Ecotoxicological Impacts Of Traditional And Emerging Microplastics On Marine Zooplanktons: Implications For Aquaculture And Coastal Ecosystem Health

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Abstract:

Marine ecosystem health is threatened by an increasing worldwide problem if microplastic pollution (MP). The “emerging” microplastics such as biodegradable bio-plastics, tyre wear particles (TWPs), and synthetic microfibers, are associated with highly complex chemical and physical risk profiles in coastal waters, whereas well studies legacy petroleum-based polymers (polystyrene, polyethylene, polypropylene) are known. Marine zooplankton are important in the environment and a link in the transfer of energy from phytoplankton to higher trophic levels including species of economic importance for aquaculture. This review summarises the current scientific knowledge on the ingestion mechanisms, tissue deposition, and multi- level ecotoxicological effects of traditional and emerging MPs on marine zooplankton communities. Physiological and physical disruption due to MP exposure such as oxidative stress cascade, neurotoxicity, due to enzyme inhibition, endocrine disruption and reproductive failure is discussed. In addition, persistent organic pollutants (POPs) and heavy metals (the “Trojan Horse” effect) are analysed in details and the leaching kinetics of toxic endogenous additives (e.g., phthalates, bisphenols, 6PPD- quinone) is studied. Finally, we address the trophic transfer of these particles into coastal aquaculture systems, which negatively affects the seafood safety, sustainability and biological carbon pump. This paper describes the methodological deficits and highlights the major research needs in ecotoxicology, and sets the ground for an adapted future approach of coastal management policies.

Keywords**:** Microplastics; Emerging Pollutants; Marine Zooplankton; Aquaculture; Ecotoxicology; Trophic Transfer; Coastal Ecosystem Health

1. Introduction:

Plastic pollution has become a systemic problem on a global scale during this Anthropocene era, impacting on the marine environments of the world (Geyer et al., 2017). Insufficient waste management, river discharges, municipal and marine shipping are thought to be the main sources accounting for more than 4.8 million metric tons entering the ocean annually, a figure that could reach 12.7 million metric tons annually (Plastics Europe, 2024). Macroscopic plastic debris is constantly exposed to weathering and fragmentation (Thompson et al. 2004) through chronic exposure to solar ultraviolet (UV) radiation, mechanical wave action and microbial colonization. The resulting products are micro- and nano-plastics (<5 mm and <100 nm) which can be seen in various marine matrices (Gigault et al., 2018).

The pelagic food webs start with marine zooplankton. They play a key role in the global oceans as a consumer of primary producers, and are a primary food source for larval and adult finfish, cephalopods and marine mammals, controlling the flow of energy, carbon and nutrients (Cole et al., 2013). Many of the zooplankton taxa are non-selective planktonic suspension or filter feeders that may also be size matched with the MPs in the environment and thus be susceptible to accidental ingestion (Desforges et al. 2015).

The last decade, ecotoxicological approaches have mainly been targeting "traditional" commodity plastics (Amelia et al., 2021). The introduction of new environmentally friendly alternatives to conventional plastics manufacturing and the urban discharge of "emerging" plastics have led to the emergence of a new type of microplastics that are entering into the coastal environment (Lambert & Wagner, 2017). This is a diverse group that consists of:

a) Substitutes for single use packaging such as biodegradable and bio-based polyesters such as polylactic acid [PLA] and polyhydroxyalkanoates [PHA],

b) Abrasive particles of tire wear from vehicle wear on coastal roads,

c) Microfibers from textile laundering and industrial effluents.

The models and principles to date which have been used for the toxicological evaluation of traditional relatively nonreactive polymers may not hold true to these particles under development. Emerging MPs have often undergone changes to their physiochemical properties and/or possess high degradation rates, and are often intentionally formulated with toxic additives, such as tire-related agents such as 6PPD-quinone (Tian et al., 2021).

The purpose of this literature review is to present a full picture of comparative ecotoxicology of traditional and emerging microplastics to marine zooplankton. It describes the cascading consequences of these interactions on the health of coastal aquaculture systems and the ecosystem at large, highlights the need and opportunities for structural research, and identifies strategic pathways for mitigating the future.

2. Categorization of Traditional vs. Emerging Microplastics:

It is crucial to understand the difference between legacy polymers and emerging particulates and to understand that these two classes are fundamentally different in chemical backbone, environmental half-life, prevailing morphology, and chemical additives that accompany the polymer.

2.1 Traditional Petroleum-Based Microplastics:

The traditional petroleum based microplastics have stable carbon-carbon (C-C) backbones, which are resistant to the enzymatic cleavage, and have very high environmental persistence (Erni-Cassola et al., 2019). Polyethylene (PE): It is the most common polymer recovered from marine environments and usually comes as low-density (LDPE) and high-density (HDPE) PE, which typically are single-use packaging, agricultural films and maritime floats. Acrylonitrile butadiene styrene (ABS): Found in household items like food packaging, toys, and electronic components. Polyethylene (PE): Used in a large range of plastic products, such as packaging and many other consumer goods. Polystyrene (PS): Delivered to ocean through waste expanded foam insulation and protective packaging. Polyvinyl Chloride (PVC) and Polyethylene Terephthalate (PET): Mostly from industrial wastewater and consumer beverage bottles. These polymers are characterized by having high hydrophobic character, low surface polarities and high accumulation of ambient hydrophobic contaminants in the water column (Ullah et al., 2025).

2.2 Emerging Microplastics:

Emerging microplastics represent structurally complex, chemically active particulate classes whose environmental behaviours deviate from legacy plastics:

Biodegradable and Bio-based Plastics (e.g., PLA, PHA, PBS): These types of polymers are designed to degrade under industrial composting conditions (>60^{o}C specific microbial communities), and some of these are expected to persist in cold, dark, hypoxic marine benthic and pelagic environments for long periods of time (Harrison et al., 2018). If the environmental conditions are set to be UV, their fragmentation rates may exceed that of conventional plastics. There is an accelerated weathering process with the rapid production of local high levels of nano plastics that can cross biological barriers (Lambert & Wagner, 2017).

Tire Wear Particles (TWPs): Elongated particles that are produced by the abrasion of the tire and the pavement during road travel. TWPs are complicated blends of synthetic and natural rubber rubbers, carbon black fillers, and/or heavy metals such as Zinc (Brinkmann et al., 2022), which are imported into coastal ecosystems through urban stormwater runoff. They contain very toxic anti- ozonant such as N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD) and its photo-oxidation product, 6PPD-quinone (Tian et al. 2021).

Synthetic Microfibers: Mostly nylon, polyester, and acrylic fibres that are released during the washing of textiles and in the manufacturing of fibres (Browne et al., 2011).

They are much longer than beads or uniform fragments of similar size (spherical beads or uniform fragments) which have shorter residence times in the digestive systems of marine organisms (Carr, 2017).

Physicochemical Attribute	Traditional Microplastics (PE, PP, PS)	Emerging Bio-Plastics (PLA, PHA)	Tire Wear Particles (TWPs)	Synthetic Microfibers (Nylon, Polyester)
Primary Chemical Backbone	Aliphatic hydrocarbon or aromatic carbon rings (C-C bonds)	Aliphatic polyesters (Ester linkages, C-O bonds)	Vulcanized elastomer matrix with carbon black fillers	Polyamides or linear synthetic polyesters
Environmental Half-Life	Centurial to Millennial	Months to Decades (highly variable by temperature)	Decades; high density causes rapid sedimentation	Decades; high structural persistence
Dominant Morphology	Spheres, fragments, pellets	Irregular fragments, films	Elongated, rough cylinders/aggregates	High aspect-ratio fibers, filaments
Primary Toxicological Additives	Phthalates, Bisphenol A, alkylphenols, brominated flame retardants	Organotin catalysts, plasticizers, chain extenders	6PPD, 6PPD-quinone, Zinc, polycyclic aromatic hydrocarbons (PAHs)	Azo dyes, heavy metals (Cr, Co), per- and polyfluoroalkyl substances (PFAS)
Sorptive Affinity for POPs	High (due to high hydrophobicity and low polarity)	Moderate to High (variable ester interactions)	Exceptionally High (due to high carbon black content)	Moderate; highly variable dependent on surface finishes

Table 1. Comparative Physicochemical Characteristics, Environmental Persistence, Morphology, Toxicological Additives, and Pollutant Sorption Properties of Major Microplastic Categories.

3. Exposure Pathways and Mechanistic Ingestion by Marine Zooplankton**:**

The bioavailability of microplastics to marine zooplankton depends on particle vertical distribution, hydrodynamics, biofouling kinetics, and specific organismal feeding strategies.

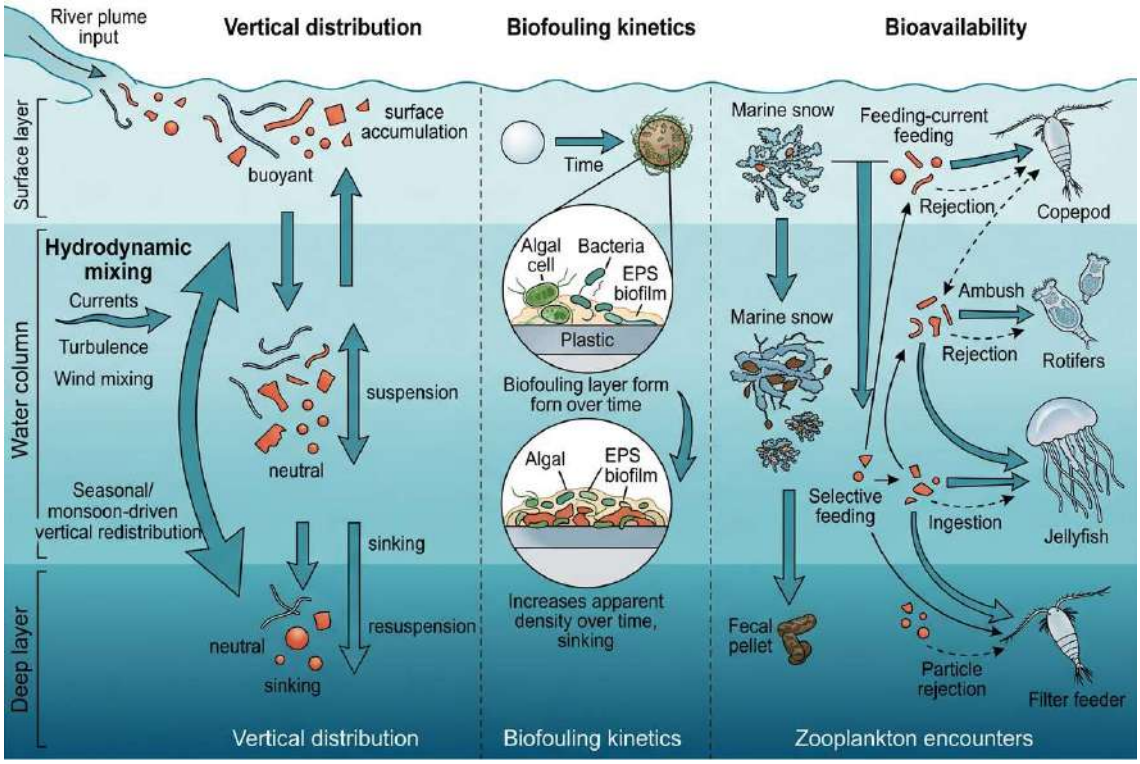


Figure 1: Conceptual Framework Illustrating the Vertical Distribution, Biofouling Dynamics, and Zooplankton-Mediated Bioavailability of Microplastics in Aquatic Ecosystems.

3.1 Distribution in the vertical plane and formation of an eco-Corona:

Traditional pristine plastics generally have low or equal density to seawater, such as PE (0.91-0.96 g/cm^3), PP (0.89-0.91 g/cm^3), and are initially segregated to the surface waters where live neustonic zooplankton are found. However, after release into environment, biofouling occurs very rapidly as marine bacteria, diatoms and fungi grow on the surface of the plastic as seen in Figure 1. This biological succession forms an "eco-corona", which modifies the hydrodynamic density of the particle and transforms it from a negative buoyancy to a positive buoyancy (Galloway et al., 2017).

This leads to vertical sub-surface and benthic boundary layer transport of MPs. High density emerging particles, e.g. TWPs (1.2–1.3 g/cm³), however, do not persist on the surface long enough to interact with the surface zooplankton (epibenthos or benthos) but are deposited to the coastal sediments, thus exposing only the surface communities.

3.2 Ingestion Mechanics across Zooplankton Taxa:

The marine zooplankton use various feeding modalities, each of which has a variable interaction with the microplastic profiles:

Filter Feeders (Cladocera, Salps, Appendicularians): Mechanically filter huge amounts of water using setal combs or mucous nets. The organisms are very sensitive to the microplastics that are the same size as them, since they do not have the means to distinguish between food and plastic particles (Cole et al., 2013).

Suspension Feeders (e.g., Calanoid Copepods): Have complex chemosensory and mechanosensory receptors on their antennae and maxillipeds that assess viability of ingested prey. They can, however, absorb the synthetic nature of the plastic as an environmental 'eco-corona' and mimic the biochemical signature (dimethylsulfide, amino acids) of organic prey, resulting in active plastic ingestion (Cole et al., 2015).

Passive Ambush/Raptorial Feeders such as Cyclopoid copepods or Chaetognaths: feed on moving or vibrating prey. They are not as likely to ingest static spherical beads, but often they ingest microplastic-phytoplankton aggregates and/or high-aspect-ratio microfibers that twist and drift in currents, simulating the motions of larval prey (Desforges et al., 2015).

4. Multi-Level Ecotoxicological Impacts on Marine Zooplankton:

Once ingested, microplastics exert a combination of physical constraints and chemical toxicities that manifest across cellular, physiological, and organismal organization levels.

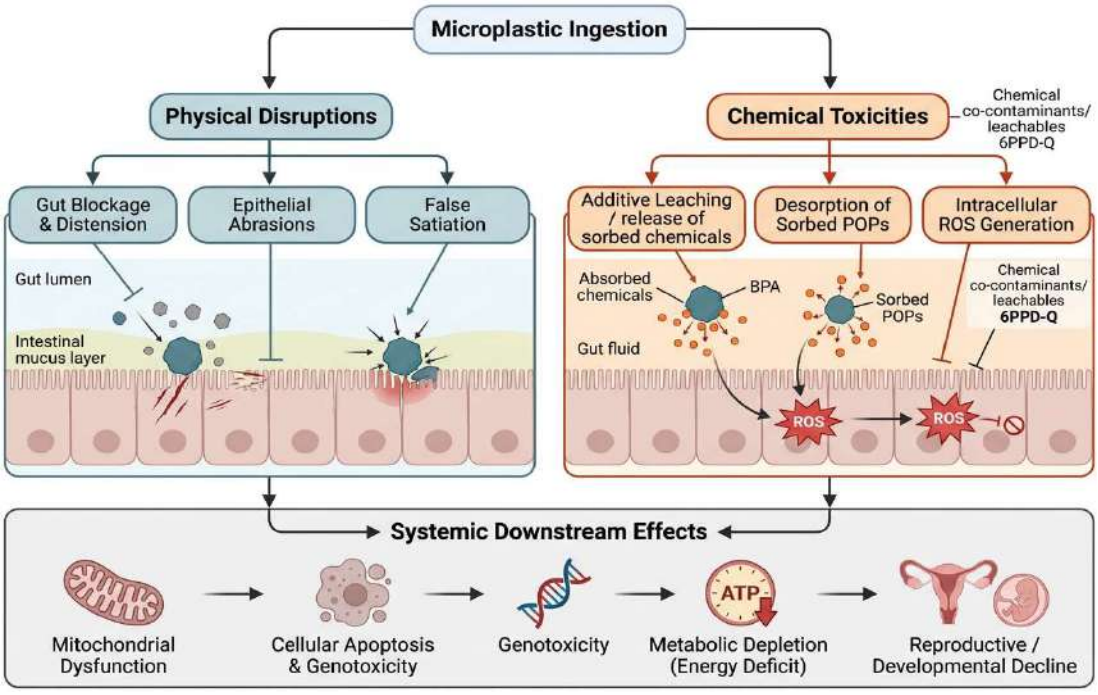


Figure 2: Mechanistic pathways of physical disruptions and chemical toxicities due to ingestion of microplastics (MPs). The infographic illustrates the two vectors of hazard due to microplastics in the gut. Left sided: Disruption of gut lumen (gut blockage, gut distension), abrasion of the intestinal mucus layer, and false satiation by mechanoreceptors. RIGHT: Chemical toxicities in the gut fluid, such as the leaching of internal manufacturing additives (e.g., Bisphenol A [BPA]), leaching of surface bound persistent organic pollutants (POPs), and the generation of intracellular reactive oxygen species (ROS) by highly toxic leachable such as 6PPD-quinone (6PPD-Q). These primary pathways lead to significant systemic downstream effects: mitochondrial dysfunction, cellular apoptosis, genotoxicity, metabolic depletion (ATP energy deficit) and subsequent reproductive or developmental decline.

4.1 Physical and Histopathological Disruptions:

The main effect of MP ingestion is mechanical interference in the gastrointestinal tract. In abundance, these stiff fragments or knotted microfibers can clog the gut, causing structural distension of the gut walls and severe injury through rubbing (Cole et al., 2013; Ogonowski et al., 2016). These synthetic particles are indigestible and create a false sense of fullness. When the mechanoreceptors in the gut signal that the organism is satiated, the drive to eat is reduced and there is marked reduction in the assimilation of carbon and nutrients. This energy imbalance will lead to the organism to use available metabolic reserves to sustain basic metabolic functions of somatic maintenance and cellular repair, thus compromising somatic growth and vitellogenesis (Costa et al., 2016).

4.2 Oxidative Stress and Cellular Cytotoxicity:

Both traditional MPs and emerging MPs produce a significant amount of reactive oxygen species (ROS) at the cellular level (Witczak et al., 2024). Microplastics and nano plastics of very small size directly interact with lysosomal and mitochondrial membranes of gut epithelial cells and disrupt electron transport chains (Jeong et al., 2016). This intracellular oxidative stress activates primary antioxidant enzyme defence systems such as:

a) Superoxide Dismutase (SOD),

b) Catalase (CAT),

c) Glutathione Peroxidase (GPx).

If the endogenous enzymatic clearance capacity for ROS production is surpassed, lipid peroxidation cascades take place (Witczak et al., 2024). This affects the fluidity of cell membranes, the functioning of transmembrane ion channels, genomic instability (DNA fragmentation), and programmed cell death (apoptosis) of zooplankton tissues (Jeong et al., 2016).

4.3 Neurotoxicity and Behavioural Impairment:

Micro-plastics interfere with the communication between the brains of zooplankton. Both traditional polystyrene beads and the new tire wear leachates have a potent effect against

acetylcholinesterase (AChE) activity (Gambardella et al., 2017; Ribeiro et al., 2018). The enzyme (AChE) is normally used to break down neurotransmitter acetylcholine. The absence of AChE function results in the build-up of acetylcholine, resulting in the over-activation of receptors, muscular spasms and eventually paralysis. This is manifested macroscopically by a decrease in swimming speed, disorientation, and decrease in predator avoidance response in some key organisms of the ecosystem such as Tigriopus japonicus and Acartia tonsa (Gambardella et al., 2017).

4.4 Endocrine Disruption and Reproductive Failure:

The toxic chemicals from micro plastics are mainly due to the leaching of endogeneous plasticizers, stabilizers and catalysts. Many of these chemicals are very potent endocrine disrupting chemicals (EDCs). Traditional plastics (Legacy compounds) leach the ecdysteroid receptor mimicking compounds such as Bisphenol A (BPA) and di-(2-ethylhexyl) phthalate (DEHP) in arthropod zooplankton (Oehlmann et al., 2009).

In invertebrates, this imbalance in the endocrine axis leads to profound reproductive abnormalities such as an incomplete or dysynchronous molting process, delays in the stages of embryonic development, dramatic decreases in the number of eggs produced (fecundity) and smaller hatching success rates of resting eggs (Sussarellu et al., 2016). The exposure concentrations at which these emerging contaminants are found (ng/L) have been demonstrated to high levels of toxicity to aquatic taxa in terms of acute lethality and reproductive impairment, particularly the transformation product 6PPD-quinone found in urban runoff (Tian et al., 2021; Brinkmann et al., 2022).

5. Trophic Transfer, Aquaculture Implications, and Coastal Ecosystem Health:

The ecotoxicological challenges associated with microplastics extend beyond individual zooplankton species. They propagate vertically through marine food webs, altering community structures and threatening economic sectors like aquaculture.

5.1 Mechanisms of Trophic Biomagnification:

Zooplankton can be a trophozoon in the food chain for microplastics to move between different trophozoon levels. The upper trophic level consumers (larval finfish e.g., Dicentrarchus labrax, Sparus aurata) or the planktivorous pelagic species feed on the biomass of the prey and also the synthetic burden accumulated in the prey (Setälä et al., 2014). Plastic particles can survive digestion by predators' stomachs, thus entering into the predator's stomach or bloodstream (Carbery et al., 2018). This is the biomagnification pathway for plastic associated chemicals along the food chain in the ocean.

5.2 The "Trojan Horse" Effect:

Micro plastics can be excellent vectors for environmental pollutants that are hydrophobic. Traditional MPs are highly surface area to volume ratio and low in polarity and thus have the potential to take up persistent organic pollutants (POPs) from their environment by a factor of up to 100,000 – 1000,000 times the ambient concentration (Koelmans et al., 2016; Ullah et al., 2025). The digestive tract of a zooplankton organism has an extremely low pH and high surfactant concentration changing the thermodynamic equilibrium and allowing these high concentrations of chemical pollutants to rapidly desorb directly into the lipid-rich tissues of the organism (Ullah et al., 2025). This synergistic effect is an extra physical risk, and builds on top of the systemic toxicities of legacy chemical contaminants.

5.3 Implications for Coastal Aquaculture Systems:

Concentrated inputs of microplastics are often found in coastal areas with aquaculture installations such as shellfish longlines and finfish sea cages. The economic viability and biosecurity of these operations is directly impacted by MP pollution:

Bivalve Cultivation (Mussels, Oysters, Clams): Bivalves, as nonselective filter feeders, consume large amounts of MPs and microfibers in the water, which can contaminate the food they harvest (Li et al., 2016). This exposure lowers clearance rates, decreases energy reserves and slows growth to marketable sizes (Ward et al., 2019).

Finfish Aquaculture: MPs are responsible for the fusion, necrosis and deterioration of internal gill lamellae and intestinal microvilli which has led to a decline in nutrient absorption

efficiencies (Islamy et al., 2025). Also, pathogenic marine bacteria such as Vibriaceae species colonizing the "plastisphere" can enter the high-density aquaculture ponds with microplastics, leading to high mortalities (Jacob et al., 2020).

Microplastics in harvested aquaculture products can cause food-safety problems: Seafood Quality and Safety. The translocation of nanoplastics and chemical additives to the edible tissues of fish/shellfish could lead to regulatory action, rejection of the market, and consumer mistrust (Carbery et al., 2018).

5.4 Changes in Carbon Cycling and Ecosystem Services:

Zooplankton are important to the biological carbon pump, as they ingest primary production at the surface and return it in the form of dense, rapidly settling fecal pellets which sequester carbon in deep benthic sinks (Cole et al., 2016). Low-density microplastics are ingested and become part of these fecal matrices.

This will reduce the density and fall speed of the pellets, which will increase the time they remain in warmer surface waters and lead to increased microbial remineralization (Wieczorek et al., 2018). This mechanism could cause changes in the ocean's ability to sequester carbon, turning coastal ecosystems into sources of carbon rather than sinks.

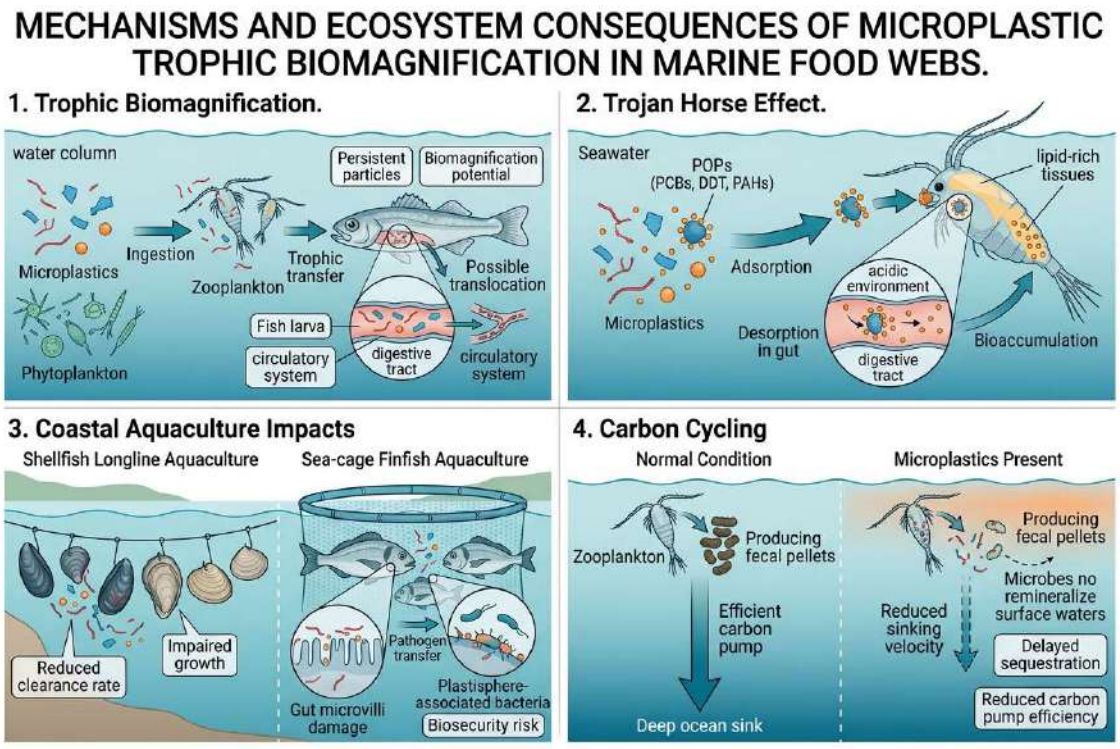


Figure 3: Biomagnification of micro-plastics in marine food webs and the mechanisms and consequences of this phenomenon. The multi-panel infographic explains the main ecological and physiological effects of the propagation of microplastic. Trophic Biomagnification: describes the ingestion of microplastic by marine zooplankton along with primary producers (phytoplankton), followed by the trophic transfer to higher order consumers (e.g. fish larvae), and possible cellular translocation from digestive system to circulatory system. (2) Trojan Horse Effect: Describes the ability of microplastics to absorb persistent ambient organic pollutants (POPs including PCBs, DDT, PAHs) from ocean water and rapid chemical release of these pollutants under the acidic conditions of the consumer's digestive tract, which leads to systemic bioaccumulation in lipid-rich tissues. (3) Coastal Aquaculture Impacts: discusses industry-specific impacts such as decreased clearance rates and stunted growth in shellfish longline facilities, and damage to gut microvilli, spread of disease-causing bacteria and biosecurity concerns in sea-cage finfish facilities associated with the presence of the plastisphere. (4) Carbon Cycling: Describes a normal biological carbon pump with dense plankton fecal pellets, which promote carbon transport to the deep ocean sink, and a scenario with high concentrations of microplastics leading to low density of plastic incorporation in the fecal pellets and therefore slow transport of carbon to the deep ocean sink, while increasing the microbial remineralization on the surface layer.

6. Methodological challenges and research gaps:

Based on a critical literature review, several methodological stumbling blocks in the prediction of ecotoxicological effects in the real world were identified:

Environmental Relevant Exposure Concentrations: Many laboratory toxicity studies are conducted using MP exposure concentrations (1–100 mg/L) which are much higher than the verified environmental baseline (1–100 particles/m^3), and limit the predictive ecological risk modelling potential of these studies (Ogonowski et al., 2016).

Pristine Spherical Models: In the lab, assays are mostly performed with homogeneous and pristine polystyrene microbeads, as these are commercially available. But these smooth spheres are not realistic representations of the irregular shape, weathered surfaces, high aspect ratios and biofouled "ecoshells" found in the wild marine microplastics (Lambert & Wagner, 2017).

Not accounting for Multi-Stressor Dynamics: The conventional toxicity testing method assumes a single-stressor scenario, which is not representative of the multi-faceted impacts of global climate change. Ocean acidification, thermal anomalies and hypoxic events are multiple and interacting stressors affecting both the metabolic rates of zooplankton and degradation rates of microplastics in coastal systems (Galloway et al., 2017).

7. Strategic Mitigation and Future Perspectives:

There is a need for a multi-level mitigation strategy to tackle the threats of microplastic pollution in coastal areas that includes material innovation, infrastructure improvements and the implementation of common monitoring procedures:

The development of new marine-degradable polymers that can be quickly degraded by the marine microorganisms in unmanaged environments over early generation bio-plastics, which are likely to remain in the marine environment, should be investigated in the future (Harrison et al., 2018).

Specialized stormwater retention basins, bioretention cells, and advanced structural wetlands need to be included in the design of coastal urban infrastructure to capture road runoff prior to reaching coastal habitats, to prevent tire wear particles and associated compounds, such as 6PPD-quinone, from entering these sensitive areas (Tian et al., 2021).

The capture efficiency of the wastewater treatment plants (WWTPs) can be elevated by using more sophisticated microfiltration, disc filters and membrane bioreactors (MBRs) in WWTPs with high capture efficiency > 99% for synthetic microfibers (Carr, 2017).

The Standardisation of Analytical Workflows is essential for the development of consistent datasets and to support evidence-based international environmental policy, especially when developing international standardised workflows (automated micro-Raman and Fourier-Transform Infrared (μ-FTIR) spectroscopy) for the isolation and characterisation of micro-plastics (Gigault et al., 2018).

8. Conclusion:

The effects of the traditional and emerging micro-plastic pollution on marine zooplankton, coastal aquaculture and marine food webs are a highly dynamic and complex threat. Tire wear particles, high aspect-ratio micro-fibers, bio-plastics and other emerging contaminants have physical and chemical properties which result in unique toxicological characteristics, while traditional commodity polymers place long-term physical and chemical stresses.

These synthetic particles are an important link to commercially valuable seafoods, spreading physical injury and chemical toxicity to them via zooplankton. The transfer of tropho zooplankton may lead to tissue damage, disease outbreaks, reduced productivity in oceanic aquaculture facilities and impact oceanic carbon pumps and the supply of oceanic ecosystem services.

Future research should step up to tests conducted in more environmentally realistic multi-stressor experiments, consistent analytical procedures, and even more specifically designed interventions, for the protection of the health of coastal ecosystems and for a stable future chain of seafoods. It is crucial to reduce the threat posed by legacy and emerging microplastics in order to maintain the structural and economic health of our oceans.

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