximal effective concentration at 10% inhibition), EC_{20} (maximal effective concentration at 20% inhibition) and EC_{50} of Cu alone on algae (*Tetraselmis chuii*) growth inhibition did not differ from the obtained EC_x when PE MPs were added with Cu [70]. Therefore, it could be said that PA, PS and PE MPs did not affect the toxicity of the cefalexin, BPA, dimethoate and deltamethrin, phenanthrene and Cu to aquatic organisms [65].

For other chemicals, such as glyphosate, 17 α -ethinylestradiol and Ni, toxicity and MPs type (e.g. PVC), reports have suggested that MP-presence may decrease or increase contaminant toxicity depending on treatment methods. Zhang et al. observed an antagonistic effect on the growth of the algae (*Microcystis aeruginosa*) due to the interaction of glyphosate and PS-NH₂ [64]. A gene expression study reported that the bioavailability of phenanthrene and 17 α -ethinylestradiol to zebrafish in the presence of MPs decreased significantly due to sorption of these chemicals to PVC [71]. Additive effect such as increasing bioaccumulation of phenanthrene was observed for small plastic particles (50 nm) in combination with phenanthrene on *D. magna* [72]. PS and PS-COOH in water showed antagonistic and synergistic effects on Ni toxicity to *D. magna* [73]. The toxicity of the latter may have been enhanced by the

presence of carboxylic acid functional group, which enabled easy bonding with water molecules. Mateos-Cárdenas et. al., [27], recently observed that at 24 and 48 h exposure of *G. duebeni* to PE MPs via trophic transfer from contaminated *L. minor* showed negligible effect on the amphipod mortality or mobility. Furthermore, juveniles of a planktivorous fish (*Acanthochromis polyacanthus*) showed great tolerance to acute and chronic exposure to polyethylene terephthalate (PET) with no significant effect on growth, body condition or behavior [74].

For terrestrial organisms, soil invertebrates, such as nematodes, collembolan, oligochaeta (e.g. earthworms) and isopods have been studied [1,9,56]. The toxicological effect of MPs on soil organisms have been extensively discussed and reviewed [1,9]. Toxicity is controlled by exposure concentration, type and shape of MPs and organismal susceptibility. Effects were low ranging from MPs affecting growth or survival, feeding behavior and energy reserve of soil animals while high effects including death have not been reported. There is a need for studies for MPs in the presence of chemical containment on soil animals [1]. However, as pointed by van Gestel and Selonen, studies focusing on a full dose-response be conducted to address the precise toxicity effects of MPs on organisms is required and if such study adopted a co-exposure of MPs and chemical contaminants treatment testing, the experimental design should allow some kind of comparison between single and combined toxicities [65,75].

Human

Currently, the toxicity of MPs to humans is still speculative as there are no studies yet to confirm the toxic effect. Previous reviews have explained in detail the potential effects of MPs to human from different environmental compartments [1,4,5,16,17,39,50,76,77]. These studies critically assessed the potential levels of exposure of particles, chemical and microbial hazards associated with MPs and also inform understanding of uptake, internalization, impacts and potential adverse human health outcomes of MPs. Overall, the plausible impact may include particle localization, microbial (biofilm with associated toxins) or chemical toxicity (with associated toxic chemicals).

Some recent *in vitro* studies have demonstrated the potential effects of MPs on human-derived cells [83-85]. These effects ranged from inflammation to DNA damage. Poma et al. analyzed the effects of PS nanoparticles (PS-NPs) in the Hs27 cell line at different time windows and polymer nanoparticle (PNP) concentrations [83]. The authors adopted the cytokinesis-block micronucleus (CBMN) assay to evaluate the geno-

toxic effects of the PS and the after exposure to PNP. The results obtained in the study showed damage in the DNA at different parameters of the CBMN test, which increased the formation of micronuclei and nuclear buds. The cellular responses of secondary PP MPs (~20 µm and 25–200 µm) were investigated in different conditions, such as size of normal cells, immune cells, blood cells, and murine immune cells by cytokine analysis, ROS assay, polarization assay and proliferation assay [84]. They found that PP particles showed low cytotoxicity effect in size and concentration of cells, however, a high concentration, small-sized, DMSO (dimethyl sulfoxide) method of PP particles stimulated the immune system and enhanced potential hypersensitivity to PP particles via an increase in the levels of cytokines and histamines in peripheral blood mononuclear cell (PBMCs), Raw 264.7 and HMC-1 cells. Wu et al. adopted a transcriptomic analytic method, and the molecular toxicity mechanisms of PS MPs was performed *in vitro* Caco-2 cell model [85]. The authors observed that PS-MPs decreased cell viability and it is dose-dependent while the responsible genes and involved pathways that might make contribution to PS-MBs-induced toxicity to Caco-2 cells were identified with Illumina RNA sequences. These pathways are involved in modulating cell inflammatory and proliferation. These studies defined the toxicity of small-sized plastic particles to human-derived cell and the resulting damage to DNA and inflammatory diseases. Further, providing a new insight into the understanding of the toxicity effects of MPs induced intestinal inflammatory diseases. However, further studies are needed to clarify the internalization process of MPs.

CONCLUSION, RECOMMENDATION AND KNOWLEDGE GAPS

Currently MPs are a threat to ecosystems. Studies on exposure akin toxicity in tandem with toxic chemical is very important to understanding MPs dynamics and developing a mitigation strategy. Humans are perhaps the most exposed organism mainly because they are at the top of the food chain. Exposure and toxicology effect to marine and freshwater organisms are classified based on exposure dosage as either high - involving decreased reproductive output, damages to organ and death, or low - involving changes in behavior with time. Although toxicity studies regarding humans are still ongoing as per reports, plants and animals are still scantily studied. It is recommended that if a study adopted a co-exposure of MPs and chemical contaminants treatment testing, the experimental design should allow some kind of comparison between single and combined toxicities [65] because it is still difficult to

compare these studies. This study, therefore, identified the following knowledge gaps that need to be filled:

- Few plants have only been studied for MPs exposure and effects on vegetative and reproductive growth. Meanwhile, there are more than 200,000 plant species, so it is clear that there is a need for more studies on more different plant species to better understand their response to MPs exposure.
- There is a need for study to determine if plants can accumulate toxic chemicals and MPs together from the soil. Also determining if the combined exposure effect on plants is synergistic, antagonistic or additive. This is a basis for precise risk assessment.
- As pointed by van Gestel and Selonen, studies focusing on a full dose-response be conducted to address the precise toxicity effects of MPs on organisms is required [75].
- There is a clear need for more scientific studies on the effects of MPs on human health.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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