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Impact of Nanoplastics on Marine Life: A Review

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ABSTRACT

Minute plastic subdivisions like microplastics and nanoplastics have recently gained considerable attention because of their toxic effects on the environment and human health. Many plastics have been consumed worldwide regularly, and most are thrown away after a single use. They all end up in the sea and ocean, leading to a large debris of plastic garbage in the marine environment. Different physical and chemical processes occur in the marine ecosystem to degrade the macroplastics into micro- and nano-level plastics. Owing to their small size and large surface area, nanoplastics can easily be ingested into the tissues and organs of various marine species (both vertebrates and invertebrates) and accumulate more toxic materials in them than micro and macroplastics. Several reports have been obtained on the toxicity of plastics and microplastics on marine organisms. Still, till now, a cursory report has been found on the potential risk of nanoplastics in connection with marine life. This review highlights the origins of nanoplastics (NPs), their properties, characterization, and impact on marine ecosystems, along with their remediation and future aspects. The review will also untangle and specify the area of nanoplastics on which further research is urgently needed to better understand its toxic effect and eco-friendly restoration on the environment, especially on marine life.

INTRODUCTION

Plastics, a widely used synthetic or semi-synthetic material, are mainly synthesized by the polymerization and polycondensation of different monomeric components like ethylene, styrene, propylene, vinyl chloride, tetrafluoroethylene, etc. (Eyerer et al. 2010). It was developed and marketized in the early 19th century, and in the middle of the 20th century, the globalization of plastics occurred due to its large production and applications worldwide (Geyer et al. 2020). One-third of the total plastic production is used for making plastic bags, another one-third for preparing housing components, and the rest for industrial and medical purposes. Plastics are generally lightweight, but many are hard, have high longevity, are easy to prepare, and are inexpensive (Stolbov et al. 2021). Harnessing these properties, the uses of plastics propagate very rapidly all over the world in the modern era, so geologists identify this age as the 'plastic age' (Blocker et al. 2020).

Along with the abrupt use of plastics, the hazards associated with plastics also increase daily. Plastic is inherently a chemically stable compound and non-biodegradable. Thereby, it can accumulate more toxic materials in the environment. Nowadays, during the production of plastics, various additives are incorporated into them, which further increase their strength and durability (Jain et al. 2019). After the introduction of plastics, it has become a good substitute for wood, which reduces the cutting of trees and thereby helps the environment. However, improper disposal of plastics on the land causes loss of soil fertility and quality, and the plastic garbage in the aquatic environment decreases the survival rate of aquatic animals. Ingestion of plastics through food and water causes serious health problems in humans (Alabi et al. 2019).

According to famous environmentalists all over the world, plastic is the main litter in the marine environment as well as in the terrestrial area. Plastics thrown away end up in the sea or oceans through various draining systems, and these are the main sources of plastic waste in the marine environment. These macro-sized plastic garbages transform into small-sized nanoplastics (NPs) through UV irradiation (Mao et al. 2020), mechanical abrasion (Sun et al. 2022), and biodegradation (Jaiswal et al. 2020). Nanoplastics possess a wide range of interesting properties because of their small size and large surface area. Due to their large surface curvature, nanoplastics can easily be adsorbed and transferred into the tissues of marine organisms (Bhagat et al. 2021). Even during breathing, several tiny particles of nanoplastic are entered into various sea animals and accumulate in their respiratory tract. It is also incorporated into the food chain and spreads rapidly within the ecosystem, endangering all marine life (Zaki & Aris 2022) (Fig. 1). The main problem encountered with that is that the degradation of plastics is not a controllable fact. In the micro- and nanoscale, PE (polyethylene), PVC (polyvinylchloride), PS (polystyrene), PET (polyethylene terephthalate), and PMMA (polymethylmethacrylate) were observed (Baig et al. 2022). Literature has illustrated the toxic effect of polystyrene (PS) and polymethylmethacrylate (PMMA) nanoplastics on marine animals. This review briefly describes the source, sampling, degradation procedure, effect of nanoplastic on different types of marine organisms, and some of its remediation procedures. The future aspects of this research are also discussed in this context, which will help the upcoming researchers explore nanoplastics more and find a suitable way out of the present situation.

ORIGIN OF NANOPLASTICS IN MARINE ENVIRONMENT

The two primary origins of plastics (Liu et al. 2020) in the sea and ocean are (i) primary, i.e., plastic particles that are produced in a definite size range, and (ii) secondary, which indicates the smaller-sized plastics that are obtained from the degradation of the larger-sized plastics. Nanoplastics that are found in the marine environment are of secondary origin and mainly emerge from different household, industrial, anthropogenic, and public drainage systems, a variety of constructions on the coastal side, business and landfill waste, and different types of litter disposal from varieties of water transports, fishing fleets, and entertainment activities (Koelmans et al. 2015). Survey reports revealed that in 2010, 2.5 billion metric tons of solid waste were produced worldwide, of which 275 million metric tons were plastics, and out of this, 4.4 to 12.7 million metric tons were found in the sea and ocean (Jambeck et al. 2015). The nano-sized plastic particles are also discharged into the sea and ocean from the plastic production and processing industries during their manufacturing and carriages through the release of wastewater from various plastic industries. These tiny plastic particles have a size in the nanometer range and have been found primarily in the beach surroundings, coastal regions, and industrial belts, along with spreading secondarily in the remote non-industrial zone. A survey report reveals a high concentration of household and consumer goods plastics has been widely found in the various seaside areas. This plastic is then degraded through various methods into tiny particles on the nanometer scale (Fotopoulou & Karapanagioti 2017). It has also been observed that the nanoplastics found in this region are of lower density, indicating that the composition of the plastics has been altered near this beach area.

DEGRADATION OF PLASTICS FROM MACRO TO MICRO TO NANO-SIZED PLASTICS

Generally, the fragmentation of macroplastics into meso, micro, and, ultimately, nanoplastics (Amobonye et al. 2021) occurs due to the weathering of plastics. Nowadays, environmental experts classify the degradation processes of plastics into six categories: thermal, hydrolytic, mechanical, thermo-oxidative, photo, and biodegradation (Isaacson et al. 2021, Elsawy et al. 2017, Ravishankar et al. 2018, Kumagai et al. 2022, Berenstein et al. 2022, Ahmed et al. 2018). The thermal method indicates the degradation of plastics due to in situ heat generation. Hydrolytic breakdown arises due to the breakage of bonds by adding water. Mechanical abrasion occurs with the hit of a wave or the force of water flow. In the thermo-oxidative process, the macro-sized plastics are degraded into tiny particles through a slow oxidation process. Photodegradation is induced by sunlight, and the breakdown of larger plastics influenced by various living organisms like bacteria is termed “biodegradation. Among them, hydrolytic and mechanical degradation are the two most common degradation processes that take place in the marine environment. Different degradation processes will result in plastics of various sizes, from the micro- to the nanometer range. This review mainly deals with plastics in the nanometer range that possess a large surface area and can effectively interact with marine organisms.

It has been observed that, by degradation, a plastic carrying bag produces nano-sized plastics with a surface area of 2600 m^2, which are very harmful to our environment. So, the indiscriminate use of plastic bags should be strictly prohibited.

NANOPLASTIC PARTICLE TRANSPORTER OF OTHER CHEMICALS

The ability of nanoplastics to adsorb and transport various types of toxic materials is primarily responsible for their toxicity. Moreover, the ingredients of the nanoplastic itself contain many chemical additives such as bisphenol A, organotin, triclosan, phthalates, and brominated flame retardants (Baig et al. 2022). The high surface polarity of nanoplastics increases their affinity to adsorb different hydrophobic materials like persistent organic pollutants (POPs) like PCBs, nonylphenol, various pesticides, phenanthrene, etc., along with heavy metals, antibiotics, and the antibiotic resistance genes (ARGS) through different transport mechanisms (Alprol et al. 2021). Liu et al. have revealed from their studies that low concentrations of polystyrene nanoplastics in the saturated soil solution can effectively transport nonpolar pyrene and weakly polar 2,2′,4′-tetrabromodiphenyl ether but have no effect on the

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transport of polar molecules like bisphenol A, bisphenol F, and 4-nonylphenol (Liu et al. 2018). All the soil and land nanoplastic litter finally ends up in the sea and ocean. Nanoplastics impart a large surface area, thereby adsorbing the chemicals above to a large extent. These nanoplastics can easily pass into the tissues of marine organisms from seawater, as can the transported chemicals that largely affect the lives of marine organisms.

SPECIAL FEATURES OF NANOPLASTICS

The mode of interaction of nanoplastics with living organisms is distinctly different from that of macroplastics. The exceptional behaviors arise due to their nano-level size. The small size and large surface area help them pass easily into marine organisms' biological tissues and make the intercellular interaction and accumulation within the organ more feasible. The increased surface area greatly increases the reactivity of the plastic particles. Chemical composition, size heterogeneity, doping, surface modification, stability, solubility, biodegradability, duration of exposure, interaction with other nanoparticles, and behavior under electromagnetic radiation are some characteristics that distinguish them as unique environmental hazards (Cartraud et al. 2019).

CHARACTERIZATIONS OF NANOPLASTICS IN MARINE ENVIRONMENT

Since nanoplastics contain very tiny particles, their identification, characterization, and quantification in the marine system have become a great challenge to researchers. Still, it is very urgent to better understand its potential risk factors for marine life. Nanoplastics can be separated and identified from seawater by ultrafiltration or nanofiltration using membranes with pore sizes of 0.02–5 m. A dynamic light scattering technique further quantifies the separated particles (Zhang et al. 2022).

EFFECT OF NANOPLASTICS ON MARINE ORGANISMS

Nanoplastic particles found in the marine ecosystem have been proven to affect more than 600 marine species all over the world (United Nations Environment Programme and Secretariat of the Convention on Biological Diversity 2012). Some of the special features of nanoplastics, including their hardness, high longevity, and non-degradability, are primarily responsible for making them severe environmental hazards. The adverse effects of nanoplastics on various living marine species are discussed thoroughly in the following sections.

Effect of Nanoplastics on Primary Marine Producers

Algae are the initial producers and the initiators of the food web in the marine ecosystem. They appear in veritable shapes and sizes, ranging from nanometers to several meters. The major algae cell wall component is cellulose, which interacts with various particles in the water body. Still, its action towards plastic nanoparticles has been less explored to date. Wang et al. (2020) studied the effect of PS NPs of 70 nm size on *Platymonas shelgolandica,* a green marine microalga,

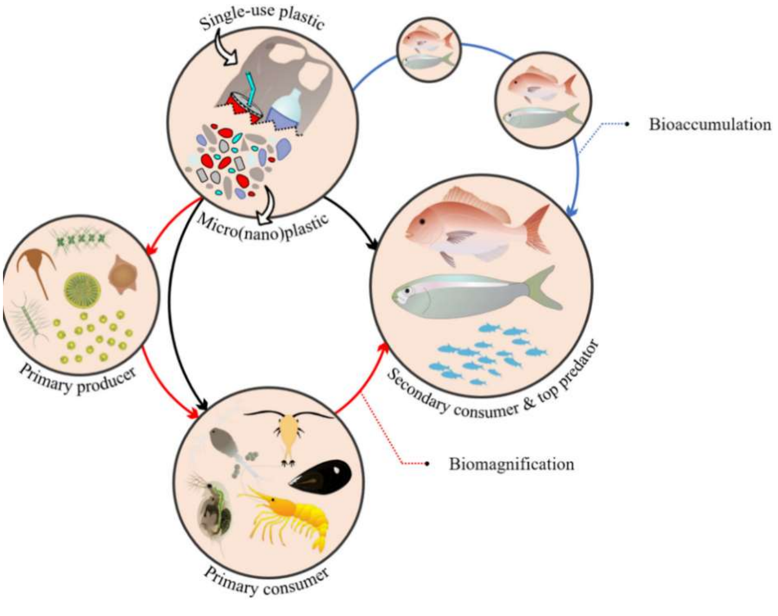

Fig. 1: Transfer of nanoplastics from primary producers to secondary consumers via primary consumers [adapted from Zaki et al. 2022].

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upon explosions of 20, 200, and 2,000 $g.L^{-1}$ concentration for 6 days. After 3 days of exposure, algal growth decreased, and later, in 6 days, photosynthetic efficiency reduced significantly along with the rate of mortality, which increased abruptly. L. Hazeem et al. (2020) investigated the growth inhibition, reduced chlorophyll, and reactive oxygen species production effects of carboxyl-functionalized polystyrene nanoplastics of diameters 20–50 nm on microalgae named *Chlorella_vulgaris*. To understand the surface charge interaction of NPs with the marine microalgae, Sjollema et al. (2016) and Bergami et al. (2017) explored the effect of PS-NH $_2$ (50 nm) and PS-COOH (40 nm) on *Dunaliella tertiolecta* at a concentration level of 250 $g.mL^{-1}$ for 48 and 72 h, respectively. PS-COOH shows no effect, whereas PS-NH_2 exhibits a reduction of cellular growth and cell density. This is presumably due to the electrostatic interaction between the positively charged PS beads and the cellulose of the cell wall. The red microalgae, *Rhodomonas baltica,* was exposed to PMMA and PMMA-COOH (Gomes et al. 2020) of 50 nm size and 0.5-100 $g.mL^{-1}$ concentration for 72 h. PMMA-COOH inhibits cellular growth, whereas PMMA exposure causes multi-cellular malfunctions such as reduced lipid metabolism, photosynthetic efficiency, reactive oxygen species generation, etc. Venancio et al. (2020) examined the effect of PMMA nanoplastics on four marine algae and one rotifer. One algae named *Thalassiosira weissflogii* shows the highest sensitivity, and the rotifer species are far more sensitive than the marine algae. Their experiment's species sensitivity distribution curve shows that PMMA NPs are less harmful than PS NPs. Furthermore, the toxicity of nanoplastics increases to a great extent in aggregation with other toxic nanoparticles present in marine water. F.-F. Liu et al. (2022) revealed from their experiment that the hazards of CuO nanoparticles enhance significantly in combination with polystyrene NPs towards *Platymonas shelgolandica* var. *tsingtaoensis*. The combined effect of CuO and PS nanoparticles greatly influences cell oxidative stress and cell membrane permeability compared to single CuO nanoparticles. In contrast to this observation, Natarajan et al. (2022) represented that PS NPs diminish the toxic effect of TiO_2 nanoparticles on one type of microalga, *Chlorella* sp. Some other observations related to marine algae have been summarized in Table 1.

The above case studies reveal that growth, rate of fertilization, photosynthetic ability, chlorophyll formation, and cell wall formation of the marine algae have been highly affected by the amide-containing PS nanoplastics. In contrast, PMMA NPs have a comparatively lesser effect on marine algae. The -COOH analog PS NPs have a very poor effect on marine algae. The toxicity of some suspended metal oxides increases to a far greater extent (Liu et al. 2022), whereas nanoplastics themselves can reduce the toxic effect of some other metal oxides (Natarajan et al. 2022). Still, further investigation should be carried out to better understand the interaction of NPS with marine algae.

Effect of Nanoplastics on Marine Primary Consumers

Primary consumers have an important role in maintaining stability among the primary producers and secondary consumers in the food chain of an ecosystem. They are mostly larvae of different vertebrates and invertebrates of marine organisms. Primary consumers are primarily herbivores but can also be omnivores, selective feeders, or passive feeders in an oceanic ecosystem. Depending on their omnipresence, nanoplastics are absorbed and transferred within the food web of the prevailing ecosystem. Primary marine consumers like rotifers, polychaetes, echinoderms like sea urchins, mollusks like mussels and oysters, and crustaceans like copepods, shrimp, barnacles, krill, and waterfowl experience severe adverse effects due to the adsorption of nanoplastics.

Effect of nano plastic on marine feeders: The feeders primarily consume different types of suspended marine

Table 1: Effect of nanoplastics on marine primary producers.

Species	Type	Size (nm)	Concentrations ($\mu g.L^{-1}$)	Exposure time	Effect	References
Phaeodactylum tricornutum	PS	50	0.1-50	24 and 72 h	After 24 h, cell size, and photosynthetic efficiency decrease, and after 72 hrs exposure mitochondrial membrane depolarisation occurs	Sendra et al. 2019
Thalassiosira pseudonana	PS	55	0.0001–250	48 h	Cellular stress increases severalfold in the phytoplankton species	Shiu et al. 2020
Karenia mikimotoi	PS	65 and 100	1 and 10	3 to 13 days	Increase the cellular stress, and the growth rate decreases abruptly	Zhao et al. 2020
Chlorella vulgaris	PS-NH_2	90	25-100	24-72 h	Cellular aggregates take place, and cell size decreases significantly.	Khoshnamvand et al. 2021

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Table 2: Effect of nanoplastics on marine filter feeders.

Species	Type	Size	Concentrations	Effect	References
Blue Mussel *Mytilus edulis*	PS NPS	30 nm	100-300 μg.mL^{-1}	Production of pseudofaces increases with an increase in the concentration of NPS.	Wegner et al. 2012
Mytilus galloprovincialis	PS NPs + Cbz (carbamazepine)	50 nm	0.05 mg.L^{-1}+ 6.3 μg.L^{-1}	A decrease in lysosomal membrane stability increases the rate of oxyradical generation, leading to cellular harm.	Brandts et al. 2018
Gametes of the oyster *Crassostrea gigas*	PS-COOH	500 nm	4.9 μg.mL^{-1}	Gammet and larva remain unaffected.	Tallec et al. 2018
Gametes and embryo-larva of *C. gigas*	PS-NH_2	50 nm	0.15 μg.mL^{-1}	Highly affects the rate of the fertilization process and causes total malfunction of gametes and larva.	Tallec et al. 2018

matter. They help to keep the aquatic environment clean. The filter feeders primarily consume the aquatic nanoparticles, mostly combined with others. But, the effect of nanoplastics on the filter feeders has been rarely studied.

The aquatic feeders take up the plastic particles as they find them similar to their prey (like colorful plastic balloons or carrying bags), or they ingest foods that inherently contain nanoplastics. Marine filter feeders include clams, krill, sponges, and many fish, like different sharks. The effect of nanoplastics on marine filter feeders is described in Table 2.

Rotifers: Rotifers are marine planktonic species that mainly reside in marine water. It plays an important connector role between the primary producers and secondary consumers. They are very sensitive to different water contaminants, including nanoplastics, which prompted their selection as the test species. Manfra et al. (2017) examined the effect of PS-COOH and PS-NH_2 nanoplastics on the *Brachionus plicatilis*, a marine rotifer, at concentrations between 0.5 and 50 mg.L^{-1} for 24-48 h. PS-COOH does not significantly affect the target species, even at higher concentrations and long-term exposure. However, PS-NH_2 nanoplastics result in a reduced survival rate even at lower concentrations and lower exposure times. It has also been observed that treating *B. plicatilis* with PMMA nanoplastics at a concentration of 4.69 mg.L^{-1} for 48 hrs does not significantly affect the survival rate (Venancio et al. 2019). However, PMMA nanoplastics are far more toxic than PS nanoplastics. The result indicates that in the marine environment, several topological changes in nanoplastics occur that also affect the extent of their toxicity. Moreover, some special features of nanoplastics, like their large surface area and hydrophobic nature, enable them to absorb various organic pollutants suspended in the water bodies of the marine environment. Nanoplastics combined with these pollutants exhibit a greater toxic effect than their non-combined form, as observed in marine algae (Liu et al. 2022).

Polychaetes: Benthic species in marine environments are highly affected by nanoplastic pollution. The concentration of nanoplastics at the surface and inside the ocean's water column can be influenced by biological processes like biofouling and physical abrasion in the adjacent environment. Therefore, the nanoplastics in the sedimented water of the ocean become available for the adsorption of benthic species like polychaetes. They are mainly tested to identify the bioaccumulation of various water pollutants, including nanoplastics. The first effect of nanoplastic on polychaetes was first studied by Silva et al. (2020). They used a 100-nm PS nanoplastic on the polychaete *Hedistediversi color* at a concentration ranging from 0.005 to 0.5 mg.L^{-1}. It results in a neurotransmission change in the aforesaid polychaete species. Since The polychaetes play an important role in stabilizing the marine ecosystem, the ingested nanoplastics flow in the trophic level via the food web from them. Further investigation is needed to identify the toxic level in this polychaete species.

Echinoderms: Another important benthic species widely used for ecotoxicological studies in marine environments is the echinoderm, mainly found in the coral reef. It plays a pivotal role in stabilizing the reef ecosystem by providing shelter to small fish. Some reports (Trifuoggi et al. 2019, Oliviero et al. 2019) are found on the effect of microplastics on echinoderms, but investigation on the effect of nanoplastics on this species is very limited to date; only two such reports have been found using *Paracentrotus lividus* (Murano et al. 2021) and *Sterechinus neumayeri* (Bergami et al. 2019) as biomarkers. Murano et al. investigated the effect of PS-NH_2 and PS-COOH nanoplastics on *P. Vidus* for 48 hrs. PS-NH_2 treatment decreases cell viability for short-time exposure; this result is accompanied by the reduction of growth and development of its larva at 3.85 mg.L^{-1} for long-term exposure. However, short-term exposure to PS-COOH nanoplastics has little effect, including a decrease

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in the lysosomal membrane stability, whereas long-term treatment can hamper their immune system. Treatment of *Sterechinus neumayeri* with PS-NH_2 and PS-COOH gives rise to phagocytosis and chronic inflammation in response to oxidative stress after 24 h. The results indicate that the surface charge of nanoplastics increases their toxicity many times because they adhere to the cell walls of target species by electrostatic and van der Waal interactions. This is also influenced by external environmental factors and the species' physicochemical properties.

Molluscs: Naval mollusks are important biomarkers for evaluating the influence of nanoplastics in the marine environment, as they behave as excellent filter feeders. They can ingest suspended contaminants in the water body and nanoplastics by mistake, accumulating in their digestive tract and flowing into secondary consumers, including humans, through the food web. Wang et al. (2021) detected an accumulation and preservation of 70-nm PS nanoplastic in the digestive tract of *Mytilus coruscus*. Long-term exposure to PS nanoplastics (30 nm) on *M. edulis* decreases its filtering activity (Wegner et al. 2021). Capolupo et al. (2021) assessed a rise in general stress and a weakening of neurological and immunological function in the *Mytilus galloprovincialis* after long-term exposure (21 days) to PS nanoplastics at a concentration of 1.5-150 mg.L^{-1}. In this study, the concentration of nanoplastics is very low, but it has had a long-term impact on the marine mollusk variety.

Oysters: Nano-sized plastic particles can harm oyster species in their early stages; however, adult oysters are rarely affected by nanoplastic exposure because self-immunity develops in the matured stage. Ingestion of 70 nm PS by *Crassostrea gigas* shows no significant effect on their growth rate (Cole & Galloway 2015). In contrast, a significant increase in cell size was observed due to the adherence of PS-COOH and PS-NH_2 nanoplastics on its gametes (González-Fernández et al. 2018). In the same manner, the embryonic development of *M. galloprovincialis* was restricted by PS-NH_2 exposure at concentrations of 2.5-10 mg.L^{-1}, and the effect became more pronounced with the increase in the concentration of the exposing nanoplastics (Balbi et al. 2017). Similarly, the embryo's development was further inhibited at higher exposure concentrations (e.g., 20 mg.L^{-1}). The above and other additional results have been summarized in Table 3.

The above study reflects that the adhesion also influences ingestion and toxicity regarding oysters. Through these two

Table 3: Effect of nanoplastics on marine primary consumers.

Species	Type	Size	Concentrations	Effect	References
Daphnia magna	polystyrene NPS	100 nm	1 mg.L^{-1}	Decrease in feeding capacity	Rist et al. 2017
Brachionus plicatilis (Rotifers)	PS-NH_2	50 nm	0.5-50 mg.L^{-1}	High mortality	Manfra et al. 2017
	PS-COOH	40 nm		No acute toxicity	Manfra et al. 2017
Brachionus plicatilis	PMMA	40 nm	4.7-75.0 mg.L^{-1}	Affect the survival rate	Venancio et al. 2019
Brachionus koreanus	PS NPs	50 nm, 500 nm	10-20 mg.L^{-1}	All sizes led to a decrease in growth rate and lifespan and longer reproduction time.	Jeong et al. 2016
Hediste diversicolor	PS NPS	100 nm	0.005-50 mg.L^{-1}	Inhibit neurotransmission behavior	Silva et al. 2020
Sea Urchin	PS-NH_2	50 nm	10 mg.L^{-1}	Decrease in lysosomal membrane stability and apoptotic-like nuclear interaction.	Marques -Santos et al. 2018
Blue mussel larvae	PS nanoplastics	100 nm	0.42 µg.L^{-1} 28.2 µg.L^{-1} 282 µg.L^{-1}	Abnormal larval development and cellular malformation become significant with increased concentration.	Rist et al. 2019
Pecten maximus	^{14}C-radiolabeled nano polystyrene	24 nm	15 µg.L^{-1}	Dispersed throughout the body, caused translocation of the epithermal membrane.	Al-Sid-Cheikh et al. 2018
		250 nm	15 µg.L^{-1}	Accumulated in the digestive system hamper the feeding habit.	

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processes, adhesion and ingestion, the chemical additives are extracted from the nanoplastics to a water body that seems harmful to marine life.

Effect of Nanoplastics on Marine Secondary Consumers

Various fish-like species are primarily considered secondary consumers of the marine ecosystem. Consumption and accumulation of nanoplastics within the secondary consumer's body due to consuming contaminated species as food in the marine environment. The ingestion of microplastic waste by different marine animals has become very harmful to sea turtles and marine mammals like seals (Rice et al. 2021). This causes physiological problems, such as decreased fitness, increased sinking tendency, decreased food-catching ability, and hampered fat formation in sea birds. The first evidence of plastic ingestion from marine debris was found in Fulmars (Feldkamp et al. 1989), a type of seabird. Between the mid-1980s and 1990s, the concentration of plastics in Fulmar and other sea animals increased significantly. To our surprise, some specific shapes or colors of plastic were found within some marine species, namely sea turtles and some fish. This occurred because those aquatic animals ingested those plastics as their target to feed by mistake; however, the adsorption of nanoplastics in marine secondary consumers has not been extensively studied. Investigation by Catraud et al. (2019) showed that an appreciable amount of nanoplastics has been ingested by a variety of sea birds, sea turtles, etc., which results in a decrease in the total amount of nanoplastics in the marine environment. These nanoplastics and the corresponding pollutants enter the food chain via these marine organisms, endangering marine life. This process also increases the bioavailability of nanoplastics in sea animals; however, incorporating such materials into the food web has not been studied in depth. Cedervall et al. (2012) and Chae et al. (2018) used algae, zooplankton, and fish to characterize trophic stages in a fresh marine-water ecosystem, and it was discovered that fish species are severely impacted by nanoplastic exposure. Secondary consumers are critical in moving ingested nanoplastics up the food chain, as humans consume these as food ingredients. Zebrafish is one variety of marine fish that has been widely tested to examine the effect of nanoplastics on marine secondary consumers (Chen et al. 2017, Trevisan et al. 2019, Torres-Ruiz et al. 2021).

Kang et al. (2021) revealed the fact from their experiment that exposure of 10 mg.L^{-1} of PS nanoplastics to medaka larvae, *Oryzias melastigma*, for 7 days causes rapid accumulation and dispersion within the larva's body, increasing oxidative stress. Longer induction times may cause severe toxicity as they readily penetrate the biological tissues. The harmful effect of nanoplastics on marine secondary consumers is related to the change in functional groups of the nanoplastics. Positively charged NH_2-containing nanoplastics seem more toxic to marine organisms' larvae than their negatively charged COOH-containing analog. Brandts et al. (2018) employed adult *Dicentrarchus labrax* to examine the impact of 45-nm PMMA nanoplastics for a short exposure time. The result is that the genes connected to lipid metabolism exhibit up-regulation, whereas genes related to the immune system and cell-tissue repair remain unchanged. This group further examined the exposure of *Sparus aurata* to 0.001 to 10 mg.L^{-1} of nanoplastics for 24 to 96 hours; this resulted in

Table 4: Effect of nanoplastics on marine secondary consumers.

Species	Type	Size	Concentrations	Effect	References
Seabream *Sparus aurata*	PMMA	45 nm	0-10 µg.mL^{-1}	Increase in plasma cholesterol and tri glyceraldehyde	Brandts et al. 2021
Sparus aurata	PMMA	45 nm	0.001-10 mg.L^{-1}	Transcriptional level of genes and antioxidant response inhibited; increase the anti-inflammatory response.	Balasch et al. 2021
Larimichthys crocea	PS	100 nm	5.5×10^{-12}-5.50×10^{-7} mg.L^{-1}	Oxidative stress increases, survival rate decreases	Gu et al. 2020
Zebra fish	PS	50 nm	1 mg.L^{-1}	Upregulation of GFAP and α1-tubulin, nervous system related genes	Chen et al. 2017
Zebra fish	PS NPs	<1 µm	0.1-10 ppm	Mitochondrial dysfunction hamper ATP production, resulting in the reduction of energy production.	Trevisan et al. 2019
Zebra fish	PS NPs + PAH	<1 µm	0.1-10 ppm + 5.07-25.36 ppb	Agglomeration of PS NPs and PAH occurs, thereby minimizing the effect of single PAH exposure, only marginally affecting energy production.	
Zebra fish	PS NPS	20-200 nm	10 mg.L^{-1}	Affects internal organs like the brain, eyes, heart, liver, and pancreas.	Torres-Ruiz et al. 2021
		>200 nm	10 mg.L^{-1}	Affects the guts, gills, and skin	

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the total malfunction of the lever and nervous system. Lai et al. (2021) observed the result of the exposure of nanoplastics (80 nm) to a large yellow croaker, *Larimichthys crocea*, a commercially available fish in China. They suggested that the increased accumulation level of nanoplastics in the lever system caused a total malfunction.

Similarly, Gu et al. (2020) examined the effect of nanoplastics accumulation on the intestines of marine species. Exposure of nanoplastics to *L. crocea* at a concentration level ranging from 5.50×10^{-12} to 5.50×10^{-7} $mg.L^{-1}$ for more than 14 days decreases survival and growth rate. The effect of NPs on marine secondary consumers is depicted in Table 4.

Overall, the experimental results indicate that secondary marine consumers have been severely affected by the NPS of different sizes, including loss of cell growth, lever malfunction, decrease in the rate of lipid metabolism, and other enzymatic action. It has also been observed that the juvenile species are worse affected than the adult organisms because of their better adaptation capacity to the environment. Furthermore, the effect of nanoplastics on adult marine species has been scarcely studied, whereas various experiments have been performed in the early stages of the life cycle of marine species.

FUTURE CHALLENGES AND REMEDIATION

The accumulation of nanoplastics in the environment has now turned into something quite shocking as it is incorporated into the water bodies of the marine environment by some anthropogenic along with the effluents of different industrial and wastewater treatment activities. This, in turn, enters the bodies of marine organisms by ingestion, adsorption, and feeding. The accumulation of so much nanoplastic within marine creatures from low to high levels also affects human health indirectly through drinking water or the uptake of seafood. It has been proved that the accumulation of nanoplastics can hamper living marine organisms' growth, immune, and reproductive systems, affecting the human body.

Contemporary studies have established that the availability of nanoplastics is similar to that of microplastics because the fragmentation of microplastics produces them. But still, studies on the effects of nanoplastics on living beings are quite scarce compared to those on microplastics. This is due to the lack of advanced technologies and experimental methods for identifying and monitoring nanoplastics in environmental matrices. Besides, developing highly sensitive, optimal analytical methods and experimental setups is difficult and expensive. Therefore, concerning nanoplastic pollution in the marine environment, its source of exposure, quantification, detection, and provision in nature should be strictly identified. Secondly, the degradation process of macroplastics into nanoplastics should be assessed. Lastly, a more thorough investigation of the influence of nanoplastics on marine life will be urgently needed.

Recently, researchers have been developing new substitutes that are equally useful as plastics but can simultaneously reduce the toxic effects of nanoplastics. A safe, eco-friendly alternative to plastic, known as "bioplastic" (Muneer et al. 2021), is one such substitute, but its application is still limited. The sustainable, recycled, and biodegradable plastic alternatives synthesized from corn starch, bamboo fiber, weeds, and palm leaves (Dutta & Dutta, 2023) are now in various food packaging. A recent study explored how graphene oxide is used to minimize the toxic effect of PS nanoplastic on *Picochlorum* sp. (Yesilay et al. 2022). Gupta et al. (2022) highlighted methods like photocatalysis, adsorption on biochar, flocculation, eco-corona membrane, filtration, electrospun membrane, etc., to minimize the adverse effect of nanoplastics on marine life. However, a significant development of new technologies is strictly needed to make this remedial process more popular.

In the preceding sections, we have discussed the harmful effect of nanoplastics on marine life, which disturbs the whole ecosystem. Some remediation has also been deliberated to reduce this detrimental outcome (Yesilay et al. 2022, Gupta et al. 2022, Dutta & Dutta 2023). Since plastic has become indispensable to our daily life, I think a suitable alternative to plastic, namely bioplastic, should be introduced that possess similar properties to plastics but will be bio-degradable and eco-friendly. Shafqat et al. (2021) synthesize bioplastic using the banana peel, corn starch, rice starch, wood dust, potato peel, and two polysaccharides, glycerol, and sorbitol, as plasticizers in 1:1 molar ratios. The use of other vegetable starch (sugarcane, peas, lentils), bamboo fiber, and paper pulp mixed with different polysaccharides like glycerol, mannitol, etc. as plasticizers in different molar ratios can extend this work to form bioplastics in green maintainable method. Research on developing plant plastic derived from mushroom roots, baggase (by-product of sugarcane processing), wheat, and barley is urgently needed to reduce plastic hazards. Moreover, necessary steps must be taken to flourish jute and paper technology, which will become efficient substitutes for plastics.

CONCLUSION

In the modern era of industrialization and globalization, nanoplastics have become alarming marine environmental pollutants. The sampling, quantification, distribution, and identification of nanoplastics in the environment, including the marine environment, has not been sufficiently

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investigated compared to microplastics due to a lack of experimental and analytical methods. However, adequate research has been done to identify the toxicological effects of PS and PMMA nanoplastics on marine organisms. It has also been reported that some marine organisms accumulate nanoplastics in high concentrations, which flow into other species, including humans, through the food web. The exact mechanism for the transportation of nanoplastics at the trophic level has not been well established. For a better understanding of the potential risk aspect of nanoplastics, the occurrence, distribution, degradation procedure, and their fate in the environment should be thoroughly studied. This also increases the necessity of developing a reliable methodology to identify the origin of the risk factor of the nanoplastics and to sort out the probable pathways to minimize the problem if it arises. Keeping in mind the toxic effect of microplastics, an attempt has been made to examine the lethal effect of nanoplastics on marine environments. This review provides a brief overview of the harmful effects of nanoplastics on various types of marine organisms, supported by experimental evidence. The toxicity of marine organisms is highly dependent on their size, concentration, exposure time, and variety. Surface functionalization of nanoplastics also plays an important role in inducing toxic effects. Positively charged nanoplastics seem more harmful than negatively charged nanoplastics to marine organisms. Several organic contaminants adsorbed on nanoplastics enhance their toxicity far more.

Some bioremediation processes to reduce the effect of nanoplastics on them have also been highlighted in this aspect. Some marine organisms change their outer surfaces to inhibit themselves from the toxic effects of nanoplastics. Literature found to date demonstrates only the toxic effects of PS and PMMA nanoplastics. So, further investigation of other types of nanoplastics is required. This review also highlights the need for further thorough investigation and quantification of nanoplastics worldwide. It also includes the active involvement of authorities and the public in improving and properly implementing the existing policies to assess and reduce the risk factors related to nanoplastics in the environment. This review also opens the door for future researchers to explore new eco-friendly remedial processes to minimize the toxic effects of nanoplastics after thorough assessments of their adverse effects on marine life.

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REFERENCES

Ahmed, T., Shahid, M., Azeem, F., Rasul, I., Shah, A.A., Noman, M., Hameed, A., Manzoor, I. and Muhammad, S. 2018. Biodegradation of plastics: current scenario and future prospects for environmental safety. Environ. Sci. Pollut. Res., 25: 7287-7298.

Alabi, O.A., Ologbonjaye, K.I., Awosolu, O. and Alalade, O.E. 2019. Public and environmental health effects of plastic waste disposal: A review. J. Toxicol. Risk Assess., 5(2): 1-13.

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.

Al-Sid-Cheikh, M., Rowland, S.J., Stevenson, K., Rouleau, C., Henry, T.B. and Thompson, R.C. 2018. Uptake, whole-body distribution, and depuration of nanoplastics by the Scallop *Pecten maximus* at environmentally realistic concentrations. Environ. Sci. Technol., 52(24): 14480-14486.

Amobonye, A., Bhagwat, P., Raveendran, S., Singh, S. and Pillai, S. 2021. Environmental impacts of microplastics and nanoplastics: A current overview. Front. Microbiol., 12.

Baig, A., Zubair, M., Zafar, M.N., Farid, M., Nazar, M.F. and Sumrra, S.H. (ed.) 2022. Nano Biodegradation of Plastic Waste: Biodegradation, and Biodeterioration at the Nanoscale. Elsevier, Singapore, pp. 239-259.

Balasch, J.C., Brandts, I., Barría, C., Martins, M.A., Tvarijonaviciute, A., Tort, L., Oliveira, M. and Teles, M. 2021. Short-term exposure to polymethylmethacrylate nanoplastics alters muscle antioxidant response, development, and growth in *Sparus Aurata*. Mar. Pollut. Bull., 172: 112918.

Balbi, T., Camisassi, G., Montagna, M., Fabbri, R., Franzellitti, S., Carbone, C., Dawson, K. and Canesi, L. 2017. Impact of cationic polystyrene nanoparticles (PS-NH_2) on early embryo development of Mytilus galloprovincialis: effects on shell formation. Chemosphere, 186: 1-9.

Berenstein, G., Hughes, E.A., Zalts, A., Basack, S., Bonesi, S.M. and Montserrat, J.M. 2022. Environmental fate of dibutyl phthalate in agricultural plastics: Photodegradation, migration and ecotoxicological impact on soil. Chemosphere, 290: 133221.

Bergami, E., Krupinski Emerenciano, A., González-Aravena, M., Cárdenas, C.A., Hernández, P., Silva, J.R.M.C. and Corsi, I. 2019. Polystyrene nanoparticles affect the innate immune system of the Antarctic sea urchin *Sterechinusneumayeri*. Polar Biol., 42(4): 743–757.

Bhagat, J., Nishimura, N. and Shimada, Y. 2021. Toxicological interactions of microplastics/nanoplastics and environmental contaminants: Current knowledge and future perspectives. J. Hazard. Mater., 405: 123913.

Blöcker, L., Watson, C. and Wichern, F. 2020. Living in the plastic age - Different short-term microbial responses to microplastics addition to arable soils with contrasting soil organic matter content and farm management legacy. Environ. Pollut., 267: 114568.

Brandts, I., Barría, C., Martins, M. A., Franco-Martínez, L., Barreto, A., Tvarijonaviciute, A., Tort, L., Oliveira, M. and Teles, M. 2021. Waterborne exposure of gilthead seabream (Sparus aurata) to polymethylmethacrylate nanoplastics causes effects at cellular and molecular levels. J. Hazard. Mater., 403: 123590.

Brandts, I., Teles, M., Gonçalves, A.P., Barreto, A., Franco-Martinez, L., Tvarijonaviciute , A., Martins, M.A., Soares, A.M.V.M., Tort, L. and Oliveira, M. 2018. Effects of nanoplastics on *Mytilus galloprovincialis* after individual and combined exposure with carbamazepine. Sci. Total Environ., 643: 775-784.

Brandts, I., Teles, M., Tvarijonaviciute, A., Pereira, M.L., Martins, M.A., Tort, L. and Oliveira, M. 2018. Effects of polymethylmethacrylate nanoplastics on Dicentrarchuslabrax. Genomics, 110(6): 435–441.

Capolupo, M., Valbonesi, P. and Fabbri, E. 2021. A comparative assessment of the chronic effects of micro-and nano-plastics on the physiology of the Mediterranean mussel Mytilus galloprovincialis. Nanomaterials, 11(3): 649.

This publication is licensed under a Creative Commons Attribution 4.0 International License

Cartraud, A.E., Corre, M.L., Turquetb, J. and Tourmetz, J. 2019. Plastic ingestion in seabirds of the western Indian Ocean. Mar. Pollut. Bull., 140: 308-314.

Cedervall, T., Hansson, L.A., Lard, M., Frohm, B. and Linse, S. 2012. Food chain transport of nanoparticles affects behavior and fat metabolism in fish. PLoS One, 7(2): e32254.

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): 1–11.

Chen, Q., Gundlach, M., Yang, S., Jiang, J., Velki, M., Yin, D. and Hollert, H. 2017. Quantitative investigation of the mechanisms of microplastics and nanoplastics toward zebrafish larvae locomotor activity. Sci. Total Environ., 584-585: 1022-1031.

Cole, M. and Galloway, T. S. 2015. Ingestion of nanoplastics and microplastics by Pacific oyster larvae. Environ. Sci. Technol., 49(24): 14625-14632.

Dutta, P. and Dutta, M. 2023. Microplastic hazards and possible mitigation. Eco. Environ. Cons., 29(1): 314-320.

Elsawy, M.A., Kim, K.H., Park, J.W. and Deep, A. 2017. Hydrolytic degradation of polylactic acid (PLA) and its composites. Renew. Sustain. Energy Rev., 79: 1346-1352.

Eyerer, P. 2010. Synthesis (Manufacture, Production) of Plastics: Polymers-Opportunities and Risks. Elsevier, Singapore, pp. 19-46.

Feldkamp, S.D., Costa, D. P. and Dekrey, G.K. 1989. Fish B. Noaa, 87(1): 85-94.

Fotopoulou, K.N. and Karapanagioti, H.K. (ed.) 2017. Degradation of Various Plastics in the Environment. Hazardous Chemicals Associated with Plastics in the Marine Environment. 78: pp. 71–92.

Geyer, R. (ed.) 2020. A Brief History of Plastics, Springer, NY, pp. 31-47.

Gomes, T., Almeida, A.C., and Georgantzopoulou, A. 2020. Characterization of cell responses in *Rhodomonasbaltica* exposed to PMMA nanoplastics. Sci. Total Environ., 726: 138547.

González-Fernández, C., Tallec, K., Le Goïc, N., Lambert, C., Soudant, P., Huvet, A., Suquet, M., Berchel, M. and Paul-Pont, I. 2018. Cellular responses of Pacific oyster (Crassostrea gigas) gametes exposed in vitro to polystyrene nanoparticles. Chemosphere, 208: 764-772.

Gu, H., Wang, S., Wang, X., Yu, X., Hu, M., Huang, W. and Wang, Y. 2020. Nanoplastics impair the intestinal health of the juvenile large yellow croaker Larimichthyscrocea. J. Hazard. Mater., 397: 122773.

Gupta, C., Kaushik, S., Jain, S., Dhanwani, I., Garg, S., Paul A., Pant, P. and Gupta, N. 2022. Bioaccumulation and toxicity of polystyrene nanoplastics on marine and terrestrial organisms with possible remediation strategies: A review. Environ. Advan., 8: 100227.

Hazeem, J.L., Yesilay, G., Bououdina, M., Perna, S., Cetin, D., Suludere, Z., Barras, A. and Boukherroub, R. 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.

Isaacson, K.P., Proctor, C.R., Wang, Q.E., Edwards, E.Y., Noh, Y., Shah, A.D. and Whelton, A.J. 2021. Drinking water contamination from the thermal degradation of plastics: implications for wildfire and structure fire response. Environ. Sci. Water Res. Technol., 7: 274-284.

Jain, A., Siddique, S., Gupta, T., Jain, S., Sharma, R.K. and Chaudhury, S. 2019. Fresh, strength, durability, and microstructural properties of shredded waste plastic concrete. Iran J. Sci. Technol, Trans. A Sci., 43: 455-465.

Jaiswal, J., Sharma, B. and Shukla, P. 2020. Integrated approaches in microbial degradation of plastics. Environ.Technol. Innov., 17: 100567.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M. and Andrady, A. 2015. Plastic waste inputs from land into the ocean. Science, 347(6223): 768-771.

Jeong, C.B., Won, E.J., Kang, H.M., Lee, M.C., Hwang, D.S., Un, K.H., Zhou, B., Souissi, S., Jae L., Su, L. and Jae, S. 2016. Microplastic size-dependent toxicity, oxidative stress induction, and p-JNK and p-P38 activation in the monogonont rotifer (*Brachionus koreanus*). Environ. Sci. Technol., 50: 8849-8857.

Kang, H.M., Byeon, E., Jeong, H., Kim, M.S., Chen, Q. and Lee, J.S. 2021. Different effects of nano-and microplastics on oxidative status and gut microbiota in the marine medaka *Oryzias melastigma*. J. Hazard. Mater., 405: 124207.

Khoshnamvand, M., Hanachi, P., Ashtiani, S. and Walker, T.R. 2021. Toxic effects of polystyrene nanoplastics on microalgae Chlorella vulgaris: changes in biomass, photosynthetic pigments and morphology. Chemosphere, 280: 130725.

Koelmans, A.A., Besseling, B. and Shim, W.J. 2015. Nanoplastics in the Aquatic Environment. Critical Review, Marine Anthropogenic Litter, 325-340.

Kumagai, S., Sato, M., Ma, C., Nakai, Y., Kameda, T., Saito, Y., Watanabe, A., Watanabe, C., Teramae, N. and Yoshioka, T. 2022. A comprehensive study into the thermo-oxidative degradation of sulfur-based engineering plastics. J. Anal. Appl Pyrolysis, 168: 105754.

Lai, W., Xu, D., Li, J., Wang, Z., Ding, Y., Wang, X., Li, X., Xu, N., Mai, K. and Ai, Q. 2021. Dietary polystyrene nanoplastics exposure alters liver lipid metabolism and muscle nutritional quality in carnivorous marine fish large yellow croaker (Larimichthyscrocea). J. Hazard. Mater., 419: 126454.

Liu, F.-F., Gao, Z.Y., Chu, W.C. and Wang, S.C. 2022. Polystyrene nanoplastics alleviate the toxicity of CuO nanoparticles to the marine algae *Platymonashelgolandica* var. *tsingtaoensis,* Front. Mar. Sci., 1-10.

Liu, J., Ma, Y., Zhu, D., Xia, T., Qi, Y., Yao, Y., Guo, X., Ji, R. and Chen, W. 2018. Polystyrene Nanoplastics-enhanced contaminant transport: Role of irreversible adsorption in glassy polymeric domain. Environ. Sci. Technol., 52(5): 2677-2685.

Liu, Y., Huang, J., Jin, J., Lou, S., Shen, C., Zang, H. and Wang, L. 2020. The classification of micro-plastics and biodegradation of plastics/micro-plastics. J. Eng. Technol Sci., 3(6): 181-190.

Manfra, L., Rotini, A., Bergami, E., Grassi, G., Faleri, C. and Corsi, I. 2017. Comparative ecotoxicity of polystyrene nanoparticles in natural seawater and reconstituted seawater using the rotifer Brachionusplicatilis. Ecotoxicol. Environ. Saf., 145: 557-563.

Mao, R., Lang, M., Yu, X., Wu, R., Yang, X. and Guo, X. 2020. Aging mechanism of microplastics with UV irradiation and its effects on the adsorption of heavy metals. J. Hazard. Mater.. 393: 122515.

Marques-Santos, L.F., Grassi, G., Bergami, E., Faleri, C., Balbi, T., Salis, A., Rist Damonte, G., Canesi, L. and Corsi, I. 2018. Cationic polystyrene nanoparticle and the sea urchin immune system: Biocorona formation, cell toxicity, and multixenobiotic resistance phenotype. Nanotoxicology, 17: 1-21.

Muneer, F., Nadeem, H., Arif, A. and Zaheer, W. 2021. Bioplastics from Biopolymers: An Eco-Friendly and Sustainable Solution of Plastic Pollution, Polym. Sci. Ser. C, 63: 47-63.

Murano, C., Bergami, E., Liberatori, G., Palumbo, A. and Corsi, I. 2021. Interplay between nanoplastics and the immune system of the Mediterranean Sea urchin Paracentrotuslividus. Front. Mar. Sci., 8: 234.

Natarajan, L., Jenifer, M.A., Chandrasekaran, N., Suraishkumar, G.K. and Mukherjee, A. (2022). Polystyrene nanoplastics diminish the toxic effects of Nano-TiO_2 in marine algae *Chlorella* sp. Environ. Res., 204: 112400.

Oliviero, M., Tato, T., Schiavo, S., Fernández, V., Manzo, S. and Beiras, R. 2019. Leachates of micronized plastic toys provoke embryotoxic effects upon sea urchin *Paracentrotuslividus*. Environ. Pollut., 247: 706-715.

Ravishankar, K., Ramesh, P.S., Sadhasivam, B. and Raghavachari, D. 2018. Wear-induced mechanical degradation of plastics by low-energy wet-grinding. Polym. Degrad. Stab., 158: 212-219.

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Rice, N., Hirama, S. and Whiterington, B. 2021. High frequency of micro- and meso-plastics ingestion in a sample of neonate sea turtles from a major rookery. Mar. Pollut. Bull., 167: 112363.

Rist, S., Baun, A. and Hartmann, N.B. 2017. Ingestion of micro- and nanoplastics in *Daphnia magna* – Quantification of body burdens and assessment of feeding rates and reproduction, Environ. Pollut., 228: 398-407.

Rist, S., Baun, A., Almeda, R. and Hartmann, N.B. 2019. Ingestion and effects of micro- and nanoplastics in blue mussel (*Mytilus edulis*) larvae, Mar. Pollut. Bull., 140: 423-430.

Sendra, M., Staffieri, E., Yeste, M.P., Moreno-Garrido, I., Gatica, J.M., Corsi, I. and Blasco, J. 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.

Shafqat, A., Al-Zaqri, N., Tahir, A. and Alsalme, A. 2021. Synthesis and characterization of starch based bioplastics using varying plant-based ingredients, plasticizers, and natural fillers. Saudi J. Biol. Sci., 28: 1739-1749.

Shiu, R.F., Vazquez, C.I., Chiang, C.Y., Chiu, M.H., Chen, C.S., Ni, C.W., Gong, G.C., Quigg, A., Santschi, P.H. and Chin, W.C. 2020. Nano- and microplastics trigger the secretion of protein-rich extracellular polymeric substances from phytoplankton. Sci. Total Environ., 748: 141469.

Silva, M.S.S., Oliveira, M., Valente, P., Figueira, E., Martins, M. and Pires, A. 2020. Behavior and biochemical responses of the polychaeta *Hediste diversicolor* to polystyrene nanoplastics. Sci. Total Environ., 707: 134434.

Sjollema, S.B., Redondo-Hasselerharm, P., Leslie, H.A., Kraak, M.H.S., and Vethaak, A.D. 2016. Do plastic particles affect microalgal photosynthesis and growth? Aquat. Toxicol., 170: 259-261.

Stolbov, D.N., Smirnova, A.I., Savilov, S.V., Shilov, M.A., Burkov, A.A., Parfenov, A.S. and Usol'tseva, N.V. 2021. Influence of different types of carbon nanoflakes on tribological and rheological properties of plastic lubricants. Fullerenes, Nanotubes, and Carbon Nanostructures. Proceedings of the 15th International Conference "Advanced Carbon Nanostructures". 177-184.

Sun, J., Zheng, H., Xiang, H., Fan, J. and Jiang, H. 2022. The surface degradation and release of microplastics from plastic films are studied by UV radiation and mechanical abrasion. Sci. Total Environ., 838: 156369.

Tallec, K., Huvet, A., Poi, C.D., González-Fernández, C., Lambert, C., Petton, B., Goïc, N. L., Berchel, M., Soudant, P. and Paul-Pont, I. 2018. Nanoplastics impaired oyster free-living stages, gametes, and embryos. Environ. Pollut., 242: 1226-1235.

Torres-Ruiz, M., Vieja, A.D.L., Gonzalez, M.D.A., Lopez, M.E., Calvo, A.C. and Portilla, A.I. C. 2021. Toxicity of nanoplastics for zebrafish embryos, what we know and where to go next. Sci. Total Environ., 797: 149125.

Trevisan, R., Voy, C., Chen, S. and Giulio, R.T.D. 2019. Nanoplastics decrease the toxicity of a complex PAH mixture but impair mitochondrial energy production in developing zebrafish. Environ. Sci. Technol., 53(14): 8405-8415**.**

Trifuoggi, M., Pagano, G., Oral, R., Pavičić-Hamer, D., Burić, P., Kovačić, I., Siciliano, A., Toscanesi, M., Thomas, P.J., Paduano, L., Guida, M. & Lyons, D.M. 2019. Microplastic induced damage in early embryonal development of sea urchin *Sphaerechinus granularis*. Environ. Res., 179: 108815.

United Nations Environment Programme and Secretariat of the Convention on Biological Diversity 2012. Impacts of Marine Debris on Biodiversity: Current Status and Potential Solutions. CBD Technical Series No. 67. Available at: https://wedocs.unep.org/20.500.11822/32622

Venâncio, C., Ferreira, I., Martins, M.A., Soares , A.M.V. M., Lopes, I. and Oliveira, M. 2019. The effects of nanoplastics on marine plankton: A case study with polymethylmethacrylate. Ecotoxicol. Environ. Saf., 184: 109632.

Wang, S., Hu, M., Zheng, J., Huang, W., Shang, Y., Fang, J.K.H., Shi, H. and Wang, Y. 2021. Ingestion of nano/microplastic particles by the mussel *Mytilus coruscus* is size-dependent. Chemosphere, 263: 127957.

Wang, S., Liu, M., Wang, J., Huang, J. and Wang, J. 2020. Polystyrene nanoplastics cause growth inhibition, morphological damage, and physiological disturbance in the marine microalga *Platymonas helgolandica*. Mar. Pollut. Bull., 158: 111403.

Wegner, A., Besseling, E., Foekema, E.M., Kamermans, P. and Koelmans, A.A. 2012. Effects of nanopolystyrene on the feeding behavior of the blue mussel (*Mytilus edulis* L.). Environ. Toxicol. Chem., 31: 2490-2497.

Yesilay, G., Hazeem, L., Bououdina, M., Cetin, D., Suludere, Z., Barras, A. and Boukherroub, R. 2022. Influence of graphene oxide on the toxicity of polystyrene nanoplastics to the marine microalgae *Picochlorum* sp. Environ. Sci. Pollut. Res., 29: 75870-75882.

Zaki, M.R.M. and Aris, A.Z. 2022. An overview of the effects of nanoplastics on marine organisms. Sci. Total Environ., 831: 154757.

Zhang, W., Wang, Q. and Chen, H. 2022. Challenges in Characterization of Nanoplastics in the Environment. Front. Environ. Sci. Eng., 16(1): 11.

Zhao, T., Tan, L., Zhu, X., Huang, W. and Wang, J. 2020. Size-dependent oxidative stress effect of nano/micro-scaled polystyrene on Kareniamikimotoi. Mar. Pollut. Bull., 154: 111074.

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