Nano-Scale Plastic Pollution in the Marine Species: A Review

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ABSTRACT

The long-term properties of plastic have been causing persistent marine pollution for decades. The adverse impacts have been found in marine organisms worldwide. Currently, their degraded products—microplastics and nanoplastics—represent emerging plastic issues. Microplastic pollution has drawn attention in many research fields and the general public. Many types of literature have documented their adverse impacts, distribution, and origins. Hence, many review studies have been conducted on microplastics rather than nanoplastics. Therefore, this review is focused on nanoplastic contamination in marine ecosystems, their origins, distributions, fate, and impacts on marine organisms. This review paper provides an overall picture of nanoplastic pollution on a global scale. The impacts of nanoplastic on marine organisms’ gene expression at the cellular and tissue levels are evaluated. Moreover, the adverse effects of nanoplastics on the embryonic stages, growth, and mortality of marine species are also discussed. The present review also gathers information to generate future research perspectives, and aims to highlight the need for researching on nanoplastics in the aquatic environment while providing critical perspectives for setting future research objectives.

1. Introduction

Plastic pollution in the marine environment is a growing concern among current pollution issues [1]. In the 21st century, plastic waste management represents a challenge to the scientific community, as the exponential consumption of plastics since the 1950s has led to the significant release of plastic waste into the marine environment [2-4]. In 2010, there was approximately 13,200 to 34,800 tons of plastic litter released to into the marine environment, and this figure is expected to increase by an order by 2025 [5]. Legislation related to plastic worldwide has been implemented and showed positive outcomes [6]; however, plastic pollution has not been entirely solved by the implemented legislation. Although the plastic degradation could occur in the marine environment, the breakdown of larger debris into smaller plastic particles remains harmful to the environment [7]. The smaller plastic debris particles are generally classified as either microplastic (MP) or nanoplastic (NP) (Table 1).

Table 1 | Size class definition of aquatic nanoplastic from current research studies

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Size Class</th>
<th>Size Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano</td>
<td>Nanoplastic</td>
<td>&lt;20 µm</td>
<td>[8]</td>
</tr>
<tr>
<td></td>
<td>&lt;0.1 µm</td>
<td>[9]</td>
<td></td>
</tr>
<tr>
<td>Micro</td>
<td>Microlitter</td>
<td>~0.06 – 0.5 mm</td>
<td>[10]</td>
</tr>
<tr>
<td>Microplastic</td>
<td>&lt;0.5 mm</td>
<td>[11-15]</td>
<td></td>
</tr>
<tr>
<td>Microdebris</td>
<td>0.33 – 5.0 mm</td>
<td>[16]</td>
<td></td>
</tr>
<tr>
<td>Small microplastic</td>
<td>&lt;1 mm</td>
<td>[17]</td>
<td></td>
</tr>
<tr>
<td>Microplastic</td>
<td>&lt;2 mm</td>
<td>[18,19]</td>
<td></td>
</tr>
<tr>
<td>Large microplastic</td>
<td>0.2 – 1 mm</td>
<td>[19]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt;0.3 mm (&lt;1 mm)</td>
<td>[20]</td>
<td></td>
</tr>
</tbody>
</table>

NP is defined as plastic of a particle size smaller than 20 µm, based on [8]. This review paper considers particles between 0.1 and 2.0 µm in size as the NP particle size-class in the marine environment, and evaluates NP studies with corresponding impacts. The origins, distribution, and concentrations of NPs in the marine environment were evaluated based on current research. Their adverse impacts to marine organisms are evaluated at the molecular, cellular, and physiological level, while also evaluating impacts on growth and reproductive output. Based on current survey studies and ecotoxicity, this paper provides improvement strategies and future perspectives for NP research in order to increase the coverage of the NP research field.

2. Distribution and Origins of Nanoplastic

2.1 Distribution of Plastic Pollution

The marine environment has been affected by plastic pollution for decades. Many surveys have been conducted on the concentration of plastic particles in the USA, Belgium, France, Australia, and Russia (Table 2). The observed distribution suggests that plastic pollution affects marine ecosystem on a global scale. The highest plastic particle concentration was observed in the North Pacific Central Gyre (334,271 plastic fragments/km²) (Table 2). Plastic particles distributed in the marine environment are strongly related to the climate system in this particular area, which has resulted in a high concentration of particles [21]. The survey conducted in the North Pacific Ocean indicated that climate conditions were the drivers for the results. The dominant clockwise gyral currents act as a retention mechanism that prevents plastic particles from moving toward coasts [21]. In addition, surface current modelling simulated that plastic particles in the North Pacific Ocean could remain in the area for at least 12 years [21]. Moreover, other climatic factors could include the natural eddy system concentrating plastic particles in the area [21]. While the accumulation of plastic materials in the marine environment is increasing over time, they will be degrading slowly into MP and NP in the North Pacific Ocean [1]. Hence, as new plastics were added, MP and NP formation could not exit the oceanic system once introduced. The hydrodynamic effects distributed this plastic debris around the Australian region. An Australian coastline survey on plastic pollution indicated that plastics travelled with a range of currents, including the Antarctic Circumpolar current [22]. Moreover, the South Equatorial current in the Pacific Ocean brought the plastics to Australia, Fiji, and New Caledonia [22, 23]. The East Australian current carried plastic debris from the Australian populated area (Brisbane and Sydney) to the east coast of Australia and the Tasman Sea [22, 24]. Furthermore, the Holloway, Leeuwin, South Australian, and Zeehan coastal current systems brought plastic from international areas to the North West Shelf [25-28]. In addition, the West Australia current brought plastics from the Indian Gyre...
to the North West Shelf and Perth area [28]. These oceanic hydrodynamics indicated that climate conditions could be associated with marine plastic pollution.

| Table 2 Microplastic distributed in marine environment in worldwide |
|------------|-------------------------------|-----------------|-----------------|
| Country    | Location                      | Concentration   | Ref.            |
| USA        | North Pacific Central Gyre     | 334,271 plastic fragments/km² | [21]          |
| USA        | North Atlantic Subtropical     | 20,3282,324      | [29]            |
| USA        | North Pacific Subtropical      | 0.002-6.649 particles/m²   | [30]            |
| Gyre       | Alaska                         | 0.000-0.140 particles/m²   |                |
| Gyre       | California Current             | 0.000-0.228 particles/m²   | [31]            |
| Gyre       | Eastern Tropical Pacific       | 0.000-0.034 particles/m²   | [32]            |
| Gyre       | Total                          | 0.000-6.496 particles/m²   | [33]            |
| Belgium    | Northwestern                    | 0.116-0.092 particles/m²   |                |
| Australia  | Mediterranean Sea              | Particles/m²          |                |
| Australia  | Australian vessels             | 4256.4-757.79       | [34]            |
| Russia     | Kuril-Kamchatka                | 60-2020 particles/m²     | [35]            |
| Trenchera  |                               |                               |                |

2.2. Origins of Nanoplastics

Nanoplastics can be classified into two major categories: primary and secondary nanoplastic. The primary sources of NP are defined as primarily produced in the nano-scale size. NP products include plastics from medical applications and cosmetic products. The medical applications of NP are primarily used in drug delivery with biodegradable solid lipid properties [34]. Cosmetic products include plastic microbeads in skin cleansers for exfoliating scrubs [35]. The smallest size of nanoplastic cleansing beads was found to be 4 μm [36].

Secondary NPs are classified as products of the degradation of larger plastics or microplastics [1]. There are three major mechanisms forming secondary NP, which can be divided into physical degradation, photodegradation, and biological breakdown. This degradation is caused by weak bonding between polymer chains. For example, expanded polystyrene (EP) beads were fragmented in a mechanical degradation experiment that accelerated mechanical abrasion using glass beads and sand to produce smaller plastics from larger plastic sources (EP beads) under experimental conditions [36]. While the conditions were not involved with other factors, the results indicated that natural secondary NP production could occur in beach and river systems. In fact, the realistic situations of sunlight UV exposure, temperature, and humidity could accelerate secondary NP production time. Photodegradation is another pathway for the breakdown of larger plastics into smaller plastics [37]. Furthermore, biological mechanisms can also break down larger plastics through the action of microorganisms and other marine organisms. For example, Harshvardhan et al. [38] determined that the marine microorganisms Kocuria palustris, Bacillus pumilus, and Bacillus subtilis were able to degrade plastics such as polystyrene. Overall PE mass loss was 1.75% higher following 30 days of exposure to microorganisms [38].

Recently, the biological breakdown of microplastic into nanoplastic was observed in a keystone species in the Antarctic ecosystem when Antarctic krill (Euphausia superba) was exposed to polypropylene (PE) microbeads (27-32 μm) alongside algal food resources [39]. The ingested PE was fragmented by the Antarctic krill into particles less than 1 μm (diameter) in size [40].

3. Impacts to Organisms

The existence of NPs in the marine environment could lead to damage in organisms (Fig. 1 and Table 3). Numerous research studies have found that marine organisms were capable of NP uptake, which can cause molecular, cell, tissue, and embryo level damages. Moreover, the growth, biochemistry, and behaviour of marine species can also be negatively impacted. Herein, this section evaluates previous studies on such adverse effects on marine species.

3.1 Ingestion of Nanoplastics and Trophic Transfer

In one study, high-density polyethylene (HDPE) NPs were taken up by Mytilus edulis L. (blue mussel) cells and tissues edibh caused significant adverse effects [41]. The HDPE particles were drawn into the stomach and transported into the digestive gland, and then eventually accumulated in the lysosomal system [41]. Histological changes, a strong inflammatory response (granulocytoma formation), and lysosomal membrane destabilisation were observed within blue mussels [41]. Another exposure experiment demonstrated that blue mussels ingested and accumulated plastic particles (3.0 or 9.6 μm) within their guts [42]. Hence, following ingestion, the plastic particles caused damage, as NP was translocated to the circulatory system from the digestive system in Mytilus edulis [42]. This translocation occurred within 3 days and persisted for over six weeks [42]. These studies suggest that NPs could affect entire physiological systems within marine organisms through multiple routes. Furthermore, blue mussels exposed to both NP (30 nm) and their typical food resource (Pavlova lutheri) altered their filtering activity [43]. The exposure assessment was conducted with present of algae and NP indicated that filtering activity decreased, though NP concentration in water remained low [43]. This indicates that the NP was ingested by the blue mussels and decreased filtering activity conditions. Moreover, the bivalves produced pseudofaeces while exposed to both NP and Pavlova lutheri (algae) (contaminated by NP) [43]. The energy consumed in the production of pseudofaeces and reduced filtering activity indicated that the ingestion of NP led to starvation [43]. In another study, the aggregation of polystyrene (PS) beads enhanced the uptake efficiency of studied marine species [Mytilus edulis and Grassostrea virginica] [44], as the NPs travelled into the digestive gland tubules and was taken up by digestive cells via endocytosis [44]. This suggests that bioaccumulation occurred within the organisms and potentially transferred to higher trophic levels of marine organisms. The retention of NP within blue mussels does not only impact the marine species that feed on them, but human consumption could also represent another serious issue. Furthermore, a trophic transfer study by [45] indicated that polystyrene (PS) spheres were transferred by blue mussel to Carcinus maenas (L.) (littoral crab) through predation. This translocation was observed within the crab through the discovery of PS spheres within the haemolymph and tissues [45]. Furthermore, the polystyrene (PS) plastic particles (smallest size ~10 μm) were found inside scleractinian corals (Dipsastrea pallida, classified as Favia pallida) [46]. Scleractinian corals took up plastic particles and accumulated them in mesenterial tissue within the gut cavity [40]. This implies that high concentrations of PE particles could induce health impairments in corals [40]. Moreover, the marine copepod Calanus helgolandicus ingested PS beads (20 μm), resulting in an eventual 40% decrease in carbon biomass [46]. Moreover, prolonged NP exposure caused a significant reduction in hatching success, resulting in the production of smaller eggs, as well as reduced reproductive output [46]. Furthermore, Littorina littorea (marine snails) could not distinguish between plastic particles, clean algae (Puerus vesiculosus, seaweed), and contaminated algae [47]. The plastics were found in the stomach and gut of snails following feeding with NP-contaminated algae.

Polystyrene nanoparticles (PS-NP) significantly increased Amphora sp. exopolymyxigen substances (EPS) assembly and eventually formed PS-EPS microsopic gel [approximately 4-6 μm] [48]. EPS is a polyanshagride-rich anionic gel polymer released by microorganisms [48] and is the most important source of marine dissolved organic carbon and particulate organic carbon in the marine environment [49–52]. This disturbance could further affect the carbon cycle in the marine ecosystem [48]. However, Amphibulans amphitrite (barnacles) ingested poly methyl methacrylate (PMMA) NP during planktonic larval stages, and the NP persisted into their adult stages [53]. This persistence of NP within the barnacles implies long-term impacts of NP within sessile invertebrate communities. Bioaccumulation even occurred at low PMMA NP concentrations, though some (but not all) PMMA particles were ejected through molting and faecal excrement during acute exposure to PMMA NP [53]. Moreover, ingestion frequency and the magnitude of NP were determined by age, NP size, and NP surface properties [54]. For instance, the inanimate surface of PS-NP was ingested and retained more frequently than the
effects were caused by PS-NH₂ [64]. The increase of relative spermatozoa and oocyte cell size and complexity could increase NP adhesion effects [64].

**Brachionus keruensis** (monogonont rotifer) serves a role in transferring energy in the aquatic food chain, and also has the ability to carry contaminants to higher trophic levels via ingestion and accumulation [65-67]. Moreover, they experience adverse physiological responses following exposing to NP particles. The MAPKs and c-Jun N-terminal kinase (JNK) were phosphorylated in response to 0.05µm PS beads [66]. However, the negative correlation of ROS levels and NP size was observed [66]. ROS plays a major role in the activation of the MAPK pathway, and NP-induced ROS is the major toxicity factor in response to NP exposure among rotifers [66].

### 3.3 Growth Inhibition, Mortality, and Behaviour Changes

Dunaliella tertiolecta (green microalgae) and Artemia franciscana (brine shrimp) ingested PS-NH₂ and caused growth inhibition (EC₅₀=12.97 µg/mL) in green microalgae as well as mortality (LC₅₀=0.83 µg/mL) in brine shrimp [58]. The exposure of Brachionus keruensis (monogonont rotifer) to PS beads resulted in a reduced growth rate, reduced fecundity, decreased lifespan, and longer reproduction period [66]. Furthermore, such reduced fecundity and lifespan could lead to decreasing rotifer populations.

Fecundity is associated with population growth, which can be negatively affected by the number of offspring being reduced due to ingestion of PS beads [66]. Moreover, a longer reproduction period was caused by a lower rate of growth following PS bead ingestion [66]. In another study, uncharged PS particles (0.05 µm) reduced Dunaliella tertiolecta cell density by up to 45% at a concentration of 2.50 mg/L [68]. The D. tertiolecta growth rate was inhibited by 57% following exposure to PS particles [68]. In addition, decreasing NP particle sizes led to increased inhibition of microalgal growth [68].

NP exposure can also lead to mortality in marine organisms. PS particles increased hemocyte mortality in Mytilus spp. caused by a decrease in circulating granulocytes and total hemocyte concentration, which indicates the recruitment of active hemocytes for incursion in PS-exposed mussels [62]. This could modify the balance of live circulating hemocytes in the hemolymph [62].

*Tigriopus japonicus* (copepod) exposed to a PS bead concentration of 12.5 µg/mL caused mortality in nauplii and copepodes in the F₂ generation [69], while a PS bead concentration reaching 1.25 µg/mL caused F₁ generation mortality [69]. Also, PS-NH₂ exposure caused mortality (LC₅₀=0.83 µg/mL) in Artemia franciscana (brine shrimp) [55,58]. The surface properties of NP could be a key factor responsible for the behavioural and ecological interactions of marine species [58]. Notably, behavioural changes were observed following NP ingestion in Pomatoschistus microps (common goby). The predatory performance of common gobies exposed to chromium (VI) (Cr (VI)) and PE spheres decreased by nearly 67% [70]. In the long-term, it could reduce individual performance and eventually cause death with negative effects on the population fitness.

### 3.4 Embryo Impacts

The Talles et al. [71] performed a PS-NP dose-response experiment on C. gigas (Pacific oyster) gametes. PS-NP decreased fertilization success and embryo-larval development with various malformations and some cases of total developmental arrest [71]. The study determined that 50nm PS-NP exhibited the strongest toxicity to both gametes (EC₅₀=4.9 µg/mL) and embryos (EC₅₀=0.15 µg/mL). Furthermore, Paracentrotus lividus (sea urchin) embryos demonstrated a dose-dependent response to various surface coatings of PS-NP (PS-COOH and PS-NH₂) [72].

While several development were defects brought on by PS-NH₂ at EC₅₀ concentrations of 3.85 µg/mL (24 hpf) and 2.61 µg/mL (48 hpf), there was upregulation in the AbCl₁ gene at 48 hpf by PS-COOH, and the cad3 gene was induced by PS-NH₂ at 24 hpf [72]. The two types of PS-NP were distributed in differently early growth stage stages and embryos in PS-COOH were distributed in the digestive tract and PS-NH₂ was dispersed [72]. Overall, PS-NH₂ impaired the development of the normal D-shaped larvae of *Mytilus galloprovincialis* at 48 hpf, and also affected shell formation (EC₅₀=0.142 mg/L) [73]. The high embryo toxicity/developmental arrest in *Mytilus galloprovincialis* was observed at a PS-NH₂ NP concentration of 5.20 mg/L [73]. Moreover, PS-NH₂ NP induced dysregulation of gene transcription at the 24 and 48 hpf stage of shell formation (Chitin synthesis, Carbonic anhydrase, extrapallial protein) in *Mytilus galloprovincialis* [73]. During the 4hps mussel embryo stage, mRNA levels of the ABC transporter p-glycoprotein-ABCB and lysozyme were decreased [73].
Amphibalanus Amphitrite (urchin embryos) and Mytilus galloprovincialis (mussel) with sulfate groups) and Polystyrene (PS) (coated with carbamazepine (Cbz)) with carboxylic group or amine group. Significant increase of Reactive Oxygen Species production were only observed in sperm cell when exposed to PS-COOH and PS-NH₂. Decreased in number of single spermatozoon while exposed to PS-COOH due to spermatozoa aggregates for the NP condition. Spermatozoon exposed PS-COOH and PS-NH₂ showed 4–5% increase in its size. Higher celler relative complexity was observed.

**Table 3 The adverse effects on aquatic organisms**

<table>
<thead>
<tr>
<th>Species</th>
<th>NP Type and Condition</th>
<th>NP Size</th>
<th>Exposure Concentration</th>
<th>Effect</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paracentrotus lividus (urchin embryos)</td>
<td>Carboxylated polystyrene</td>
<td>40 nm</td>
<td>50 μg/mL</td>
<td>No embryotoxicity: Accumulated inside embryo’s digestive tract</td>
<td>[72]</td>
</tr>
<tr>
<td>Allorchestes compressa (amphipods)</td>
<td>Polyethylene sorbed with PBDEs</td>
<td>11−700 μm</td>
<td>3 μg/mL</td>
<td>caspase gene at 24 hpf (apoptotic pathway)</td>
<td>[56]</td>
</tr>
<tr>
<td>Crouassota gigas (pacific oyster gametes)</td>
<td>Polyurethane (coated with carboxylic or amine group)</td>
<td>100 nm</td>
<td>10 mg/L</td>
<td>Higher relative cellular complexity was observed while exposed to PS-COOH and PS-NH₂</td>
<td>[64]</td>
</tr>
<tr>
<td>Dunalilla tertiolecta, Thalassiosira pseudonana and Chlorella vulgaris (microalgae)</td>
<td>Polyethylene (negatively charged and uncharged)</td>
<td>0.05, 0.5 and 6 μm</td>
<td>250 mg/L</td>
<td>Microalgal growth was suppressed at 45% by uncharged NP. The relationship between microalgal growth and NP size was negatively related.</td>
<td>[68]</td>
</tr>
<tr>
<td>Pomatoschistus microphyllus (goby)</td>
<td>Polyethylene (with Potassium dichromate (Cr(VI)))</td>
<td>1.5 μm</td>
<td>Cr(VI) + NP: 5.6 mg/L + 0.184 mg/L; 8.4 mg/L + 0.184 mg/L; 12.6 mg/L + 0.184 mg/L; 18.9 mg/L + 0.184 mg/L; 28.4 mg/L + 0.184 mg/L</td>
<td>Significant decrease of the predatory performance at ≤67% and significant inhibition of AChE activity at ≤31%. Significant increase of lipid peroxidation levels.</td>
<td>[70]</td>
</tr>
<tr>
<td>Vibrio fisheri (bacteria)</td>
<td>Polyethyleneimine polystyrene-silica (PS-PEI)</td>
<td>50 nm and 100 nm</td>
<td>10 μg and 10 μg spheres/L</td>
<td>Significant but transient effects on branchial function through gill chamber inhalation. Lowered oxygen consumption. Significant drop in the concentration of Na⁺ ions within the hemolymph with increasing neutral plastic dose.</td>
<td>[75]</td>
</tr>
<tr>
<td>Carcinus maenas (shore crab)</td>
<td>Polyurethane (coated with carboxylic group or amine group)</td>
<td>8 μm</td>
<td>10⁴ and 10⁵ spheres/L</td>
<td>Significant increase of Reactive Oxygen Species production were only observed in sperm cell when exposed to PS-COOH and PS-NH₂. Decreased in number of single spermatozoon while exposed to PS-COOH due to spermatozoa aggregates for the NP condition. Spermatozoon exposed PS-COOH and PS-NH₂ showed 4–5% increase in its size. Higher celler relative complexity was observed.</td>
<td>[48]</td>
</tr>
<tr>
<td>Amphora sp., Ankistrodesmus angustus and Phaeodactylum tricornutum (phytoplankton)</td>
<td>Polyethylene</td>
<td>5 nm</td>
<td>1-1000 μg/mL</td>
<td>EC50 &gt;1000 μg/mL</td>
<td>[74]</td>
</tr>
<tr>
<td>Mytilus galloprovincialis (mussel)</td>
<td>Polystyrene (PS)</td>
<td>129 nm</td>
<td>0.05-50 mg/L (PS)</td>
<td>Total oxidant status increased in digestive glands after exposure to 0.5 mg/L PS. In digestive glands and gills, the total antioxidant capacity and esterase activity were increased at 50 mg/L PS. Inhibition of cholinesterase activity in haemolymph was observed. Genotoxicity was found in haemocytes after exposure. Lipid peroxidation (oxidative damage) was found while exposed to 0.05 mg/L of PS. Induced significant downregulation in gene expression (e.g., hsp70) when compared to individual exposure. Genotoxicity was found in haemocytes after exposure.</td>
<td>[57]</td>
</tr>
<tr>
<td>Mytilus galloprovincialis (mussel)</td>
<td>Polystyrene (PS) (with and carbamazepine (Cbz))</td>
<td>129 nm</td>
<td>0.05 mg/L/PS, 6.3 μg/L (Cbz)</td>
<td>Total oxidant status increased in digestive glands after exposure to 0.5 mg/L PS. In digestive glands and gills, the total antioxidant capacity and esterase activity were increased at 50 mg/L PS. Inhibition of cholinesterase activity in haemolymph was observed. Genotoxicity was found in haemocytes after exposure. Lipid peroxidation (oxidative damage) was found while exposed to 0.05 mg/L of PS. Induced significant downregulation in gene expression (e.g., hsp70) when compared to individual exposure. Genotoxicity was found in haemocytes after exposure.</td>
<td>[57]</td>
</tr>
<tr>
<td>Mytilus edulis (blue mussel)</td>
<td>Polystyrene (PS) (coated with sulphate groups) and Pandova lutheri</td>
<td>30 nm</td>
<td>0.1, 0.2, and 0.3 g/L</td>
<td>Produced pseudofeces. The total weight of the feces and pseudofeces increased along with increasing NP and algae concentration. Filtering activity was decreased but still remove the NP in the water.</td>
<td>[43]</td>
</tr>
<tr>
<td>Mytilus galloprovincialis</td>
<td>Polyurethane (coated with amine group)</td>
<td>50 nm</td>
<td>1, 5, 50 μg/mL</td>
<td>Decrease in phagocytic activity and increase in lysozyme activity were found. The NP stimulated increase in extracellular reactive oxygen species (ROS) and nitric oxide (NO) production, with maximal effects at 1 mg/mL of NP. The NP induced apoptotic process while at 50 μg/mL.</td>
<td>[61]</td>
</tr>
<tr>
<td>Littorina littorea</td>
<td>Polystyrene (adhered on seaweed Fucus vesiculosus)</td>
<td>1−100 μm</td>
<td>/</td>
<td>Plastic found in the stomach and in the gut but not found in midgut gland.</td>
<td>[47]</td>
</tr>
<tr>
<td>Mytilus spp (mussels)</td>
<td>Polystyrene</td>
<td>2 and 6 μm</td>
<td>32 μg/L</td>
<td>An increase in hemocyte mortality and triggered substantial modulation of cellular oxidative balance. An increase in reactive oxygen species production in hemocytes and enhancement of anti-oxidant and glutathione-related enzymes in mussel tissues were detected.</td>
<td>[62]</td>
</tr>
<tr>
<td>Amphibalanus Amphitrite (barnacle)</td>
<td>Poly(methyl methacrylate) (PMMA)</td>
<td>&lt;0.2 μm</td>
<td>Stage II nauplii exposed to PMMA particles at</td>
<td>Acute exposure (occurred at 25ppm, 3hrs exposure) indicated that NP persist in the body throughout stages of growth and development (from nauplius to cyprid and juvenile barnacle,</td>
<td>[53]</td>
</tr>
</tbody>
</table>
Macoma balthica, Mytilus trossulus, Gammarus spp., Mysid shrimps, Monoporeia affinis, Marenzelleria spp.
Mytilus galloprovincialis (embryo)
Mytilus galloprovincialis (mussel)
Dunaliella tertiolecta (green microalga)
Artemia franciscana (brine shrimp)
Mytilus edulis (mussels)
Crassostrea virginica (oyster)
Dipastrea palida/ Favia palida (coral)
Brachionus koreanus (Monogonont Rotifer)
Crassostrea gigas (oyster)
Artemia franciscana (brine shrimp larvae)
Pomatoschistus microps (Teleostei, Gobiidae)
Tigriopus japonicus (copepod)

Gammarus spp
Continuous exposure. Egestion of NP was through moulting and fecal excretion. While chronic exposure (occurred at 1 ppm) showed that bioaccumulation of the NP occurred at low concentration.

Rank of beads ingested: Bivalves (Mytilus trossulus>Macoma balthica) Free-swimming crustaceans (Gammarus spp. and Mysid shrimps)
Benthic animals (Monoporeia affinis and Marenzelleria spp.)
Benthic animals (Monoporeia affinis and Marenzelleria spp.)

NP affected the formation of normal D-shaped larvae at 48 hpf (EC50=0.142 mg/L). At EC10, the shell formation was affected. This concentration induced dysregulation of transcription of genes involved in early shell formation (Chitin synthase, Carbonic anhydrase, Extrapallial Protein) at both 24 and 48 hpf. At 5-20 mg/L, it resulted in high embryotoxicity/developmental arrest.

Predatory Crassostrea gigas (Monogonont Rotifer) Brachionus koreanus (brine shrimp)
Dunaliella tertiolecta (green microalga)
Artemia franciscana (brine shrimp)
Mytilus edulis (mussels)
Crassostrea virginica (oyster)
Dipastrea palida/ Favia palida (coral)
Brachionus koreanus (Monogonont Rotifer)
Crassostrea gigas (oyster)
Artemia franciscana (brine shrimp larvae)
Pomatoschistus microps (Teleostei, Gobiidae)
Tigriopus japonicus (copepod)

Concentrations of 5, 10, and 25 ppm; continuous exposure. Egestion of NP was through moulting and fecal excretion. While chronic exposure (occurred at 1 ppm) showed that bioaccumulation of the NP occurred at low concentration.

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Artemia franciscana (brine shrimp)
Mytilus edulis (mussels)
Crassostrea virginica (oyster)
Dipastrea palida/ Favia palida (coral)
Brachionus koreanus (Monogonont Rotifer)
Crassostrea gigas (oyster)
Artemia franciscana (brine shrimp larvae)
Pomatoschistus microps (Teleostei, Gobiidae)
Tigriopus japonicus (copepod)

Concentrations of 5, 10, and 25 ppm; continuous exposure. Egestion of NP was through moulting and fecal excretion. While chronic exposure (occurred at 1 ppm) showed that bioaccumulation of the NP occurred at low concentration.

Rank of beads ingested: Bivalves (Mytilus trossulus>Macoma balthica) Free-swimming crustaceans (Gammarus spp. and Mysid shrimps)
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4. Future Perspectives

Based on the aforementioned information, marine NP pollution has been extensively documented as harmful to marine species. As such, there is an urgent need for further NP studies to be conducted, as numerous knowledge gaps remain to be filled. The physical and chemical properties of NP demonstrate different behaviours in marine organisms and the environment. Suggested areas for future research on NP are summarised below.

While NP ingestion has been observed upon studying the digestive systems of many marine organisms, studies on the biological uptake and effects of ingested NP particles in the marine environment remain scarce. Notably, uptake facilitation mechanisms should be studied. Moreover, Carcinus maenas altered rope fibre size and shape following NP ingestion and egestion, which reduced plastic size and formed ball-shaped plastic through their gut [37,78]. Furthermore, Antarctic krill are capable of reducing MP to NP [39,78]. The physical changes occurring in plastic materials following ingestion and egestion by marine organisms requires further study due to these abilities being critical to studying how NP is distributed in the marine environment, as well as its environmental fate and origin.

Additionally, further research is required to support the potential of NP particles to adsorb organic/metal contaminants. Also, the combined toxicological interactions between NP and organic/metal contaminants also require further study. For instance, Manila clams (Ruditapes philippinarum) are a seafood resource for human consumption. The sorption of other contaminants onto NP surfaces may pose a synergistic effect in marine organisms or even humans. Short-term and long-term exposure to NP and its interaction with metal/organic pollutants should also be further researched. Notably, NP could act as a vector in transporting chemicals to marine organisms. Future studies should evaluate the transfer of adsorbed chemicals on NP through trophic levels. Importantly, the biomagnification of NP could accumulate pollutants and impact the health of marine animals, and ultimately humans. NP accumulates up through the trophic levels, among which humans are the end consumers. Hence, NP issues related to the seafood industry must be adequately monitored.

Furthermore, the adverse effects of NP on early life stages should be accounted for in the ‘Adverse Outcome Pathway’ scheme for marine organisms. This is because NP toxicity affecting early life stages could influence offspring viability and overall reproductive output [71]. Most current studies have focused on the effects of a few types of NP on limited types of marine organisms in a controlled environment, which is not sufficient to represent the overall impacts of marine NP pollution on marine organisms. As different marine species expose to different polymer types, sizes, shapes, and environmental conditions, they may demonstrate different responses. Therefore, additional research on a broader range of species, NP types, and chemicals remain vitally important.

5. Conclusion

With regards to occurrence and distribution studies, the current lack of available techniques for the accurate measurement of environmental concentrations of NP at smaller particle sizes should be improved. While NP concentrations in the environment are increasing overall due to larger plastic debris and MP degradation, industrial NP production is also increasing and resulting in an increased amount of NP in the environment. The enhancement, variation, and modification of current NP protocols should be improved in order to develop revised protocols for future NP research. The development of these methods is urgently required for research, monitoring, and risk assessment purposes. A full risk assessment of NP with different physical and chemical properties for different marine organisms is also required. Moreover, current NP research studies tend to investigate the effects of higher concentrations than those present in the natural marine environment. Environmentally relevant concentrations should thus be studied to evaluate realistic scenarios. The bioavailability of NP in the marine environment and its impact on keystone species and commercial species must also be investigated. Long-term studies on NP bioavailability and its effects on marine organisms are thus required. The characterisation and quantification of NP occurrence in various marine organisms is also needed.

Furthermore, biochemical molecular biological traits (e.g., variations in RNA content and gene expression patterns) related to stress and detoxification should also be studied. In addition, further investigations on the effect of different plastic types on the growth, hatching, and reproduction of various marine organisms are also needed. The toxic endpoints (maintenance costs, immune responses, detoxification, and oxidative balance regulation) of NP should also be studied further. Current research studies lack information on specific protective mechanisms and pathways against NP toxicity in marine species, which should be elucidated. Further details regarding NP properties and their stability in natural seawater are also needed in relation to their characteristics upon exposure to embryos, as different aggregation states may bring about different bioavailability and disposition routes to affected embryos. Many studies have focused on carboxylated andaminated groups of PS-NP, but have neglected the study of additional surface coatings. Moreover, many NP ecotoxicity studies have focused directly on NPs in relation to their impacts on marine organisms and the environment. However, the indirect influences of NPs were ignored. In fact, unknown indirect impacts could potentially be posing a greater environmental threat than known direct impacts. For instance, the high concentration of NP interrupted the N2-N conversion efficiencies of Halomonas alkaiphila through enhanced ROS genetion [77]. This implies that NP could indirectly affect the marine nitrogen cycles. As such, further studies on the indirect impacts of NPs are needed.

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References


