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Unraveling the ecotoxicological effects of micro and nano-plastics on aquatic organisms and human health

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Plastic pollution ranks among the most severe environmental disasters caused by humans, generating millions of tonnes of waste annually. The extensive and unregulated use of plastics has led to ecotoxicity and environmental imbalance. Microplastics (MPs) are prevalent in aquatic environments, and these MPs further degrade into even smaller particles known as nano-plastics (NPs). Both MPs and NPs impact the environment by readily absorbing organic pollutants and pathogens from their surroundings, owing to their bigger surface area to volume ratio. This review focuses on the source of origin, bioaccumulation, and potential impact of MPs and NPs on aquatic organisms and human health. Additionally, the review explores various methods employed for identification and quantification of these particles in aquatic ecosystems. Sufficient information is available on their characteristics, distributions, and effects on marine ecosystems compared with freshwater ecosystems. For plastic particles <10 μm, more toxicological effects were observed compared with larger size particles, in aquatic life. Understanding the mechanism of action and ecotoxicological effects of micro/nano-plastics on the health of aquatic life across various trophic levels, as well as human health, is of utmost importance. We address knowledge gaps and provide insights into future research approaches for a better understanding of the interactive mechanisms between binary pollutants.

KEYWORDS

plastics, marine ecosystems, pollution, aquatic organism, public health, toxicity

1 Introduction

Plastic debris has emerged as a global environmental issue, and the improper handling of plastic waste has led to a rapid escalation of its presence in ecosystems (Oliveira et al., 2019; Yu et al., 2019) especially aquatic ecosystems (Han et al., 2024). The worldwide annual production of plastic materials now exceeds 320 million tonnes, with 40% dedicated to single-use packaging (Food and Agriculture Organization, 2013). A staggering 70% of plastic material, amounting to 5,800 million tonnes, has transformed

TABLE 1 Toxicological effects of various microplastics and nanoplastics on aquatic organisms.

Test organism	Size (nm)	Concentration (mg/L)	Contaminant type	Exposure duration	Observations	References
Ctenopharyngdon idella	470	0.034	Polystyrene	20 days	DNA damage, erythrocytes mutagenic and cytotoxic effect	Guimarães et al. (2021)
Daphnia pulex	60	76.69	Polystyrene	96 h	Nanoplastics induce immune defence and oxidative stress	Liu et al. (2021)
Macrobrachium nipponense	75	40	Polystyrene	28 days	Effects on reproduction	Li et al. (2021)
Hydra viridissima	40	40	Polymethyl Methacrylate	96 h	Morphological alteration like partial or complete loss of tentacles	Venancio et al. (2021)
Daphnia pulex	75	.001	Polystyrene	21 days	Effects on growth rate and reproduction	Liu et al. (2020)
Danio rerio	1,000	50	Polystyrene NPs	12 h	Nanoplastics induce immune response in test organism	Brandts et al. (2020)
Phaedactylum tricornutum	60	100	Carboxylated polystyrene	72 h	Reduction of intracellular generation rate of ROS	Grassi et al. (2020)
Chlorella vulgaris	500	250	Polystyrene	12 h	Deformation of cell wall, cellular stress	Gomes et al. (2020), Hazeem et al. (2020)
Rhodomonas baltica	50	0.5–100	Polymethyl Methacrylate	72 h	Pigment overproduction, membrane integrity lost, and mitochondrial membrane hyperpolarization	
Artemia franciscana	100	500	Polystyrene	24 h	Greater bioaccumulation of PS in stomach and gut	Qiao et al. (2019b), Sendra et al. (2020)
Danio rerio	5,000	0.5	Polystyrene	3 weeks	Inflammation and thinning of intestinal wall, intestinal damage 86%	
Danio rerio	20,000–100000	0.01	Nano-plastics	21 days	An increase in mast cells based on intestinal epithelium, Defects in the intestinal mucosa	Qiao et al. (2019a)
Chaetoceros neogracile	50	5	Polystyrene amino modified	4 days	Chlorophyll rate decrease due to microplastic exposure	González-Fernández et al. (2019), Sallam et al. (2020)
Mytilus galloprovincialis	2–4,000 μm	5×10^5 particles/L	Polystyrene, polypropylene, polyethylene terephthalate	3 days	Sex and gametogenesis cycle could influence contaminant uptake and elimination or biomarkers levels in molluscs	Pizzurro et al. (2024)
Isochrysis galbana	40	83.7	Polymethyl Methacrylate	96 h	Effects on growth rate	Venâncio et al. (2019)
Phaeodactylum tricornutum	50	50	Polystrene	72 h	Population growth inhibition and decrease in chlorophyll content	Sendra et al. (2019)
Carassius auratus	700,000–5000000	100	Polystyrene	6 weeks	Intestinal inflammation, liver inflammation and infiltration	Jabeen et al. (2018)
Caenorhabditis elegans	5,000	0.01–10	Polystyrene	10 days	Reproduction inhibition and swollen abdomen in dead fish	Lei et al. (2018)

*ROS (Reactive oxygen species), PS (Polystyrene).

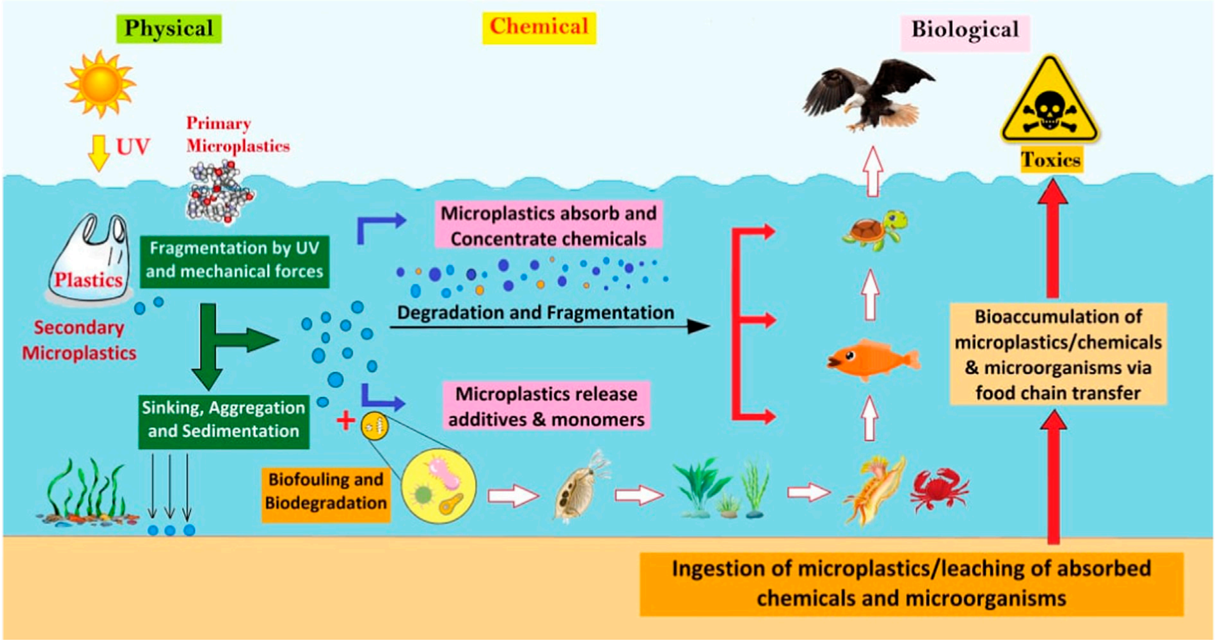

FIGURE 1
Different processes affecting microplastics in aquatic systems.

into debris, and approximately 79% (4,900 million tonnes) has amassed in ecosystems or landfills as of 2015 (Geyer et al., 2017). The widespread use of plastics in various applications persists due to their cost-effective manufacturing, utility, and durability (Barría et al., 2020). Plastics have been the preferred material for many years owing to their versatility, ubiquity, lightness, durability, and adaptability (Nielsen et al., 2020). The use of plastics is also increasing every day in agriculture benefitting agricultural production. However, the misuse of plastics after agricultural operations can lead to plastic waste and consequent environmental contamination by plastic debris (Mongil-Manso et al., 2023; Kudzin et al., 2024). Unfortunately, due to careless and excessive use, improper management, and inadvertent disposal, a significant volume of plastics has amassed in aquatic systems (Peng et al., 2020). Thus, they can accumulate at higher trophic levels, infiltrate the food chain, and pose a potential risk to ecosystems, native and non-native species, and human health (Neves et al., 2024).

Plastics of various types are globally produced, with polyethylene, polyvinyl chloride, polystyrene, polypropylene, polyethylene terephthalate, and polyurethane identified as the most prevalent plastic varieties (Al-Thawadi, 2020). Through processes like mechanical abrasion and biological deterioration, plastics can undergo fragmentation, resulting in the formation of secondary microplastics (MPs) and nano-plastics (NPs), (Alimi et al., 2018; Oliveira et al., 2019). Micro/nano-plastics (MNPs), owing to their capacity to absorb and accumulate co-contaminants, exert a physical and chemical impact on the environment. The attachment of metallic/organic toxins to MNPs and their subsequent transport into animal bodies depend on sorption mechanisms primarily influenced by the physico-chemical characteristics of MNPs and the type of pollutants (Thiagarajan et al., 2021). Nanoplastics and MPs are categorized based on their size, with NPs measuring less than 1000 nm and MPs being less than 5 mm (Frias and Nash, 2019). Although there is currently no formal definition for NPs, they are generally considered to share the same origin and composition as MPs but with a size of less than 1,000 nm (Gigault et al., 2018; Ferreira et al., 2019; Barría et al., 2020). Generally, MNPs are classified into primary and secondary MNPs. Examples of primary MNPs include synthetic fibers, cosmetics, pharmaceuticals, and raw materials (Li et al., 2018; Wang et al., 2018; Wang et al., 2020). Primary MNPs, being smaller in size, have a larger surface area, facilitating the adsorption of hydrophobic constituents from marine systems, such as polycyclic aromatic hydrocarbons (PAHs), perfluorooctanoic acid (PFOA), dichlorodiphenyltrichloroethane (DDT), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and metals (Li et al., 2018; Ferreira et al., 2019).

Micro and nano plastics have caused significant pollution in water bodies including drinking water (Li et al., 2023; Brancaleone et al., 2023). Moreover, aquatic organisms are regularly being exposed to pharmaceuticals nanomaterials (PC/NM prevalent in industrial and urban areas (Naz et al., 2021; Fernandes et al., 2023). Wastewater treatment plants appear to be a major source of contamination in the aquatic ecosystem (Vaid et al., 2021; Gagné et al., 2023). Consequently, investigations into the interactions between MNPs and PC/NM, along with their ecotoxicological effects on aquatic biota, have been conducted. Fish easily ingest microplastic particles, both unintentionally due to their small size and deliberately, due to resemblance to food sources (Zubair et al., 2020; Naz et al., 2022). A study by Wang et al. (Wang et al., 2020) revealed the presence of microplastics in over 150 fish species in aquatic environments. In the Gorgan Bay of the Caspian Sea, various types of microplastics, including polypropylene, polyester, nylon,

TABLE 2 Toxicological effects of various microplastics and nanoplastics on mammals.

Animal strain	Plastic type	Particle size (μm)	Route of administration	Dose	Exposure duration	Changes	References
BALB/c mice	Polystyrene	5.0–5.9	Oral	0.01–1 mg/day	6 weeks	Decrease in sperm no., motility, and serum testosterone; increase in sperm deformity rate; oxidative stress	Xie et al. (2020)
ICR male mice	Polystyrene	20 nm	injected via tail vein	50 μg/kg·d	48 h	Inhibited StAR mRNA and protein expression in mice testis and TM3 cells. and induced mTOR/4E-BP1 phosphorylation by ERK1/2 MAPK and AKT pathways.	Sui et al. (2023)
C57BL/6 mice	Polyethylene	10–150	Oral	6, 60, and 600 μg/day	5 weeks	Intestinal inflammation, alterations in gut microbiome at 600 μg/day, changes in innate immunity at all doses	Li et al. (2020a)
BALB/c mice	Polystyrene	0.5, 4, and 10	Oral	10 mg/mL	24 h and 28 days	Spermatogenic disorder, testicular inflammation, decreased testosterone levels	Jin et al. (2021)
C57BL/6NTac mice	Polystyrene	1, 4, and 10	Oral	1.49–4.55 3,107 particles	4 weeks	No intestinal inflammation or changes in body or organ wt	Stock et al. (2019)
ICR mice	Polystyrene	5	Oral	500 μg/mL	28 days	Aggravation of dextran sodium sulfate– based acute colitis and increased intestinal permeability	Zheng et al. (2021)
Mice	Polystyrene	20 nm	TM3 cells culture	50–150 μg/mL	24 h	Mitochondrial impairment and apoptosis in TM3 cells. Compromised energy metabolism and testosterone synthesis in TM3 cells. plasma membrane integrity of TM3 cells was Destructed	Sun et al. (2023)
CD-1 mice	Polyethylene and Polystyrene	0.5–1	Oral	2 mg/L	90 days	Increased toxicity to flame retardants	Deng et al. (2018)
ICR mice	Polyethylene	~16.9	Oral	0.125–2.0 mg/kg	90 days	Changes in lymphocyte subpopulation in spleen, decrease in IgA in females, alterations in live births per dam and pup body wt	Park et al. (2020)
ICR mice	Polystyrene	5	Oral	0.6–70 μg/day	35 days	Sperm cell apoptosis and expression of proinflammatory cytokines	Hou et al. (2021)
Sprague-Dawley rats	Polystyrene	~24	Intrajugular	1.3–1.95 million beads/100 g body wt	One-time administration	Pulmonary embolism, hypoxemia, increase in alveolar neutrophil chemotaxis and decrease in survival	Zagorski et al. (2003)
Sprague-Dawley rats	Polystyrene	0.02	Intratracheal instillation	2.64 3 1014 particles	24 h	Particles present in maternal lungs, heart, spleen, placenta and fetal lungs, heart, liver, kidney, and brain	Fournier et al. (2020)

(Continued on following page)

TABLE 2 (*Continued*) Toxicological effects of various microplastics and nanoplastics on mammals.

Animal strain	Plastic type	Particle size (μm)	Route of administration	Dose	Exposure duration	Changes	References
Sprague-Dawley rats	Polystyrene	0.01	Inhalation	0.75–3 3,105 particles/cm	14 days	Male rats: decrease in inspiratory time. Female rats: decrease in inspiratory, expiratory times and respiratory frequency in some groups; elevated markers of lung fibrosis and inflammation	Lim et al. (2021)
Mice	Polystyrene	50 nm	Oral	100 mg/mL	24 h	weight loss, increased death rate, alternated biomarkers, and histological damage of the kidney	Meng et al. (2022)
Wistar rat	Polystyrene	25, 50	Oral	1–10 mg/kg	5 weeks	Subtle changes in neurobehavior	Rafiee et al. (2018)
Wistar rat	Polystyrene	0.5	Oral	0.015–1.5 mg/kg/day	90 days	Ovarian fibrosis, decrease in ovarian follicle and reserve capacity	An et al. (2021)
Mice	Polystyrene MPs	-	Oral	0.5, 4, 10 μm	28 days	Decreased sperm quality and testosterone level, and testicular inflammation	Jin et al. (2021)
Rats	Polystyrene NPs	-	Oral	1, 3, 6 and 10 mg kg−1 day−1	5 Weeks	thyroid endocrine disruption, metabolic deficit, decreased serum levels	Amereh et al. (2019)
C57BL/6 mice	Polyethylene MPs	-	Oral	6, 60, and 600 μg/day	5 weeks	Intestinal dysbacteriosis and inflammation	Li et al. (2020b)
Mice	Polystyrene MPs	0.5, 50	Oral	1,000 μg/L	5 weeks	Hepatic triglyceride (TG) and total cholesterol (TCH) levels decreased, modified the gut microbiota composition and induce hepatic lipid disorder	Lu et al. (2018)
ICR mice	Polystyrene	0.5, 5	Oral	0.024 and 0.24 mg/kg/day	3 weeks	Disorders of fatty acid metabolism were observed in the offspring of mice that consumed MPs	Luo et al. (2019)
ICR mice	Polystyrene	5	Oral	0.024 and 0.24 mg/kg/day	6 weeks	MP accumulates in the intestine, causes a disturbance of the intestinal barrier, changes in the intestinal microflora, disturbances in the metabolism of bile acids	Jin et al. (2019)
C57BL/6 mice	Polystyrene	1–10 μm and 50–100	Oral	2.4 mg/kg/days	8 weeks	MP consumption led to overproduction of ROS, the development of oxidative stress, and impaired skeletal muscle regeneration. MP suppressed myogenic and stimulated adipogenic differentiation of myosatellite cells. Muscle regeneration was negatively correlated with MP particle size	Shengchen et al. (2021), Li et al. (2023b)

and polystyrene, were detected in sediment, fishes, and benthic organisms, ranging from 80 to 105 MP/kg (Bagheri et al., 2020). Given that fish is a significant protein source for humans, the existence of microplastics in fish and their ecotoxicological effects could have adverse consequences for both aquatic food sources and human health (Barboza et al., 2018). There is an urgent need to find or develop various methods like the use of microorganisms (Herrera et al., 2023) or the use of non-toxic, novel agglomerate (Peller et al.,

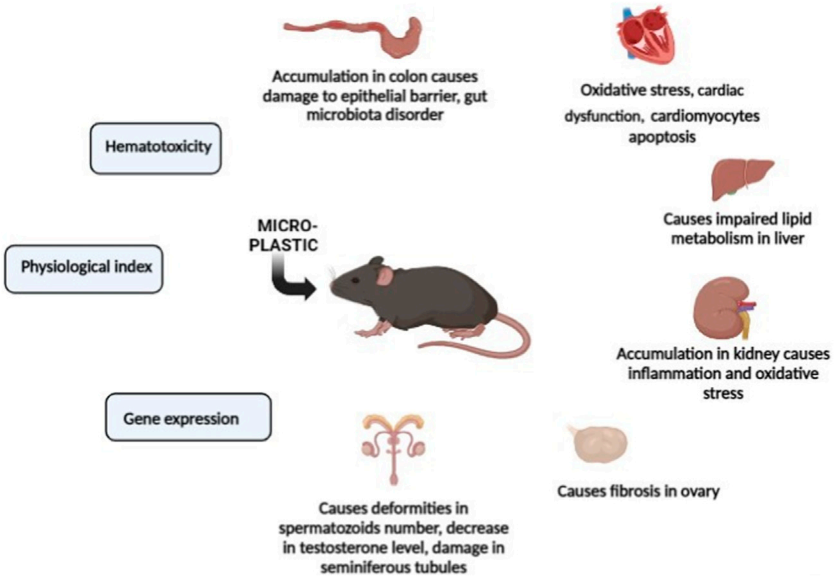

FIGURE 2
Effects of microplastics on mammals.

2024) for degradation of micro and nano plastics for sustainable plastic waste management. Furthermore, social responsibility and a shift in consumer behaviours and habits in adopting low-risk products should also be encouraged (Rashed et al., 2023). Despite an abundance of research on the ingestion and consequences of MNPs, there has been a scarcity of review publications on this topic until recently. Therefore, this review specifically focuses on a multidisciplinary approach, drawing upon insights from environmental science, ecology, toxicology, and public health. It covers various types of micro and nano-plastics, including microbeads, microfibers, and nanoplastics, and their interactions with different aquatic organisms ranging from plankton to fish. Furthermore, the review considers diverse aquatic environments such as oceans, rivers, lakes, and estuaries, acknowledging the variability in plastic pollution levels and ecological dynamics across these habitats. Additionally, the review highlights uncertainties and information gaps in understanding the fate, distribution, and harmful mechanisms of MNPs and PC/NM to aquatic organisms.

2 Toxic effects of MNPs on aquatic organisms

Microplastics (MPs) may have detrimental effects on aquatic ecosystems, impacting various organisms such as phytoplankton, invertebrates, mollusks, and fish, as they enter freshwater networks in substantial quantities (0.12–387 items/m^3) (Brandts et al., 2018; Triebskorn et al., 2019). Numerous studies have been conducted to investigate the toxic effects of MNPs on water-dwelling organisms. A study conducted by Chae et al. (Chae et al., 2018) observed the trophic transfer and effects of 51 nm polystyrene nano-plastics (PS-NPs) on four freshwater species, including the alga *Chlamydomonas reinhardtii*. Despite exposure to concentrations as high as 100 mg/L resulting in little to no mortality, confocal laser microscopy revealed the attachment of NPs to the zoospores' surface and outer layer penetration during cell division. Nano-plastics also led to reduced locomotor activity and induced histological abnormalities in the livers of fish directly exposed to them. Furthermore, the study observed that NPs could pass through embryonic walls and persist in hatched larvae yolk. In another investigation (Sökmen et al., 2020), the effects of short-term (24 h) exposure to negatively charged fluorescent PS-NPs (50 nm), aggregated with gold nanoparticles (Au ions), were explored in *Danio rerio*. Comparing the impacts of individual exposure to PS-NPs and Au ions, the study found increased mortality and deformation rates in the exposed organisms. Additionally, there was a stimulated immunological response, indicated by elevated expression of IL-6 and IL-1 β. Exposure to PS NPs or Au ions individually resulted in higher levels of reactive oxygen species (ROS), formation of intracellular vacuoles, and mitochondrial damage (Lee et al., 2019).

Exposure to 45 nm polymethyl methacrylate nanoparticles (PMMA-NPs) at concentrations of ≤20 mg/L was found to affect the immune system of fish, with an observed increase in mRNA transcripts associated with lipid metabolism (Brandts et al., 2018). In *Sebastes schlegelii* samples exposed to 0.5 and 15 μm PS-NPs (190 μg/L) exhibited clustering, reduced swimming speed, increased oxygen consumption, and ammonia excretion, as well as lower protein and lipid contents (Yin et al., 2019; Jiang et al., 2023a). Despite ingesting more than 90% of microalgae containing polystyrene nanoparticles (PS-NPs), brine shrimp (*Artemia franciscana*) did not show any significant effects (Sendra et al., 2020). Zebrafish exposed to secondary nanoparticles showed a 54% increase in cell death through skin diffusion compared to microplastics (Enfrin et al., 2020; Jiang et al., 2023b). Sökmen et al. (Sökmen et al., 2020) explored the impacts of NPs on zebrafish (*D. rerio*), revealing that 20 nm diameter PS-NPs reached and accumulated in the zebrafish brain, causing

TABLE 3 Effect of microplastics and nanoplastics on human health.

Plastic type	Size	Effect	Target cell line	References
Polypropylene MNPs	1–2 μm and 400–500 nm	Caused the death of 76.70% and 77.18% of human embryonic kidney cells after exposure of 48 and 72 h, respectively	HEK293T human embryonic kidney cell line	Hussain et al. (2023)
Polystyrene NPs	100 nm and 500 nm	500 nm PS-NPs bound to the surface of cell membranes causing cell membrane damage. 100 nm PS-NPs aggregated in the cytoplasm and blocked the autophagic flux in HUVECs	Human umbilical vein endothelial cells (HUVECs)	Lu et al. (2022)
Polystyrene MPs	1 and 10 μm	Caused a significant reduction in cell proliferation and changed the morphology of cells exposed	Cultured human alveolar A549 cells	Goodman et al. (2021)
Polystyrene MPs	50 nm	Caused genotoxicity through different mechanisms of DNA damage	Three human leukocytic cell lines: Raji-B (B-lymphocytes), TK6 (lymphoblasts) and THP-1 (monocytes)	Rubio et al. (2020)
Polystyrene MPs	5 and 20 μm	Induced inflammation Induced adverse effects on neurotransmission	Liver cells	Deng et al. (2017)
Polystyrene NPs	60 nm	Strong interaction and aggregation with mucin. Induced apoptosis	Intestinal epithelial cells	Inkielewicz-Stepniak et al. (2018)
Polystyrene NPs	60 nm	Induced ROS generation and ER stress Induced autophagic cell death	Lung epithelial cells	Xia et al. (2008)
Polystyrene MPs	5 μm	Changes in amino acid and bile acid metabolism. Induced gut microbiota dysbiosis and intestinal barrier dysfunction	Intestine	Jin et al. (2019)
Microplastics	0.5 and 5 μm	Metabolic disorder associated with gut microbiota dysbiosis and gut barrier dysfunction	Gut cells	Luo et al. (2019)
Polystyrene	44 nm	induced strong upregulation of IL-6 and IL-8 genes	Human gastric adenocarcinoma cells (AGS)	Forte et al. (2016)
Polystyrene	50, 100 nm	Size dependency regarding particle translocation	Human colon carcinoma cells (Caco-2)	Walczak et al. (2015)
Polystyrene	57 nm	Binding of mucin and induction of adoptosis	Human colon carcinoma cells	Inkielewicz-Stepniak et al. (2018)
Polystyrene	20,40, 100 nm	40 nm particles internalized faster than 20 or 100 nm particles in both cell line	human lung carcinoma cells (A549), human astrocytoma 132	Varela et al. (2012)
Polystyrene	116 nm	Cellular uptake	Human lung carcinoma cells	Deville et al. (2015)
Polystyrene	40, 50 nm	Cellular uptake irreversible, intracellular concentration increased linearly	Human lung carcinoma cells	Salvati et al. (2011)
Polystyrene	60 nm	Amino-functionalized polystyrene particles induce autophagic cell death through the induction of endoplasmic reticulum stress	Human bronchial epithelium	Chiu et al. (2015)

oxidative DNA damage. Other organs were also reported to be affected by NPs, establishing zebrafish as a valuable model for studying NP toxicity (Bhagat et al., 2020a; Sarasamma et al., 2020). The hydrophobicity of tetracycline-incubated NPs contributed to variations in toxic effects observed in the marine microalgae *Skeletonema costatum* (Feng et al., 2020a). Nano-plastics adsorption on microalgae has been documented in several studies, with some cases showing a reduction in algal growth while others did not (Bergami et al., 2017; Heinlaan et al., 2020).

The aggregation behaviour of globular PS-NPs is influenced by the chemical conditions of the solution, which may be enhanced by increasing ionic strength and electrolyte valence (Cai et al., 2021). In freshwater biofilms, PS-NPs (positively charged amide-modified) are more hazardous to photosynthesis and extracellular enzymatic activity than negatively charged particles (Miao et al., 2019). Eutrophication may be aggravated by freshwater NPs and marine rotifer *Brachionus koreanus* showed elevated stress effects from NPs, and the related oxidative stress caused damage to the lipid membranes (Jeong et al., 2018; Feng et al., 2020b). Since their ingestion has been seen in numerous aquatic species (marine mammals, turtles, and fish) as well as invertebrates (zooplankton, bivalves, and crustaceans), plastic particles have raised some serious environmental concerns (Botterell et al., 2019; Wang et al., 2019; Huang et al., 2020; Zitouni et al., 2020; Naz et al., 2023a). Aside from particle features, the environment also has an impact on how NP pollution affects aquatic species. Exopolymeric substances (EPS) are the aggregation agents produced by microorganisms; nevertheless, when synthesized by diatoms and algae, they have been proven to inhibit NP harmful effects (Grassi et al., 2020; Mao et al., 2020). Apart from that various toxicological effects of MNPs are also reported in different species (Table 1).

TABLE 4 Identification and quantification of microplastics and nanoplastics.

Technique	Advantages	Disadvantages	References
FTIR	• Simple and reliable	• High concentration for NPs	Wang et al. (2018), Strungaru et al. (2019), Granek et al. (2020), Cai et al. (2021)
	• Particle quantification	• Water interference	
	• Identifying polymeric microplastics (>10–20 µm size)	• Unable to adequately characterize very small particles or fibers (<20 µm)	
	• Non-destructive	• A time-consuming work	
	• Aliphatic compounds and polyesters are well detectable	• Limited size (~25 µm) and thickness (<100 µm)	
	• Operative for thin film NPs	• Contaminants may overlap polymeric bands	
Roman Spectroscopy	• Higher resolution	• Fluorescent interference	Wang et al. (2018), Prata et al. (2019), Strungaru et al. (2019), Alprol et al. (2021), Cai et al. (2021), Zhou et al. (2021)
	• Identify trace PS-NPs	• Trade-off between measurement time as well as representativeness	
	• Non-destructive chemical characterization of microplastics	• Lacks a high lateral resolution	
	• Lower water interference	• Low signal intensity	
	• Effective for polymer chemical composition, organic and inorganic fillers	• Are unable to adequately characterize very small particles or fibers <1 µm	
	• Aliphatic and aromatic compounds, are well detectable	• Time needed for characterization is highly limiting for environmental samples	
	• Characterization of microplastics <20 µm	• Polymer heating as well as degradation	
	• Not reserved for sample thickness or shape	• Affected by colour, additives, fluorescence, and contaminants adsorbed on microplastics	
	• Good for spatial resolution	• Long time measurement	
	• More sensitive to non-polar groups		
Mass spectrometry	• Less mass sample	• Preconcentration of sample needed	Fu et al. (2020), Cai et al. (2021), Vega-Herrera et al. (2022)
	• Numerous polymers for a single run	• Lack morphological information	
	• Purification and vaporization of polymers	• Not popular owing to severe extraction and purification	
	• Determine Mass/number concentration		
Pyrolysis GC/MS	• Analysis of polymers and additives at a time	• Expensive	Prata et al. (2019), Alprol et al. (2021)
	• Chemical characterization of microplastics (single or bulk sample)	• Need pre-selection	
		• Not effective for large quantity of sample	
		• Lack information of number, size or shape	
		• Time consuming	
TED–GC/MS	• Effective for complex matrices	• Identify few polymers as PE and PET	Prata et al. (2019), Alprol et al. (2021)
	• Use high sample masses and measure complex heterogeneous matrices for polymer identification and quantification	• Costly	
		• Need more time	
XPS	• Surface characterization	• No polymer type information	Cai et al. (2021)
		• Expensive	
SEM/TEM	• Size and number of particles	• Polymer identification required	Wang et al. (2018), Strungaru et al. (2019), Fu et al. (2020), Cai et al. (2021)
	• Provide high resolution topography images and enable microplastics differentiation from other plastics	• Costly	

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TABLE 4 (*Continued*) Identification and quantification of microplastics and nanoplastics.

Technique	Advantages	Disadvantages	References
	• Examine surface characteristics of microplastics	• Not valid for bulk samples	
	• High-resolution image require laborious preparation steps	• Representativeness issue	
		• For NPs, sample preparation needed	
MALS	• Online connection with AF4/CF3	• Nano-plastics separation needs perfectness	Cai et al. (2021)
	• Particles size distribution	• Polymer identification required	
DLS	• Simple, easy and reliable	• Not appropriate for polydisperse particles	Fu et al. (2020), Cai et al. (2021)
	• Effective for nano-sized particles and size distribution	• Need polymer identification	
	• Facile sample preparation, high throughput and reproducibility	• Cause significant bias on determination of size	
		• Merely for spherical particles	
Nanoparticle Tracking Analysis	• Simple, reliable and easy to use	• Complex in operation	Fu et al. (2020), Cai et al. (2021)
	• Size resolution	• Only for spherical particles	
	• Size distribution and particles concentration	• Data analysis affected by analysis factors	
	• More sensitive		
	• Effective for nano-sized particles		
	• Operative for single particle counts		
Impedance Spectroscopy	• Fast measurement of size and concentration of microplastics	• Need to expand this method to cover a greater (1–1,000 µm) size range	Colson and Michel (2021)
	• Characterize electrical properties of individual particles		
	• No visual sorting or filtration required		
Fluorescence Spectroscopy	• Little detection limit	• Sample preparation need fluorescent dyes or labels	Fu et al. (2020)
	• Provide single absorption or emission line, and a linear standard curve	• Less elemental sensitivity	
	• More sensitive		
Visual Sorting	• Cheap	• Unable to characterize to molecule <500 µm	Alprol et al. (2021)
	• Suitable for pre-sorting of samples	• Underestimation of small or transparent elements	
	• Classify particles by shape, size, and colour	• Non-chemical composition	
		• Less the particle size more will be the error	
		• Over-estimation owing to mis-identification	

*FTIR (Fourier transform infrared spectroscopy), TED–GC/MS (Thermoextraction and desorption coupled with gas chromatography-mass spectroscopy), XPS (X-ray photoelectron spectroscopy), SEM/TEM (Scanning electron microscopy or Transmission electron microscopy), MALS (Multi-angle light scattering), DLS (Dynamic light scattering).

3 Ecological toxicity and human health risk

3.1 Effect on organisms

In addition to their small size, physical and chemical properties of M NPs, can have a significant impact on aquatic species and human health. Adsorption of harmful chemicals on the MNPs raises concerns about how various lethal chemicals may interact with these particles, desorbing into animal tissues and causing harmful effects (Yu et al., 2019; Zhang et al., 2020). Nano-plastics have a greater surface area than MPs, allowing them to adsorb contaminants such as hazardous compounds or heavy metals at higher concentrations (Al-Thawadi, 2020; Naz et al., 2023b). These can be ingested by organisms and then transported and accumulated in their different organs. Aquatic life at all trophic levels, including bacteria, bivalves, algae, echinoderms, rotifers, arthropods, and fish, can be affected by NPs in terms of reproduction, mortality, multiple molting, growth, feeding, immunological responses, and antioxidation (Liu et al., 2019; Bibi et al., 2023). Once NPs enter the aquatic environment, they are easily transported down the food chain, posing a major threat to the ecological environment's long-term growth, as well as food safety and human health (Zhang F. et al., 2020; Shi et al., 2020).

The interaction of NPs with heavy metals, polycyclic aromatic hydrocarbons, medicines, organic halogens, and pesticides, has become a major concern of environmental risks (Jacob et al., 2020). Extensive research has been conducted on the ecological toxicity of NPs, but few have been conducted on the combined toxicity induced by compound pollution (Bhagat et al., 2020b; Zhu et al., 2020). Interactions with co-pollutants can modify the uptake and accumulation of plastics and/or contaminants in exposed organisms, causing significant changes in the surface characteristics of plastics (Ghaffar et al., 2018; Zhang et al., 2020). The toxicity of MPs to organisms is determined by their aggregate size (Zhang et al., 2019). Because particle toxicity was inversely related to size in general, the aggregated MPs could be less bioavailable to aquatic organisms (Wang et al., 2020; Choi et al., 2020). Outside the organisms, MPs aggregates may have a harmful effect. MPs aggregates, for example, impeded photosynthesis and limited the transfer of nutrients and energy by microalgae in marine ecosystems. Furthermore, MP-biota hetero-aggregates may cause physical harm to organisms, such as splits and oxidative stress (Wu et al., 2019; Zhu et al., 2019; Choi et al., 2020).

There is still a lack of knowledge about the hazardous contaminants, additives, and infections found in fish and shellfish, as well as their potential consequences on human health. According to the Food and Agriculture Organization (FAO) essential food risk evaluations are lacking, with no information on metabolism and nothing on the excretion of MPs and NPs after intake (Al-Thawadi, 2020). Accumulation and biomagnification of hazardous compounds connected with MPs in marine trophic webs is another harmful impact (Figure 1). When top predators and humans consume species polluted with MPs or chemicals released from these particles after ingestion, this magnification raises the danger of harmful effects of these chemicals (Gallo et al., 2018; Vedolin et al., 2018). As a result, it is been suggested that plastic debris raises the global risk of human and animal diseases by creating new contamination/infection pathways, introducing pathogens through the environmental spread of MPs, or migrating organisms contaminated with MPs linked to pathogens (Bhagat et al., 2020a; Al-Thawadi, 2020; Haroon et al., 2022).

3.1.1 Effects on mammals

One of the most prominent classes of non-natural products made by humans that have pervaded earth's surface environment is plastics, so much so that these durable synthetic organic polymers are heralded as a defining stratigraphic marker for the Anthropocene (Zalasiewicz et al., 2016). Geyer and colleagues (Geyer et al., 2017) recently estimated that 8.3 billion metric tons of virgin plastics have been produced up to the year 2017, and with the continuation of current production and waste management practices, about 12 billion tons of plastic waste would be found in landfills and the natural environment by 2050. Plastic wastes are persistent environmental pollutants. Larger pieces of plastic waste present well-publicized ecological problems in terms of physical entanglement and entrapment (Gündoğdu et al., 2019). In the past 3 years, a good number of studies have examined the effect of pristine MNPs in mammalian models (largely mice). These studies are summarized in Table 2 and are broadly recapped below. In mice, ingested MNPs could be found in the gut (Deng et al., 2017), liver and kidney (Yang et al., 2019). Pathological changes to the gut include a reduction in mucus secretion, gut barrier dysfunction (Jin et al., 2019), intestinal inflammation, and gut microbiota dysbiosis (Lu et al., 2018; Li B. et al., 2020). Figure 2 shows the effects of microplastic on mammalian model species (mouse).

3.2 Effects on human health

Studies on the toxic effects of M NPs on human health are mainly focused on gastrointestinal and pulmonary toxicity, which includes oxidative stress, metabolic problems, and inflammatory reactions. Furthermore, it is crucial to know whether MPs can be destroyed further after ingestion in the gut's acidic environment or inside cells' lysosomes. As a result, greater research into the long-term fate of ingested MPs and NPs in the human body is required (Yee et al., 2021).

Micro-plastics have been found in a variety of seafood species, including bivalves, fish, and shrimp as well as in sea salt and food packaging (Peixoto et al., 2019; Li et al., 2020; Jacob et al., 2020). These are thought to be bio-persistent, causing unfavourable biological responses in humans such as oxidative stress, inflammation, cell apoptosis, genotoxicity, and tissue necrosis, as well as localized cell and tissue damage, fibrosis, and even carcinogenesis (Peixoto et al., 2019). Ingestion, oral inhalation, or skin contact with NPs may occur as a result of the usage of plastic items or through unintended methods (Lehner et al., 2019). As a result, human exposure to NPs has been attributed to the ingestion of NP particles, which can be easily ingested through the consumption of contaminated seafood or water. If NPs enter the gastrointestinal tract, they can cause tissue inflammation or enter the circulatory system via the mesenteric lymph, where they can build up in the liver. Furthermore, oxidative stress, the gut microbiome, and lipid metabolism have all shown significant modifications. As a result, NPs may affect the central nervous system in humans (Mattsson et al., 2017). Most of the reported studies used polystyrene due to its ease of synthesis and processing into nanoparticles, whereas polyurethanes, polyolefins (e.g., polyethylene and polypropylene), polyesters, and are the most often used commercial plastics (Gunasekaran et al., 2020). The hazardous effects of different forms of MNPs on human health are mainly unknown due to variations in the shape, particle size, and chemical composition of plastics (Leslie and Depledge, 2020; Khan et al., 2023). Table 3 shows various studies related to the effect of micro and nano-plastics on human beings. Recent studies showed that various types of MNPs can affect the survival of human foetus during early embryonic development (Hussain et al., 2023). Likewise, the MNPs can cause severe damage to cell membrane (Lu et al., 2022), alter the morphology of the exposed human alveolar cells (Goodman et al., 2021) and cause genotoxicity in human blood cells (Rubio et al., 2020).

As a result, we recommend that future research needs focus on determining the potential risks associated with chronic exposure to various M NPs at appropriate concentrations. Unfortunately, the assessment of human exposure to NPs is still a scientific challenge owing to inappropriate methods, practiced reference materials, and standard analytical techniques (Brachner et al., 2020; Paul et al., 2020). Some common techniques used for the identification of M NPs are listed in table (Table 4).

4 Conclusion

Micro and nano-plastics are significant sources of plastic contamination in marine ecosystems and the production of M NPs has increased due to biodegradation, thermo-oxidative degradation, thermal and hydrolysis processes, and also photodegradation. The effects of MPs on marine life are well explored. However, their effects on freshwater species have very little literature as data on freshwater species is insufficient. So, freshwater systems are suffering from severe contamination compared with marine systems and the ecotoxicological effects of M NPs on freshwater species need more research efforts. The development of analytical methods for M NPs, as well as their standardization, is becoming more important to allow the detection, identification, and quantification of polymers in environmental matrices. While research on micro and nano-plastics is advancing rapidly, several significant limitations and gaps like lack of standardized methods for detection and characterization, limited understanding of fate and behavior of MNPs, ecological effects of MNPs on different trophic levels, long-term effects of MNPs, and ingestion and trophic transfer of MNPs still exist. Addressing these limitations and filling these knowledge gaps is essential for developing effective mitigation strategies, informing policy decisions, and safeguarding both aquatic ecosystems and human health from the impacts of micro and nano-plastic pollution. Furthermore, New ways to study the impacts of MNPs on the biota and humans (*in vitro*) are also required.

Author contributions

SN: Conceptualization, Data curation, Investigation, Methodology, Resources, Software, Validation, Writing–original draft, Writing–review and editing. AC: Conceptualization, Data curation, Investigation, Methodology, Writing–original draft, Writing–review and editing. NK: Conceptualization, Data curation, Investigation, Writing–review and editing. QU: Conceptualization, Project administration, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. FZ: Conceptualization, Data curation, Investigation, Writing–review and editing. AQ: Data curation, Methodology, Writing–review and editing. IM: Conceptualization, Data curation, Writing–review and editing. AK: Data curation, Investigation, Methodology, Writing–review and editing. SS: Writing–review and editing. SB: Writing–review and editing. MK: Conceptualization, Data curation, Visualization, Writing–review and editing. PH: Funding acquisition, Investigation, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Alimi, O. S., Farner Budarz, J., Hernandez, L. M., and Tufenkji, N. (2018). Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. *Environ. Sci. Technol.* 52 (4), 1704–1724. doi:10.1021/acs.est.7b05559

Alprol, A. E., Gaballah, M. S., and Hassaan, M. A. (2021). Micro and nanoplastics analysis: focus on their classification, sources, and impacts in marine environment. *Reg. Stud. Mar. Sci.* 42, 101625. doi:10.1016/j.rsma.2021.101625

Al-Thawadi, S. (2020). Microplastics and nanoplastics in aquatic environments: challenges and threats to aquatic organisms. *Arab. J. Sci. Eng.* 45 (6), 4419–4440. doi:10.1007/s13369-020-04402-z

Amereh, F., Eslami, A., Fazelipour, S., Rafiee, M., Zibaii, M. I., and Babaei, M. (2019). Thyroid endocrine status and biochemical stress responses in adult male Wistar rats chronically exposed to pristine polystyrene nanoplastics. *Toxicol. Res.* 8, 953–963. doi:10.1039/c9tx00147f

An, R., Wang, X., Yang, L., Zhang, J., Wang, N., Xu, F., et al. (2021). Polystyrene microplastics cause granulosa cells apoptosis and fibrosis in ovary through oxidative stress in rats. *Toxicology* 449, 152665. doi:10.1016/j.tox.2020.152665

Bagheri, T., Gholizadeh, M., Zakeri, M., Hedayati, A., Rabaniha, M., Aghaeimoghadam, A., et al. (2020). Microplastics distribution, abundance and composition in sediment, fishes and benthic organisms of the gorgan Bay, Caspian Sea. *Chemosphere* 257, 127201. doi:10.1016/j.chemosphere.2020.127201

Barboza, L. G. A., Vethaak, A. D., Lavorante, B. R., Lundebye, A. K., and Guilhermino, L. (2018). Marine microplastic debris: an emerging issue for food security, food safety and human health. *Mar. Pollut. Bull.* 133, 336–348. doi:10.1016/j.marpolbul.2018.05.047

Barría, C., Brandts, I., Tort, L., Oliveira, M., and Teles, M. (2020). Effect of nanoplastics on fish health and performance: a review. *Mar. Pollut. Bull.* 151, 110791. doi:10.1016/j.marpolbul.2019.110791

Bergami, E., Pugnalini, S., Vannuccini, M. L., Manfra, L., Faleri, C., Savorelli, F., et al. (2017). Long-term toxicity of surface-charged polystyrene nanoplastics to marine planktonic species Dunaliella tertiolecta and Artemia franciscana. *Aquat. Toxicol.* 189, 159–169. doi:10.1016/j.aquatox.2017.06.008

Bhagat, J., Nishimura, N., and Shimada, Y. (2020a). Toxicological interactions of microplastics/nanoplastics and environmental contaminants: current knowledge and future perspectives. *J. Hazard. Mat.* 405, 123913. doi:10.1016/j.jhazmat.2020.123913

Bhagat, J., Zang, L., Nishimura, N., and Shimada, Y. (2020b). Zebrafish: an emerging model to study microplastic and nanoplastic toxicity. *Sci. Total Environ.* 728, 138707. doi:10.1016/j.scitotenv.2020.138707

Bibi, S., Abbas, G., Khan, M. Z., Nawaz, T., Ullah, Q., Uddin, A., et al. (2023). The mutational analysis of mitochondrial DNA in maternal inheritance of polycystic ovarian syndrome. *Front. Endocrinol.* 14, 1093353. doi:10.3389/fendo.2023.1093353

Botterell, Z. L., Beaumont, N., Dorrington, T., Steinke, M., Thompson, R. C., and Lindeque, P. K. (2019). Bioavailability and effects of microplastics on marine zooplankton: a review. *Environ. Pollut.* 245, 98–110. doi:10.1016/j.envpol.2018.10.065

Brachner, A., Fragouli, D., Duarte, I. F., Farias, P., Dembski, S., Ghosh, M., et al. (2020). Assessment of human health risks posed by nano-and microplastics is currently not feasible. *Int. J. Environ. Res. Public Health* 17 (23), 8832. doi:10.3390/ijerph17238832

Brancaleone, E., Mattei, D., Fuscoletti, V., Lucentini, L., Favero, G., Frugis, A., et al. (2023). "Microplastic in drinking water: a pilot study," in *Proceedings of the 3rd international conference on microplastic pollution in the mediterranean sea* (Cham: Springer International Publishing), 165–172.

Brandts, I., Garcia-Ordoñez, M., Tort, L., Teles, M., and Roher, N. (2020). Polystyrene nanoplastics accumulate in ZFL cell lysosomes and in zebrafish larvae after acute exposure, inducing a synergistic immune response *in vitro* without affecting larval survival *in vivo*. *Environ. Sci. Nano* 7 (8), 2410–2422. doi:10.1039/d0en00553c

Brandts, I., Teles, M., Tvarijonaviciute, A., Pereira, M. L., Martins, M. A., Tort, L., et al. (2018). Effects of polymethylmethacrylate nanoplastics on *Dicentrarchus labrax*. *Genom* 110 (6), 435–441. doi:10.1016/j.ygeno.2018.10.006

Cai, H., Xu, E. G., Du, F., Li, R., Liu, J., and Shi, H. (2021). Analysis of environmental nanoplastics: progress and challenges. *Chem. Eng. J.* 410, 128208. doi:10.1016/j.cej.2020.128208

Chae, Y., Kim, D., Kim, S. W., and An, Y. J. (2018). Trophic transfer and individual impact of nano-sized polystyrene in a four-species freshwater food chain. *Sci. Rep.* 8 (1), 284–311. doi:10.1038/s41598-017-18849-y

Chiu, H. W., Xia, T., Lee, Y. H., Chen, C. W., Tsai, J. C., and Wang, Y. J. (2015). Cationic polystyrene nanospheres induce autophagic cell death through the induction of endoplasmic reticulum stress. *J. Nanobiotechnology* 13, 76. doi:10.1039/c4nr05509h

Choi, J. S., Hong, S. H., and Park, J. W. (2020). Evaluation of microplastic toxicity in accordance with different sizes and exposure times in the marine copepod Tigriopus japonicus. *Mar. Environ. Res.* 153, 104838. doi:10.1016/j.marenvres.2019.104838

Colson, B. C., and Michel, A. P. (2021). Flow-through quantification of microplastics using impedance spectroscopy. *ACS Sens.* 6 (1), 238–244. doi:10.1021/acssensors.0c02223

Deng, Y., Zhang, Y., Lemos, B., and Ren, H. (2017). Tissue accumulation of microplastics in mice and biomarker responses suggest widespread health risks of exposure. *Sci. Rep.* 7, 46687. doi:10.1038/srep46687

Deng, Y., Zhang, Y., Lemos, B., Ren, H., Yang, X., et al. (2018). Evidence that microplastics aggravate the toxicity of organophosphorus flame retardants in mice (*Mus musculus*). *J. Hazard Mater* 357, 348–354. doi:10.1016/j.jhazmat.2018.06.017

Deville, S., Penjweini, R., Smisdom, N., Notelaers, K., Nelissen, I., Hooyberghs, J., et al. (2015). Intracellular dynamics and fate of polystyrene nanoparticles in A549 lung epithelial cells monitored by image (cross-)correlation spectroscopy and single particle tracking. *Biochim. Biophys. Acta Mol. Cell Res.* 1853, 2411–2419. doi:10.1016/j.bbamcr.2015.07.004

Enfrin, M., Lee, J., Gibert, Y., Basheer, F., Kong, L., and Dumée, L. F. (2020). Release of hazardous nanoplastic contaminants due to microplastics fragmentation under shear stress forces. *J. Hazard. Mat.* 384, 121393. doi:10.1016/j.jhazmat.2019.121393

Feng, L. J., Shi, Y., Li, X. Y., Sun, X. D., Xiao, F., Sun, J. W., et al. (2020b). Nanoplastics promote microcystin synthesis and release from cyanobacterial Microcystis aeruginosa. *Environ. Sci. Technol.* 54 (6), 3386–3394. doi:10.1021/acs.est.9b06085

Feng, L. J., Sun, X. D., Zhu, F. P., Feng, Y., Duan, J. L., Xiao, F., et al. (2020a). Behavior of tetracycline and polystyrene nanoparticles in estuaries and their joint toxicity on marine microalgae Skeletonema costatum. *Environ. Pollut.* 263, 114453. doi:10.1016/j.envpol.2020.114453

Fernandes, V. C., Boesmans, D., Domingues, V. F., and Delerue-Matos, C. (2023). Evaluating contaminants in fish: plastic additives and pesticides in the context of food safety. *Biol. Life Sci. Forum.* doi:10.3390/Foods2023-15052

Ferreira, I., Venâncio, C., Lopes, I., and Oliveira, M. (2019). Nanoplastics and marine organisms: what has been studied? *Environ. Toxicol. Pharmacol.* 67, 1–7. doi:10.1016/j.etap.2019.01.006

Food and Agriculture Organization. *The state of food insecurity in the world 2013: the multiple dimensions of food security*. Rome: FAO; 2013. Available at: https://www.fao.org/news/archive/news-by-date/2013/en/(accessed on (accessed on 23 February 2024).

Forte, M., Iachetta, G., Tussellino, M., Carotenuto, R., Prisco, M., De Falco, M., et al. (2016). Polystyrene nanoparticles internalization in human gastric adenocarcinoma cells. *Toxicol Vitro* 31, 126–136. doi:10.1016/j.tiv.2015.11.006

Fournier, S. B., D'Errico, J. N., Adler, D. S., Kollontzi, S., Goedken, M. J., Fabris, L., et al. (2020). Nanopolystyrene translocation and fetal deposition after acute lung exposure during late-stage pregnancy. *Part Fibre Toxicol.* 17, 55. doi:10.1186/s12989-020-00385-9

Frias, JPGL, and Nash, R. (2019). Microplastics: finding a consensus on the definition. *Mar. Pollut. Bull.* 138, 145–147. doi:10.1016/j.marpolbul.2018.11.022

Fu, W., Min, J., Jiang, W., Li, Y., and Zhang, W. (2020). Separation, characterization and identification of microplastics and nanoplastics in the environment. *Sci. Total Environ.* 721, 137561. doi:10.1016/j.scitotenv.2020.137561

Gagné, F., Roubeau-Dumont, E., André, C., and Auclair, J. (2023). Micro and nanoplastic contamination and its effects on freshwater mussels caged in an urban area. *J. Xenobiotics* 13, 761–774. doi:10.3390/jox13040048

Gallo, F., Fossi, C., Weber, R., Santillo, D., Sousa, J., Ingram, I., et al. (2018). Marine litter plastics and microplastics and their toxic chemicals components: the need for urgent preventive measures. *Environ. Sci. Eur.* 30 (1), 13–14. doi:10.1186/s12302-018-0139-z

Geyer, R., Jambeck, J. R., and Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Sci. Adv.* 3, e1700782. doi:10.1126/sciadv.1700782

Ghaffar, A., Jamil, H., Zubair, M., Farooq, M., Murtaza, A., and Ullah, Q. (2018). Effect of dietary supplementation with propylene glycol on blood metabolites and hormones of nili-ravi Buffalo heifers: effect of dietary supplementation on blood metabolites. *Proc. Pak. Acad. Sci. B Life Environ. Sci.* 55 (3), 55–59. Available at: https://ppaspk.org/index.php/PPAS-B/article/view/164

Gigault, J., Ter Halle, A., Baudrimont, M., Pascal, P. Y., Gauffre, F., Phi, T. L., et al. (2018). Current opinion: what is a nanoplastic? *Environ. Pollut.* 235, 1030–1034. doi:10.1016/j.envpol.2018.01.024

Gomes, T., Almeida, A. C., and Georgantzopoulou, A. (2020). Characterization of cell responses in Rhodomonas baltica exposed to PMMA nanoplastics. *Sci. Total Environ.* 726, 138547. doi:10.1016/j.scitotenv.2020.138547

González-Fernández, C., Toullec, J., Lambert, C., Le Goïc, N., Seoane, M., Moriceau, B., et al. (2019). Do transparent exopolymeric particles (TEP) affect the toxicity of nanoplastics on Chaetoceros neogracile? *Environ. Pollut.* 250, 873–882. doi:10.1016/j.envpol.2019.04.093

Goodman, K. E., Hare, J. T., Khamis, Z. I., Hua, T., and Sang, Q. X. A. (2021). Exposure of human lung cells to polystyrene microplastics significantly retards cell proliferation and triggers morphological changes. *Chem. Res. Toxicol.* 34, 1069–1081. doi:10.1021/acs.chemrestox.0c00486

Granek, E. F., Brander, S., and Holland, E. B. (2020). Microplastics in aquatic organisms: improving understanding and identifying research directions for the next decade. *Limnol. Oceanogr. Lett.* 5, 1–4. doi:10.1002/lol2.10145

Grassi, G., Gabellieri, E., Cioni, P., Paccagnini, E., Faleri, C., Lupetti, P., et al. (2020). Interplay between extracellular polymeric substances (EPS) from a marine diatom and model nanoplastic through eco-corona formation. *Sci. Total Environ.* 725, 138457. doi:10.1016/j.scitotenv.2020.138457

Guimarães, A. T. B., Estrela, F. N., Pereira, P. S., Vieira, J. E. A., Rodrigues, A. S. L., Silva, F. G., et al. (2021). Toxicity of polystyrene nanoplastics in Ctenopharyngodon idella juveniles: a genotoxic, mutagenic and cytotoxic perspective. *Sci. Total Environ.* 752, 141937. doi:10.1016/j.scitotenv.2020.141937

Gunasekaran, D., Chandrasekaran, N., Jenkins, D., and Mukherjee, A. (2020). Plain polystyrene microplastics reduce the toxic effects of ZnO particles on marine microalgae Dunaliella salina. *J. Environ. Chem. Eng.* 8 (5), 104250. doi:10.1016/j.jece.2020.104250

Gündoğdu, S., Yeşilyurt, İ. N., and Erbaş, C. (2019). Potential interaction between plastic litter and green turtle *Chelonia mydas* during nesting in an extremely polluted beach. *Mar. Pollut. Bull.* 140, 138–145. doi:10.1016/j.marpolbul.2019.01.032

Han, B., Yacoub, M., Li, A., Nicholson, K., Gruver, J., Neumann, K., et al. (2024). Human activities increased microplastics contamination in the himalaya mountains. *Hydrology* 11, 4. doi:10.3390/hydrology11010004

Haroon, M., Jamil, H., Ullah, Q., Farooq, Q., and Inamullah, M. (2022). Cholesterol and serum minerals profile in the pregnancy and peurperium period of Beetal Goats. *Biosci. Res.* 19 (1), 381–385.

Hazeem, L. J., Yesilay, G., Bououdina, M., Perna, S., Cetin, D., Suludere, Z., et al. (2020). Investigation of the toxic effects of different polystyrene micro-and nanoplastics on microalgae Chlorella vulgaris by analysis of cell viability, pigment content, oxidative stress and ultrastructural changes. *Mar. Pollut. Bull.* 156, 111278. doi:10.1016/j.marpolbul.2020.111278

Heinlaan, M., Kasemets, K., Aruoja, V., Blinova, I., Bondarenko, O., Lukjanova, A., et al. (2020). Hazard evaluation of polystyrene nanoplastic with nine bioassays did not show particle-specific acute toxicity. *Sci. Total Environ.* 707, 136073. doi:10.1016/j.scitotenv.2019.136073

Herrera, D. A. G., Mojicevic, M., Pantelic, B., Joshi, A., Collins, C., Batista, M., et al. (2023). Exploring microorganisms from plastic-polluted sites: unveiling plastic degradation and PHA production potential. *Microorganisms* 11, 2914. doi:10.3390/microorganisms11122914

Hou, B., Wang, F., Liu, T., and Wang, Z. (2021). Reproductive toxicity of polystyrene microplastics: *in vivo* experimental study on testicular toxicity in mice. *J. Hazard Mater* 405, 124028. doi:10.1016/j.jhazmat.2020.124028

Huang, D., Tao, J., Cheng, M., Deng, R., Chen, S., Yin, L., et al. (2020). Microplastics and nanoplastics in the environment: macroscopic transport and effects on creatures. *J. Hazard. Mat.* 407, 124399. doi:10.1016/j.jhazmat.2020.124399

Hussain, K. A., Romanova, S., Okur, I., Zhang, D., Kuebler, J., Huang, X., et al. (2023). Assessing the release of microplastics and nanoplastics from plastic containers and reusable food pouches: implications for human health. *Environ. Sci. Technol.* 57, 9782–9792. doi:10.1021/acs.est.3c01942

Inkielewicz-Stepniak, I., Tajber, L., Behan, G., Zhang, H., Radomski, M. W., Medina, C., et al. (2018). The role of mucin in the toxicological impact of polystyrene nanoparticles. *Materials* 11, 724. doi:10.3390/ma11050724

Jabeen, K., Li, B., Chen, Q., Su, L., Wu, C., Hollert, H., et al. (2018). Effects of virgin microplastics on goldfish (*Carassius auratus*). *Chemosphere* 213, 323–332. doi:10.1016/j.chemosphere.2018.09.031

Jacob, H., Besson, M., Swarzenski, P. W., Lecchini, D., and Metian, M. (2020). Effects of virgin micro-and nanoplastics on fish: trends, meta-analysis, and perspectives. *Environ. Sci. Technol.* 54 (8), 4733–4745. doi:10.1021/acs.est.9b05995

Jeong, C. B., Kang, H. M., Lee, Y. H., Kim, M. S., Lee, J. S., Seo, J. S., et al. (2018). Nanoplastic ingestion enhances toxicity of persistent organic pollutants (POPs) in the monogonont rotifer Brachionus koreanus via multixenobiotic resistance (MXR) disruption. *Environ. Sci. Technol.* 52 (19), 11411–11418. doi:10.1021/acs.est.8b03211

Jiang, N., Luo, C., Shao, M., Zheng, Z., Ullah, Q., Khan, M. Z., et al. (2023a). Uncovering the role of ribosomal protein L8 in milk fat synthesis mechanisms in yak mammary epithelial cells. *Pak. J. Zool.*, 1–16. doi:10.17582/journal.pjz/20230415100435

Jiang, N., Naz, S., Ma, Y., Ullah, Q., Khan, M. Z., Wang, J., et al. (2023b). An overview of comet assay application for detecting DNA damage in aquatic animals. *Agriculture* 13 (3), 623. doi:10.3390/agriculture13030623

Jin, H., Ma, T., Sha, X., Liu, Z., Zhou, Y., Meng, X., et al. (2021). Polystyrene microplastics induced male reproductive toxicity in mice. *J. Hazard Mater* 401, 123430. doi:10.1016/j.jhazmat.2020.123430

Jin, Y., Lu, L., Tu, W., Luo, T., and Fu, Z. (2019). Impacts of polystyrene microplastic on the gut barrier, microbiota, and metabolism of mice. *Sci. Total Environ.* 649, 308–317. doi:10.1016/j.scitotenv.2018.08.353

Khan, R. U., Khan, M., Ullah, Q., Khan, M. Z., Sohail, A., Islam, R., et al. (2023). *In vitro* and *in vivo* effects of conventional and chitosan nanoparticle-encapsulated miltefosine drug for treatment of cutaneous leishmaniasis. *Med. Sci. Forum* 21 (1), 19. doi:10.3390/ECB2023-14334

Kudzin, M. H., Piwowarska, D., Festinger, N., and Chruściel, J. J. (2024). Risks associated with the presence of polyvinyl chloride in the environment and methods for its disposal and utilization. *Materials* 17, 173. [Online]. doi:10.3390/ma17010173

Lee, W. S., Cho, H. J., Kim, E., Huh, Y. H., Kim, H. J., Kim, B., et al. (2019). Bioaccumulation of polystyrene nanoplastics and their effect on the toxicity of Au ions in zebrafish embryos. *Nanoscale* 11 (7), 3173–3185. doi:10.1039/c8nr09321k

Lehner, R., Weder, C., Petri-Fink, A., and Rothen-Rutishauser, B. (2019). Emergence of nanoplastic in the environment and possible impact on human health. *Environ. Sci. Technol.* 53 (4), 1748–1765. doi:10.1021/acs.est.8b05512

Lei, L., Wu, S., Lu, S., Liu, M., Song, Y., Fu, Z., et al. (2018). Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode *Caenorhabditis elegans*. *Sci. Total Environ.* 619-620, 1–8. doi:10.1016/j.scitotenv.2017.11.103

Leslie, H. A., and Depledge, M. H. (2020). Where is the evidence that human exposure to microplastics is safe? *Environ. Int.* 142, 105807. doi:10.1016/j.envint.2020.105807

Li, B., Ding, Y., Cheng, X., Sheng, D., Xu, Z., Rong, Q., et al. (2020a). Polyethylene microplastics affect the distribution of gut microbiota and inflammation development in mice. *Chemosphere* 244, 125492. doi:10.1016/j.chemosphere.2019.125492

Li, B., Khan, M. Z., Khan, I. M., Ullah, Q., Cisang, Z. M., Zhang, N., et al. (2023a). Genetics, environmental stress, and amino acid supplementation affect lactational performance via mTOR signaling pathway in bovine mammary epithelial cells. *Front. Genet.* 14, 1195774. doi:10.3389/fgene.2023.1195774

Li, S., Liu, H., Gao, R., Abdurahman, A., Dai, J., and Zeng, F. (2018). Aggregation kinetics of microplastics in aquatic environment: complex roles of electrolytes, pH, and natural organic matter. *Environ. Pollut.* 237, 126–132. doi:10.1016/j.envpol.2018.02.042

Li, Y., Du, X., Liu, Z., Zhang, M., Huang, Y., Tian, J., et al. (2021). Two genes related to reproductive development in the juvenile prawn, Macrobrachium nipponense: molecular characterization and transcriptional response to nanoplastic exposure. *Chemosphere* 281, 130827. doi:10.1016/j.chemosphere.2021.130827

Li, Y., Meng, Y., Qin, L., Shen, M., Qin, T., Chen, X., et al. (2023b). Occurrence and removal efficiency of microplastics in four drinking water treatment plants in zhengzhou, China. *China. Water* 16, 131. doi:10.3390/w16010131

Li, Z., Feng, C., Wu, Y., and Guo, X. (2020b). Impacts of nanoplastics on bivalve: fluorescence tracing of organ accumulation, oxidative stress and damage. *J. Hazard Mater* 392, 122418. doi:10.1016/j.jhazmat.2020.122418

Lim, D., Jeong, J., Song, K. S., Sung, J. H., Oh, S. M., and Choi, J. (2021). Inhalation toxicity of polystyrene micro(nano)plastics using modified OECD TG 412. *Chemosphere* 262, 128330. doi:10.1016/j.chemosphere.2020.128330

Liu, Z., Cai, M., Wu, D., Yu, P., Jiao, Y., Jiang, Q., et al. (2020). Effects of nanoplastics at predicted environmental concentration on *Daphnia pulex* after exposure through multiple generations. *Environ. Pollut.* 256, 113506. doi:10.1016/j.envpol.2019.113506

Liu, Z., Li, Y., Pérez, E., Jiang, Q., Chen, Q., Jiao, Y., et al. (2021). Polystyrene nanoplastic induces oxidative stress, immune defense, and glycometabolism change in *Daphnia pulex*: application of transcriptome profiling in risk assessment of nanoplastics. *J. Hazard Mat.* 402, 123778. doi:10.1016/j.jhazmat.2020.123778

Liu, Z., Yu, P., Cai, M., Wu, D., Zhang, M., Huang, Y., et al. (2019). Polystyrene nanoplastic exposure induces immobilization, reproduction, and stress defense in the freshwater cladoceran *Daphnia pulex*. *Chemosphere* 215, 74–81. doi:10.1016/j.chemosphere.2018.09.176

Lu, L., Wan, Z., Luo, T., Fu, Z., and Jin, Y. (2018). Polystyrene microplastics induce gut microbiota dysbiosis and hepatic lipid metabolism disorder in mice. *Sci. Total Environ.* 631-632, 449–458. doi:10.1016/j.scitotenv.2018.03.051

Lu, Y. Y., Li, H., Ren, H., Zhang, X., Huang, F., Zhang, D., et al. (2022). Size-dependent effects of polystyrene nanoplastics on autophagy response in human umbilical vein endothelial cells. *J. Hazard Mater* 421, 126770. doi:10.1016/j.jhazmat.2021.126770

Luo, T., Zhang, Y., Wang, C., Wang, X., Zhou, J., Shen, M., et al. (2019). Maternal exposure to different sizes of polystyrene microplastics during gestation causes metabolic disorders in their offspring. *Environ. Pollut.* 255, 113122. doi:10.1016/j.envpol.2019.113122

Mao, Y., Li, H., Huangfu, X., Liu, Y., and He, Q. (2020). Nanoplastics display strong stability in aqueous environments: insights from aggregation behaviour and theoretical calculations. *Environ. Pollut.* 258, 113760. doi:10.1016/j.envpol.2019.113760

Mattsson, K., Johnson, E. V., Malmendal, A., Linse, S., Hansson, L. A., and Cedervall, T. (2017). Brain damage and behavioural disorders in fish induced by plastic nanoparticles delivered through the food chain. *Sci. Rep.* 7 (1), 11452–11457. doi:10.1038/s41598-017-10813-0

Meng, X., Zhang, J., Wang, W., Gonzalez-Gil, G., Vrouwenvelder, J. S., and Li, Z. (2022). Effects of nano- and microplastics on kidney: physicochemical properties, bioaccumulation, oxidative stress and immunoreaction. *Chemosphere* 288, 132631. doi:10.1016/j.chemosphere.2021.132631

Miao, L., Hou, J., You, G., Liu, Z., Liu, S., Li, T., et al. (2019). Acute effects of nanoplastics and microplastics on periphytic biofilms depending on particle size, concentration and surface modification. *Environ. Pollut.* 255, 113300. doi:10.1016/j.envpol.2019.113300

Mongil-Manso, J., Jiménez-Ballesta, R., Trujillo-González, J. M., San José Wery, A., and Díez Méndez, A. (2023). A comprehensive review of plastics in agricultural soils: a case study of castilla y león (Spain) farmlands. *Land* 12, 1888. doi:10.3390/land12101888

Naz, S., Chatha, A., Ullah, Q., Maqbool, B., Iqbal, S., Khan, A., et al. (2023a). Impact of chronic exposure to heavy metal mixtures on selected biological parameters of freshwater fish species. *J. Anim. Plant Sci.* 33, 2023. doi:10.36899/JAPS.2023.6.0677

Naz, S., Chatha, A. M. M., Téllez-Isaías, G., Ullah, S., Ullah, Q., Khan, M. Z., et al. (2023b). A comprehensive review on metallic trace elements toxicity in fishes and potential remedial measures. *Water* 15 (16), 3017. doi:10.3390/w15163017

Naz, S., Hussain, R., Ullah, Q., Chatha, A. M. M., Shaheen, A., and Khan, R. U. (2021). Toxic effect of some heavy metals on hematology and histopathology of major carp (catla catla). *Environ. Sci. Pollut. Res.* 28, 6533–6539. doi:10.1007/s11356-020-10980-0

Naz, S., Mansouri, B., Chatha, A. M. M., Ullah, Q., Abadeen, Z. U., Khan, M. Z., et al. (2022). Water quality and health risk assessment of trace elements in surface water at punjnad headworks, Punjab, Pakistan. *Environ. Sci. Pollut. Res.* 29 (40), 61457–61469. doi:10.1007/s11356-022-20210-4

Neves, R. A. F., Guimarães, T. B., and Santos, L. N. (2024). First record of microplastic contamination in the non-native dark false mussel mytilopsis leucophaeata (Bivalvia: Dreissenidae) in a coastal urban lagoon. *Int. J. Environ. Res. Public Health* 21, 44. doi:10.3390/ijerph21010044

Nielsen, T. D., Hasselbalch, J., Holmberg, K., and Stripple, J. (2020). Politics and the plastic crisis: a review throughout the plastic life cycle. *Wiley Interdiscip. Rev. Energy Environ.* 9 (1), e360. doi:10.1002/wene.360

Oliveira, M., Almeida, M., and Miguel, I. A. (2019). A micro (nano) plastic boomerang tale: a never ending story? *Trac. Trends Anal. Chem.* 112, 196–200. doi:10.1016/j.trac.2019.01.005

Park, E. J., Han, J. S., Park, E. J., Seong, E., Lee, G. H., Kim, D. W., et al. (2020). Repeated-oral dose toxicity of polyethylene microplastics and the possible implications on reproduction and development of the next generation. *Toxicol. Lett.* 324, 75–85. doi:10.1016/j.toxlet.2020.01.008

Paul, M. B., Stock, V., Cara-Carmona, J., Lisicki, E., Shopova, S., Fessard, V., et al. (2020). Micro-and nanoplastics–current state of knowledge with the focus on oral uptake and toxicity. *Nanoscale Adv.* 2 (10), 4350–4367. doi:10.1039/d0na00539h

Peixoto, D., Pinheiro, C., Amorim, J., Oliva-Teles, L., Guilhermino, L., and Vieira, M. N. (2019). Microplastic pollution in commercial salt for human consumption: a review. *Estuar. Coast Shelf Sci.* 219, 161–168. doi:10.1016/j.ecss.2019.02.018

Peller, J. R., Tabor, G., Davis, C., Iceman, C., Nwachukwu, O., Doudrick, K., et al. (2024). Distribution and fate of polyethylene microplastics released by a portable toilet manufacturer into a freshwater wetland and lake. *Water* 16, 11. doi:10.3390/w16010011

Peng, L., Fu, D., Qi, H., Lan, C. Q., Yu, H., and Ge, C. (2020). Micro- and nano-plastics in marine environment: source, distribution and threats- A review. *Sci. Total Environ.* 698, 134254. doi:10.1016/j.scitotenv.2019.134254

Pizzurro, F., Nerone, E., Ancora, M., Di Domenico, M., Mincarelli, L. F., Cammà, C., et al. (2024). Exposure of *Mytilus galloprovincialis* to microplastics: accumulation, depuration and evaluation of the expression levels of a selection of molecular biomarkers. *Animals* 14, 4. doi:10.3390/ani14010004

Prata, J. C., da Costa, J. P., Duarte, A. C., and Rocha-Santos, T. (2019). Methods for sampling and detection of microplastics in water and sediment: a critical review. *Trac. Trends Anal. Chem.* 110, 150–159. doi:10.1016/j.trac.2018.10.029

Qiao, R., Deng, Y., Zhang, S., Wolosker, M. B., Zhu, Q., Ren, H., et al. (2019a). Accumulation of different shapes of microplastics initiates intestinal injury and gut microbiota dysbiosis in the gut of zebrafish. *Chemosphere* 236, 124334. doi:10.1016/j.chemosphere.2019.07.065

Qiao, R., Sheng, C., Lu, Y., Zhang, Y., Ren, H., and Lemos, B. (2019b). Microplastics induce intestinal inflammation, oxidative stress, and disorders of metabolome and microbiome in zebrafish. *Sci. Total Environ.* 662, 246–253. doi:10.1016/j.scitotenv.2019.01.245

Rafiee, M., Dargahi, L., Eslami, A., Beirami, E., Jahangiri-Rad, M., Sabour, S., et al. (2018). Neurobehavioral assessment of rats exposed to pristine polystyrene nanoplastics upon oral exposure. *Chemosphere* 193, 745–753. doi:10.1016/j.chemosphere.2017.11.076

Rashed, A. H., Yesilay, G., Hazeem, L., Rashdan, S., Almealla, R., Kilinc, Z., et al. (2023). Micro- and nano-plastics contaminants in the environment: sources, fate, toxicity, detection, remediation, and sustainable perspectives. *Water* 15, 3535. doi:10.3390/w15203535

Rubio, L., Barguilla, I., Domenech, J., Marcos, R., and Hernández, A. (2020). Biological effects, including oxidative stress and genotoxic damage, of polystyrene nanoparticles in different human hematopoietic cell lines. *J. Hazard Mater* 398, 122900. doi:10.1016/j.jhazmat.2020.122900

Sallam, M. A., Zubair, M., Gul, S. T., Ullah, Q., and Idrees, M. (2020). Evaluating the protective effects of vitamin E and selenium on hematology and liver, lung and uterus histopathology of rabbits with cypermethrin toxicity. *Toxin Rev.* 39 (3), 236–241. doi:10.1080/15569543.2018.1518335

Salvati, A., Åberg, C., Dos Santos, T., Varela, J., Pinto, P., Lynch, I., et al. (2011). Experimental and theoretical comparison of intracellular import of polymeric nanoparticles and small molecules: toward models of uptake kinetics. *Nanomedicine* 7, 818–826. doi:10.1016/j.nano.2011.03.005

Sarasamma, S., Audira, G., Siregar, P., Malhotra, N., Lai, Y. H., Liang, S. T., et al. (2020). Nanoplastics cause neurobehavioral impairments, reproductive and oxidative damages, and biomarker responses in zebrafish: throwing up alarms of wide spread health risk of exposure. *Int. J. Mol. Sci.* 21 (4), 1410. doi:10.3390/ijms21041410

Sendra, M., Sparaventi, E., Blasco, J., Moreno-Garrido, I., and Araujo, C. V. (2020). Ingestion and bioaccumulation of polystyrene nanoplastics and their effects on the microalgal feeding of Artemia franciscana. *Ecotoxicol. Environ. Saf.* 188, 109853. doi:10.1016/j.ecoenv.2019.109853

Sendra, M., Staffieri, E., Yeste, M. P., Moreno-Garrido, I., Gatica, J. M., Corsi, I., et al. (2019). Are the primary characteristics of polystyrene nanoplastics responsible for toxicity and ad/absorption in the marine diatom Phaeodactylum tricornutum? *Environ. Pollut.* 249, 610–619. doi:10.1016/j.envpol.2019.03.047

Shengchen, W., Jing, L., Yujie, Y., Yue, W., and Shiwon, X. (2021). Polystyrene microplastics-induced ROS overproduction disrupts the skeletal muscle regeneration by converting myoblasts into adipocytes. *J. Hazard Mater* 417, 125962. doi:10.1016/j.jhazmat.2021.125962

Shi, W., Han, Y., Sun, S., Tang, Y., Zhou, W., Du, X., et al. (2020). Immunotoxicities of microplastics and sertraline, alone and in combination, to a bivalve species: size-dependent interaction and potential toxication mechanism. *J. Hazard Mat.* 396, 122603. doi:10.1016/j.jhazmat.2020.122603

Sökmen, T. Ö., Sulukan, E., Türkoğlu, M., Baran, A., Özkaraca, M., and Ceyhun, S. B. (2020). Polystyrene nanoplastics (20 nm) are able to bioaccumulate and cause oxidative DNA damages in the brain tissue of zebrafish embryo (*Danio rerio*). *NeuroToxicology* 77, 51–59. doi:10.1016/j.neuro.2019.12.010

Stock, V., Böhmert, L., Lisicki, E., Block, R., Cara-Carmona, J., Pack, L. K., et al. (2019). Uptake and effects of orally ingested polystyrene microplastic particles *in vitro* and *in vivo*. *Arch. Toxicol.* 93 (7), 1817–1833. doi:10.1007/s00204-019-02478-7

Strungaru, S. A., Jijie, R., Nicoara, M., Plavan, G., and Faggio, C. (2019). Micro-(nano) plastics in freshwater ecosystems: abundance, toxicological impact and quantification methodology. *Trac. Trends Anal. Chem.* 110, 116–128. doi:10.1016/j.trac.2018.10.025

Sui, A., Yao, C., Chen, Y., Li, Y., Yu, S., Qu, J., et al. (2023). Polystyrene nanoplastics inhibit StAR expression by activating HIF-1α via ERK1/2 MAPK and AKT pathways in TM3 Leydig cells and testicular tissues of mice. *Food Chem. Toxicol.* 173, 113634. doi:10.1016/j.fct.2023.113634

Sun, Z., Wen, Y., Zhang, F., Fu, Z., Yuan, Y., Kuang, H., et al. (2023). Exposure to nanoplastics induces mitochondrial impairment and cytomembrane destruction in Leydig cells. *Ecotoxicol. Environ. Saf.* 255, 114796. doi:10.1016/j.ecoenv.2023.114796

Thiagarajan, V., Alex, S. A., Seenivasan, R., Chandrasekaran, N., and Mukherjee, A. (2021). Interactive effects of micro/nanoplastics and nanomaterials/pharmaceuticals: their ecotoxicological consequences in the aquatic systems. *Aquat. Toxicol.* 232, 105747. doi:10.1016/j.aquatox.2021.105747

Triebskorn, R., Braunbeck, T., Grummt, T., Hanslik, L., Huppertsberg, S., Jekel, M., et al. (2019). Relevance of nano- and microplastics for freshwater ecosystems: a critical review. *Trac. Trends Anal. Chem.* 110, 375–392. doi:10.1016/j.trac.2018.11.023

Vaid, M., Sarma, K., and Gupta, A. (2021). Microplastic pollution in aquatic environments with special emphasis on riverine systems: current understanding and way forward. *J. Environ. Manage.* 293, 112860. doi:10.1016/j.jenvman.2021.112860

Varela, J. A., Bexiga, M. G., Åberg, C., Simpson, J. C., and Dawson, K. A. (2012). Quantifying size-dependent interactions between fluorescently labeled polystyrene nanoparticles and mammalian cells. *J. Nanobiotechnol* 10, 39. doi:10.1186/1477-3155-10-39

Vedolin, M. C., Teophilo, C. Y. S., Turra, A., and Figueira, R. C. L. (2018). Spatial variability in the concentrations of metals in beached microplastics. *Mar. Pollut. Bull.* 129 (2), 487–493. doi:10.1016/j.marpolbul.2017.10.019

Vega-Herrera, A., Llorca, M., Borrell-Diaz, X., Redondo-Hasselerharm, P. E., Abad, E., Villanueva, C. M., et al. (2022). Polymers of micro(nano) plastic in household tap water of the Barcelona Metropolitan Area. *Water Res.* 220, 118645. doi:10.1016/j.watres.2022.118645

Venâncio, C., Ferreira, I., Martins, M. A., Soares, A. M., Lopes, I., and Oliveira, M. (2019). The effects of nanoplastics on marine plankton: a case study with polymethylmethacrylate. *Ecotoxicol. Environ. Saf.* 184, 109632. doi:10.1016/j.ecoenv.2019.109632

Venancio, C., Savuca, A., Oliveira, M., Martins, M. A., and Lopes, I. (2021). Polymethylmethacrylate nanoplastics effects on the freshwater cnidarian *Hydra viridissima*. *J. Hazard Mat.* 402, 123773. doi:10.1016/j.jhazmat.2020.123773

Walczak, A. P., Kramer, E., Hendriksen, P. J. M., Tromp, P., Helsper, J. P. F., van der Zande, M., et al. (2015). Translocation of differently sized and charged polystyrene nanoparticles in *in vitro* intestinal cell models of increasing complexity. *Nanotoxicology* 9, 453–461. doi:10.3109/17435390.2014.944599

Wang, F., Wang, B., Qu, H., Zhao, W., Duan, L., Zhang, Y., et al. (2020a). The influence of nanoplastics on the toxic effects, bioaccumulation, biodegradation and enantioselectivity of ibuprofen in freshwater algae chlorella pyrenoidosa. *Environ. Pollut.* 263, 114593. doi:10.1016/j.envpol.2020.114593

Wang, T., Zou, X., Li, B., Yao, Y., Li, J., Hui, H., et al. (2018). Microplastics in a wind farm area: a case study at the rudong offshore wind farm, yellow sea, China. *Mar. Pollut. Bull.* 128, 466–474. doi:10.1016/j.marpolbul.2018.01.050

Wang, W., Ge, J., and Yu, X. (2020b). Bioavailability and toxicity of microplastics to fish species: a review. *Ecotoxicol. Environ. Saf.* 189, 109913. doi:10.1016/j.ecoenv.2019.109913

Wang, Y., Mao, Z., Zhang, M., Ding, G., Sun, J., Du, M., et al. (2019). The uptake and elimination of polystyrene microplastics by the brine shrimp, Artemia parthenogenetica, and its impact on its feeding behavior and intestinal histology. *Chemosphere* 234, 123–131. doi:10.1016/j.chemosphere.2019.05.267

Wu, J., Jiang, R., Lin, W., and Ouyang, G. (2019). Effect of salinity and humic acid on the aggregation and toxicity of polystyrene nanoplastics with different functional groups and charges. *Environ. Pollut.* 245, 836–843. doi:10.1016/j.envpol.2018.11.055

Xia, T., Kovochich, M., Liong, M., Zink, J. I., and Nel, A. E. (2008). Cationic polystyrene nanosphere toxicity depends on cell-specific endocytic and mitochondrial injury pathways. *ACS Nano* 2, 85–96. doi:10.1021/nn700256c

Xie, X., Deng, T., Duan, J., Xie, J., Yuan, J., and Chen, M. (2020). Exposure to polystyrene microplastics causes reproductive toxicity through oxidative stress and activation of the p38 MAPK signaling pathway. *Ecotoxicol. Environ. Saf.* 190, 110133. doi:10.1016/j.ecoenv.2019.110133

Yang, Y. F., Chen, C. Y., Lu, T. H., and Liao, C. M. (2019). Toxicity-based toxicokinetic/toxicodynamic assessment for bioaccumulation of polystyrene microplastics in mice. *J. Hazard Mater* 366, 703–713. doi:10.1016/j.jhazmat.2018.12.048

Yee, M. S. L., Hii, L. W., Looi, C. K., Lim, W. M., Wong, S. F., Kok, Y. Y., et al. (2021). Impact of microplastics and nanoplastics on human health. *Nanomaterials* 11 (2), 496. doi:10.3390/nano11020496

Yin, L., Liu, H., Cui, H., Chen, B., Li, L., and Wu, F. (2019). Impacts of polystyrene microplastics on the behavior and metabolism in a marine demersal teleost, black rockfish (Sebastes schlegelii). *J. Hazard. Mat.* 380, 120861. doi:10.1016/j.jhazmat.2019.120861

Yu, F., Yang, C., Zhu, Z., Bai, X., and Ma, J. (2019). Adsorption behavior of organic pollutants and metals on micro/nanoplastics in the aquatic environment. *Sci. Total Environ.* 694, 133643. doi:10.1016/j.scitotenv.2019.133643

Zagorski, J., Debelak, J., Gellar, M., Watts, J. A., and Kline, J. A. (2003). Chemokines accumulate in the lungs of rats with severe pulmonary embolism induced by polystyrene microspheres. *J. Immunol.* 171 (10), 5529–5536. doi:10.4049/jimmunol.171.10.5529

Zalasiewicz, J., Waters, C. N., Ivar do Sul, J. A., Corcoran, P. L., Barnosky, A. D., Cearreta, A., et al. (2016). The geological cycle of plastics and their use as a stratigraphic indicator of the Anthropocene. *Anthropocene* 13, 4–17. doi:10.1016/j.ancene.2016.01.002

Zhang, F., Wang, Z., Song, L., Fang, H., and Wang, D. G. (2020a). Aquatic toxicity of iron-oxide-doped microplastics to Chlorella pyrenoidosa and Daphnia magna. *Environ. Pollut.* 257, 113451. doi:10.1016/j.envpol.2019.113451

Zhang, F., Wang, Z., Wang, S., Fang, H., and Wang, D. (2019). Aquatic behavior and toxicity of polystyrene nanoplastic particles with different functional groups: complex roles of pH, dissolved organic carbon and divalent cations. *Chemosphere* 228, 195–203. doi:10.1016/j.chemosphere.2019.04.115

Zhang, Y., Pu, S., Lv, X., Gao, Y., and Ge, L. (2020). Global trends and prospects in microplastics research: a bibliometric analysis. *J. Hazard. Mat.* 400, 123110. doi:10.1016/j.jhazmat.2020.123110

Zheng, H., Wang, J., Wei, X., Chang, L., and Liu, S. (2021). Proinflammatory properties and lipid disturbance of polystyrene microplastics in the livers of mice with acute colitis. *Sci. Total Environ.* 750, 143085. doi:10.1016/j.scitotenv.2020.143085

Zhou, X. X., Liu, R., Hao, L. T., and Liu, J. F. (2021). Identification of polystyrene nanoplastics using surface enhanced Raman spectroscopy. *Talanta* 221, 121552. doi:10.1016/j.talanta.2020.121552

Zhu, X., Zhao, W., Chen, X., Zhao, T., Tan, L., and Wang, J. (2020). Growth inhibition of the microalgae Skeletonema costatum under copper nanoparticles with microplastic exposure. *Mar. Environ. Res.* 158, 105005. doi:10.1016/j.marenvres.2020.105005

Zhu, Z. L., Wang, S. C., Zhao, F. F., Wang, S. G., Liu, F. F., and Liu, G. Z. (2019). Joint toxicity of microplastics with triclosan to marine microalgae Skeletonema costatum. *Environ. Pollut.* 246, 509–517. doi:10.1016/j.envpol.2018.12.044

Zitouni, N., Bousserrhine, N., Belbekhouche, S., Missawi, O., Alphonse, V., Boughatass, I., et al. (2020). First report on the presence of small microplastics (≤3 μm) in tissue of the commercial fish Serranus scriba (Linnaeus, 1758) from Tunisian Coasts and associated cellular alterations. *Environ. Pollut.* 263, 114576. doi:10.1016/j.envpol.2020.114576

Zubair, M., Ahmad, M., Saleemi, M. K., Gul, S. T., Ahmad, M., Martyniuk, C. J., et al. (2020). Sodium arsenite toxicity on hematology indices and reproductive parameters in teddy goat bucks and their amelioration with vitamin C. *Environ. Sci. Pollut. Res.* 27, 15223–15232. doi:10.1007/s11356-020-08049-z