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Ecotoxicity of plastic additives to marine organisms

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Abstract: Marine pollution by plastics is a major environmental issue that is expected to increase worldwide. Thousands of chemical substances can be used as plastic additives in industrial processes for various purposes, turning plastics into chemical carriers of such substances. If plastics are discarded in the marine environment, these chemicals can be released into the environment and cause toxicity to marine species. In this review, we analyze the toxicity of chemical groups that are commonly used as plastic additives (bisphenol-A, alkylphenols, tetrabromobisphenol, phthalates, polybrominated diphenyl ethers, and per- and polyfluoroalkyl substances) in marine organisms. Little information has been obtained because only a small number of studies have been conducted on marine species. However, the existing information indicates high toxicity of most chemical groups, with the Lowest Observed Effect Concentrations (LOECs) on the order of micrograms per liter (e.g. bisphenol-A, para-nonylphenol, nonylphenol, octylphenol, Di(2-ethylhexyl) phthalate, BDE-47). Per- and polyfluoroalkyl substances (PFAS) were toxic at milligrams per liter. These results provide evidence that chemicals added to plastics may represent a threat to marine organisms, and further research on the toxicity of these substances is urgently needed.

Key words: Marine Pollution, Plasticizers, Ecotoxicology, Contaminants of Emerging Concern, Plastics, Chemical additives.

INTRODUCTION

Plastic pollution is a major global environmental issue, particularly affecting coastal and marine ecosystems worldwide. Since their introduction in the market around the 1950s, plastics have become the main material used in modern society, reaching a current global production of around 400 million tons per year (Geyer et al. 2017), which is expected to continue to increase in the coming decades (Dokl et al. 2024). Currently, approximately 11 million tons of plastics are estimated to be released into the marine environment every year (UNEP 2021), causing environmental and socioeconomic impacts and threats to human health (Izar et al. 2022). Plastics represent approximately 90% of marine litter (Milijö 2001), reaching all marine ecosystems, including remote islands, sandy beaches, estuaries, and polar regions, and accumulating in bottom sediments, water column, and sea surface, including ocean gyres (Andrades et al. 2018, Barnes et al. 2009, Wright et al. 2013, Lebreton et al. 2018, Turra et al. 2020).

After reaching the marine environment, plastics may cause adverse effects on biota, such as entanglement (Laist 1987), ingestion (Mascarenhas et al. 2004), and exposure to plastic-associated chemicals (Alimba & Fraggio 2019). Ingestion of plastics has been reported for different aquatic organisms, such as marine birds (Navarro et al. 2023), turtles (Caron et al. 2018), fish (Dantas et al. 2020), benthic organisms such as bivalves (Bruzaca et al. 2022) and crustaceans (Hara et al. 2020), and zooplankton

(Cole et al. 2013, Steer et al. 2017). Its effects include disturbances in the digestive system, such as obstruction and cellular absorption of micro-and nanoplastics, which may cause weight loss and death (Browne et al. 2011, Turra et al. 2020, Cole et al. 2013).

Moreover, plastics are a potential source of chemical contaminants because a set of chemical compounds are added to plastic polymers during their production (Groh et al. 2019, Nobre et al. 2015, França et al. 2022), aiming to provide specific properties such as hardness and flexibility or aesthetic aspects (color and shape), thermal stability, and avoid combustion (Hammer et al. 2012, Wiesinger et al. 2021). According to Wiesinger et al. (2021), virgin plastics may contain more than 10,000 substances as additives, of which over 2,400 are potentially concerning. In addition, plastics can sorb a range of chemicals from the environment (Mato et al. 2001) including metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) (Endo et al. 2005, Ogata et al. 2009, Karapanagioti & Klontza 2008, Teuten et al. 2009, Fisner et al. 2013). These contaminants can be leached from plastics into the environment (Mato et al. 2001) or released into the digestive tract of the organism when ingested (Peters et al. 2022, Peng et al. 2024). In both cases, bioaccumulation and toxicity may occur because of exposure to contaminants from plastics, such as mutagenicity (Araújo et al. 2020), genotoxicity (Sun et al. 2021), and developmental and reproductive disturbances (Kim et al. 2022).

Most plastic additives involve chemicals of emerging concern (CECs), for which there are no regulations at global or national levels, and their toxicity to marine species is poorly understood. However, an understanding of the impacts caused by plastics requires a solid knowledge of the toxicity of such substances in order to subsidize actions to mitigate this problem. This study aimed to review the existing information on some of these industrial plastic additives (specifically phenols, phthalates, polybrominated diphenyl ethers, per-and polyfluoroalkyl substances), with an emphasis on their ecotoxicological effects on marine organisms. This review aims to assess the extent of knowledge on the ecotoxicity of chemical substances used as plastic additives, providing support to initiatives aimed at communicating on this topic and establishing regulations and decision-making. This review aimed to determine if these plastic additives are toxic to marine organisms, and in positive cases, to determine the toxic thresholds, which are critical for assessing the ecological risks of plastics.

MATERIALS AND METHODS

In this review, it was used the Google Scholar, ScienceDirect, Scopus, PubMed and Web of Science databases, searching for the keywords “marine organisms” or “marine biota”, “toxicological effects”, “toxicity”, “ecotoxicity” or “ecotoxicological effects” combined to the “plastic additive name” and/or “plastic”. The chemical additives analyzed included bisphenol A (BPA), bisphenol AF (BPAF), alkylphenols (4-n-nonylphenol - NP, and 4-n-octylphenol - OP), tetrabromobisphenol (TBBPA), phthalates, polybrominated diphenyl ethers (PBDEs), and per- and polyfluoroalkyl substances (PFAS). Only studies published in English from indexed academic journals were considered. This systematic review included studies reporting acute or chronic toxicity data expressed as the lowest observed effect concentration (LOEC) or effect concentration values (e.g., EC10, EC50, and EC90) indicative of population-level responses were considered eligible for inclusion. A total of 75 scientific articles were initially raised, of which 19 studies in journals with low relevance (i.e., not indexed in reputable databases or without impact factor) or those presenting repeated or incomplete information were discarded. After this initial trial, all studies were checked for the use of reliable methods (e.g., experiments based on standardized methods, with an appropriate number of replicates, reliable Quality Assurance and Quality Control (QA/QC) procedures, and adequate statistical analyses), and those that did not meet the reliability criteria were excluded (Figure 1). A total of 56 scientific articles were analyzed in this step, of which 31 were excluded because they did not fit the established criteria. From the articles analyzed, information about species, type of toxicity (acute or chronic), exposure time, and level of effect (Lethal Concentration - LC50, Effective Concentration - EC50, Lowest Observed Effect Concentration (LOEC), and/or No Observed Effect Concentration - NOEC) were extracted for each chemical compound. This systematic review was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Liberati et al. 2009).

RESULTS AND DISCUSSION

From the initial list of 56 scientific articles, 25 met the pre-established criteria after careful individual checking of each article. The results

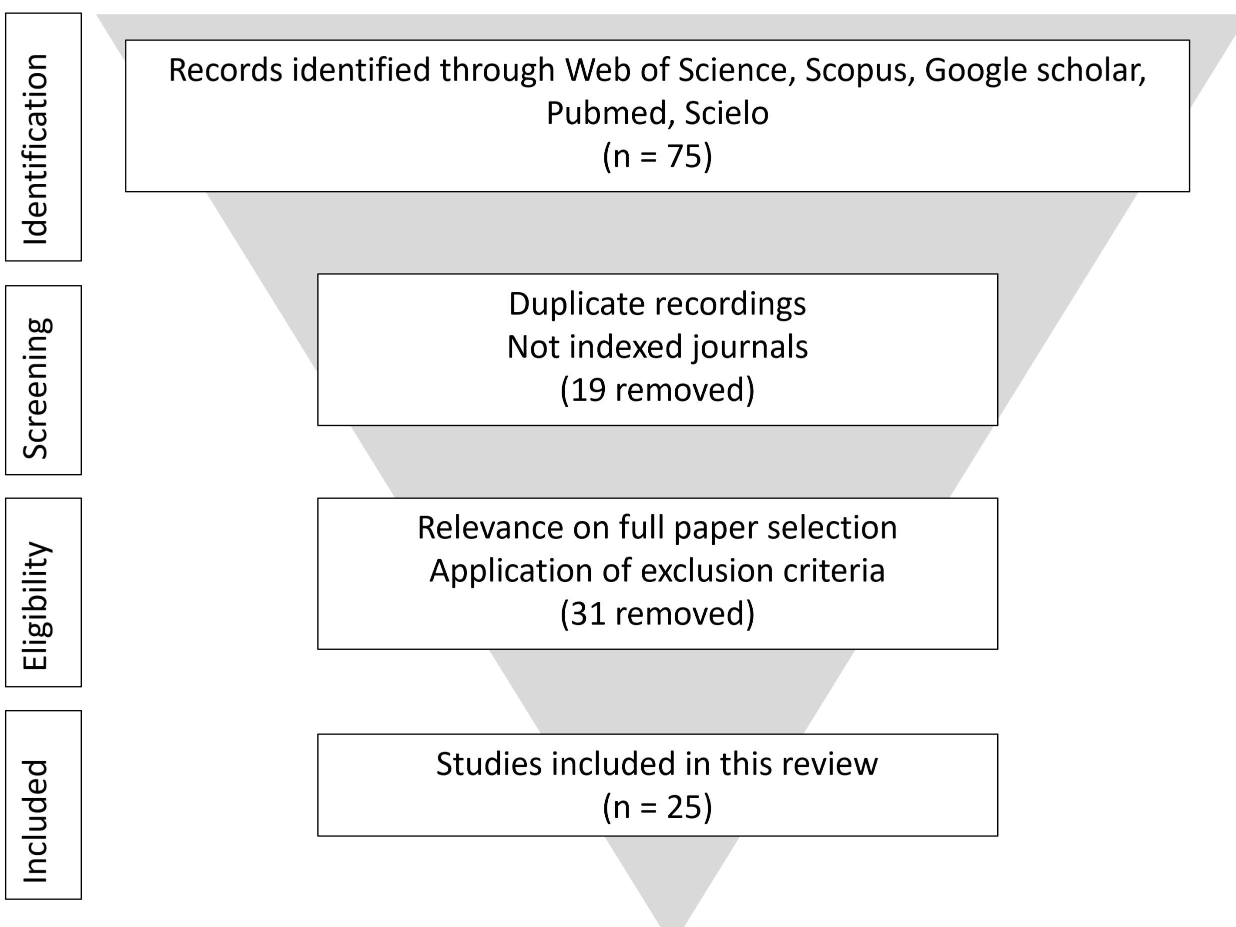

Figure 1. Flow diagram of the systematic literature search process for studies on the toxicity of plastic additives to marine organisms.

were organized separately for each chemical group, and ecotoxicological indices were compiled in tables.

Bisphenol A (BPA) and Bisphenol AF (BPAF)

Six studies were selected on the toxicity of BPA and BPAF in marine organisms; four analyzed the acute effects, while three assessed chronic effects. In total, four taxonomic groups were tested: fish (*Oryzias melastigma*, 2 papers), tunicates (*Oikopleura dioica*), mollusks (the gastropod *Haliotis discus hannai* and the bivalve *Mytillus galloprovincialis*), and echinoderms (*Dendraster excentricus*) (Table I). The literature shows that BPA toxic thresholds starts from 0.1 µg/L, when it affects the embryonic development of the mussel *M. galloprovincialis* (Fabbri et al. 2014), but may reach up to 50 µg/L, when it comes to the embryonic development of *D. excentricus* (Darin 2021). For BPAF, there is only one paper (Chen et al. 2024) reporting acute effects from 91.88 µg/L and chronic (behavior) effects from 0.61 µg/L. The compiled results (Table I) also showed that BPA and BPAF caused effects in the range of micrograms per liter, indicating that they may potentially cause adverse effects in marine organisms at low concentrations. The existing LOEC and E/LC50 values are mostly higher than the environmental median concentrations of BPA measured in marine environments (22 ng/L – Swansborough et al. 2025, Corrales et al. 2015), but some indices are quite below the maximum concentrations measured (4800 ng/L) indicating potential environmental risks due to BPA, particularly for embryonic development of *M. galloprovincialis* (Fabbri et al. 2014).

Bisphenol A (BPA) is a typical endocrine disruptor regularly used for the production of polymeric materials in the plastics industry since the 1950s, with high ability to be leached from these materials (Eladak et al. 2015, Li et al. 2023). It has also been used as a monomer in the production of polycarbonate bottles (Guart et al. 2011). BPA is ubiquitous in coastal environments due to its incomplete removal from wastewater and storage treatment systems and its bioaccumulation and persistence, implying long-term impacts on marine organisms (Li et al. 2024). According to Wu & Seebacher (2020),

Table I. Comparison of studies on the toxicity of Bisphenol A (BPA) and Bisphenol AF (BPAF) to marine species, considering exposure and types of effect.

Species (Taxonomic group)	Type of effect	Duration	Compound	LOEC	EC50/LC50	Reference
Oryzias melastigma (Fish)	Acute Survival	160 days	BPAF	91.88 µg/L	no data	Chen et al. (2024)
Oryzias melastigma (Fish)	Chronic Behavior	160 days	BPAF	0.61 µg/L	no data	Chen et al. (2024)
Oikopleura dioica (Tunicata)	Acute Survival	32 h	BPA	no data	0.142 mg/L	Li et al. (2024)
Haliotis discus hannai (Mollusca)	Chronic Cytotoxicity (haemocyte)	48 h	BPA	no data	5 µM	Kim et al. (2024)
Oryzias melastigma (Fish)	Chronic Behavior (larvae)	72h	BPA	0,5 µM	no data	Li et al. (2023)
Dendraster excentricus (Echinodermata)	Acute Embryolarval	7 days	BPA	50 µg/L	no data	Darin (2021)
Mytillus galloprovincialis (Mollusca)	Acute Embryolarval	48 h	BPA	0.1 µg/L	5.52 µg/L	Fabbri et al. (2014)

exposure to BPA can lead to behavioral changes, negative effects on growth and survival, increased abnormalities and effects on the cardiovascular system, energy metabolism, and many other physiological negative effects. BPA is currently banned in several countries, especially in products targeting infants (children up to three years old) (Almeida et al. 2018). Bisphenol analogs have been developed by the plastic industry as alternatives to BPA, including Bisphenol AF (BPAF), a fluorinated compound with trifluoromethyl groups that is more toxic (Catenza et al. 2021, Chen et al. 2024, Rifa & Lavado 2024). However, BPAF seemed to present similar levels of toxicity as BPA, as shown in Table I.

Alkylphenols

A total of 17 studies examined alkylphenols and their ecotoxicological effects on aquatic organisms, but only four of them focused on marine organisms (Liu et al. 2013, Lussier et al. 2000, Arslan et al. 2007, Arslan & Parlak 2007), as presented in Table II. Eleven species representing five distinct taxonomic groups, as fish (*Pleuronectes americanus*, *Menidia beryllina*, and *Cyprinodon variegatus*), molluscs (the clam *Mulinia lateralis*), crustaceans (the crab *Dyspanopeus sayi*, lobster *Homarus americanus*, amphipod *Leptocheirus plumulosus*, mysid *Americamysis bahia*, grass shrimp *Palaemonetes vulgaris*), echinoderms (*Paracentrotus lividus*, *Arbacia lixula*), and algae

Table II. Comparison of studies on the toxicity of alkylphenols to marine species, considering exposure and types of effect.

Species (Taxonomic group)	Type of effect	Duration	Compound	LOEC	EC50/LC50	Reference
Pleuronectes americanus (Fish)	Acute Larval	96 h	PNP	no data	17 µg/L	Lussier et al. (2000)
Mulinia lateralis (Mollusca)	Acute Embryolarval	96 h	PNP	no data	37.9 µg/L	Lussier et al. (2000)
Palaemonetes vulgaris (Crustacea)	Acute Larval	96 h	PNP	no data	59.4 µg/L	Lussier et al. (2000)
Americamysis bahia (Crustacea)	Acute Larval	96 h	PNP	no data	60.6 µg/L	Lussier et al. (2000)
Leptocheirus plumulosus (Crustacea)	Acute Larval	96 h	PNP	no data	61.6 µg/L	Lussier et al. (2000)
Menidia beryllina (Fish)	Acute Larval	96 h	PNP	no data	70 µg/L	Lussier et al. (2000)
Homarus americanus (Crustacea)	Acute Larval	96 h	PNP	no data	71 µg/L	Lussier et al. (2000)
Cyprinodon variegatus (Fish)	Acute Larval	96 h	PNP	no data	142 µg/L	Lussier et al. (2000)
Dyspanopeus sayi (Crustacea)	Acute Larval	96 h	PNP	no data	> 195 µg/L	Lussier et al. (2000)
Cyclotella caspia (Diatom)	Chronic Growth rate	96h	NP	0.18 mg/L	no data	Liu et al. (2013)
Arbacia lixula (Echinodermata)	Acute Embryolarval	72 h	NP OP	0.937 µg/L 20 µg/L	no data	Arslan & Parlak (2007)
Paracentrotus lividus (Echinodermata)	Acute Embryolarval	72 h	NP OP	0.937 µg/L 5 µg/L	no data	Arslan et al. (2007)

(*Cyclotella caspia*) were studied for the acute effects of para-nonylphenol (PNP), nonylphenol (NP), and octylphenol (OP). Only one study has examined the chronic effects of nonylphenol on a diatom species (Liu et al. 2013).

Existing data on the toxicity of alkylphenols to marine species are very limited, as most published articles do not present LOEC or NOEC values. Three studies present such values, which were 20 µg/L for OP (Arslan & Parslak 2007), 5 µg/L for NP (Arslan et al. 2007), and 0.18 mg/L for PNP (Liu et al. 2013). EC50 or LC50 values were not calculated for NP and OP, whereas for PNP, EC50 ranged from 17 µg/L (for larvae of the fish *Pseudopleuronectes americanus*) to > 195 µg/L (for the crab *Dyspanopeus sayi*) (Lussier et al. 2000). Although existing data are limited, they suggest that alkylphenols are highly toxic to marine organisms. Information on the environmental concentrations of alkyphenols are very scarce, but maximum concentrations of NP were reported as 4.1 µg/L (David et al. 2009) in estuarine regions, above the toxic thresholds for embryos of *A. lixula* and *P. lividus* (0.937 µg/L), suggesting environmental risks due to NP.

Alkylphenols and alkylphenol ethoxylates are phenol derivatives that are widely used as precursors in the production of nonionic surfactants found in various everyday products, as well as antioxidants in plastics (Klančič et al. 2022). Due to their extensive industrial and domestic use, these compounds enter aquatic environments primarily through wastewater (Bergé et al. 2012). As a result, the presence of alkylphenols has been reported in coastal environments worldwide in both coastal waters (Munaron et al. 2012) and sediments (Oliveira Santos et al. 2022). These compounds are considered lipophilic because of their high partition coefficients, which allow them to enter the food chain and accumulate in animal tissues (Acir & Guenther 2018, Diehl et al. 2012). Furthermore, there are significant concerns regarding the endocrine-disrupting effects of this class of chemicals (Acir & Guenther 2018, Klančič et al. 2022).

Tetrabromobisphenol (TBBPA)

Six articles were selected regarding the toxicity of Tetrabromobisphenol A (TBBPA) in marine organisms (Table III), in which five taxonomic groups were analyzed: crustacea (the copepods *Acartia tonsa* and *Paracartia grani*), bacteria (*Vibrio fischerii*), microalgae (*Chlorella* sp.), mollusks (the mussel *M. galloprovincialis* and the clam *Ruditapes philippinarum*), and fish (*Sarda sarda* and *Sardina plicardus*). Fish were assessed for subchronic effects (alteration of carboxylesterase activity), whereas microalgae and mollusks were assessed for chronic toxicity (growth inhibition and embryonic development, respectively). Acute toxicity in adults has also been analyzed in mollusks. Existing literature provides little information on the toxicity of TBBPA to marine organisms (Pittinger & Pecquet 2018). Interim LOECs could range between 100 µM for carboxilesterase in fish and copepod (Nos et al. 2020) and 0.1 µg/L for embryonic development of *M. galloprovincialis* (Fabbri et al. 2014). The reported CE50 values were 3.68 µg/L for mussel embryos (Fabbri et al. 2014) and 3.5 mg/L for microalgae (Debroy et al. 2024), while the LC50 for adult mussels was 7.4 mg/L (Jiang et al. 2019). For the copepod *Acartia tonsa,* Wollenberger et al. (2005) reported a 48-h LC_{50} of 0.40 mg/L (0.37–0.43 mg/L). The toxicity of degradation products was evaluated in bioassays of bacteria (*Vibrio fischerii*), and EC50 values ranged from 4.1 mg/L for B3BPA and 59.69 mg/L for B4BPA (Debenest et al. 2010). Although information on environmental concentrations of TBBPA is scarce, Gong et al. (2021) reported levels up to 0.46 µg/L in coastal waters from China, which are below the toxic thresholds for embryos of *M.*

Table III. Comparison of studies on the toxicity of Tetrabromobisphenol (TBBPA) and its by-products to marine species, considering exposure and types of effect.

Species (Taxonomic group)	Type of effect	Duration	Compound	LOEC	EC50/LC50	Reference
Paracartia grani (Copepoda)	Chronic carboxylesterases activity	30 min (*in vitro*)	TBBPA	100 µM	no data	Nos et al. (2020)
Sarda sarda (Fish)	Chronic carboxylesterases activity	30 min (*in vitro*)	TBBPA	100 µM	no data	Nos et al. (2020)
Sardina plicardus (Fish)	Cronic carboxylesterases activity	30 min (*in vitro*)	TBBPA	100 µM	no data	Nos et al. (2020)
Vibrio fischerii (Bacteria)	Acute Light Emission Inhibition	15 min	TBBPA B3BPA[1] B2BPA[2] B1BPA[3] BPA	no data	59.69 mg/L 4.1 mg/L 5.9 mg/L 4.8 mg/L 6.2 mg/L	Debenest et al. (2010)
Chlorella sp. (Chlorophyceae)	Chronic Growth Inhibition	72 h	TBBPA	0.125 mg/L	3.5 mg/L	Debroy et al. (2024)
Mytillus galloprovincialis (Mollusca)	Acute Embryolarval	48 h	TBBPA	0.1 µg/L	3.68 µg/L	Fabbri et al. (2014)
Ruditapes philippinarum (Mollusca)	Acute	96h	TBBPA	no data	7400 µg/L	Jiang et al. (2019)
Acartia tonsa (Copepoda)	Acute	48h	TBBPA	no data	0.40 mg/L	Wollenberger et al. (2005)

[1] B3BPA = tri-bromobisphenol A; [2] B2BPA[2] = di-bromobisphenol A; [3] B1BPA[3] = monobromobisphenol A.

galloprovincialis (Fabbri et al. 2014), suggesting potential of environmental risk due TBBPA.

TBBPA is a brominated flame retardant used in several consumer products such as building materials, electronics, textiles, and plastic products (Xu et al. 2024, Oral et al. 2021, Serradimigni et al. 2024). As an industrial additive, TBPA has the potential to leach, leading to its detection in many environmental matrices (Serradimigni et al. 2024), such as ocean water, at concentrations ranging from ng/L to µg/L (Zhang et al. 2022). TBBPA can persist for extended periods in the environment, and has the potential to bioaccumulate (Debroy et al. 2024). Significantly higher concentrations of TBBPA have been found in pelagic fish than in demersal species and benthic invertebrates, suggesting a greater prevalence of this compound in the water column (Choo et al. 2019) TBBPA may act as an endocrine disruptor (Baumann et al. 2016), induce oxidative stress (Nos et al. 2020), and cause effects on development (Fabbri et al. 2014) and reproduction (Serradimigni et al. 2024).

Phthalates

Twenty studies were identified examining the effects of phthalates on aquatic biota. However, only four of them met the criteria established in this review, encompassing five species exposed to this class of contaminants and representing three distinct taxonomic groups: echinoderms (the sea cucumber *Apostichopus japonicus* and sea urchin *Strongylocentrotus purpuratus*), diatoms (*Phaeodactylum tricornutum*), and dinoflagellates (*Alexandrium pacificum*) (Table IV). Chronic effects were observed in two

Table IV. Comparison of studies on the toxicity of Phthalate Esters (PAEs) to marine species, considering exposure and types of effect.

Species (Taxonomic group)	Type of effect	Duration	Compound	LOEC	EC50/LC50	Reference
Apostichopus japonicus (Echinodermata)	Acute Larval Survival	24h	PAEs leachates	< 0.3 mg/L	LC50 13,22 mg/L EC50 30,44 mg/L	Wang et al. (2023)
Apostichopus japonicus (Echinodermata)	Acute Larval Survival	48h	PAEs leachates	< 0.3 mg/L	LC50 5,21 mg/L EC50 18,27 mg/L	Wang et al. (2023)
Strongylocentrotus purpuratus (Echinodermata)	Acute Larval Survival	96h	Di(2-ethylhexyl) phthalate (DEHP)	< 0.1 mg/L	no data	Shore et al. (2022)
Alexandrium pacificum (Dinoflagellata)	Chronic cell density	96h	Di(2-ethylhexyl) phthalate (DEHP)	1 µg/L	no data	M'Rabet et al. (2018)
Phaeodactylum tricornutum (Diatom)	Chronic growth inhibition	96h	Dimethyl phthalate (DMP) diethyl phthalate (DEP)	390.5 mg/L 74.0 mg/L	no data	Gao et al. (2021)

microalgae species, whereas acute effects were reported in two echinoderm species. For leachates of phthalate esters (PAEs) the available LOEC was < 0.3 mg/L, for the embryonic development of *A. japonicus*, and EC50 5.21 mg/L (Wang et al. 2023). The LOEC of Di(2-ethylhexyl) phthalate (DEHP) was 1 µg/L, obtained from 96h exposure bioassays with dinoflagellates (M'Rabet et al. 2018). LOECs were also calculated for dimethyl phthalate (DMP) and diethyl phthalate (DEP) from bioassays with diatoms, and respectively were 390.5 mg/L and 74 mg/L, respectively (Gao et al. 2021). Net et al. (2015) reported phthalates concentrations ranging 30–5030 pg/L in the North Sea, whereas a review on the phthalates occurrence in marine ecosystems (Hidalgo-Serrano et al. 2022) reported levels of DMP up to 800 ng/L, DEP up to 6360 ng/L, and DEHP up to 35,000 ng/L. These concentrations are much below the reported toxic thresholds for marine organisms, indicating lack of environmental risks due to phthalates.

Phthalates are phthalic acid diesters widely used as plasticizers to enhance the flexibility and durability of plastics, particularly polyvinyl chloride (PVC). These chemicals are also present in lubricants, cosmetics, toys, and adhesives (ECHA 2022). As phthalates leach into the environment, they interact with various environmental compartments and have been detected in sediments (Neves et al. 2023, Okoro et al. 2024), as well as in the higher trophic levels of marine organisms, including sharks (Wang et al. 2024) and marine mammals (Hernández-Milian et al. 2023, Montoto-Martínez et al. 2021). Phthalates are recognized as endocrine disruptors (Hlisníková et al. 2020), and their bioaccumulation in biota poses a significant threat to marine ecosystems.

Polybrominated diphenyl ethers (PBDEs)

Four articles analyzing the effects of polybrominated diphenyl ethers (PBDEs) on marine organisms have been identified (Key et al. 2008, Mhadhbi et al. 2012a, b, Zhao et al. 2019), encompassing four compounds, BDE-47, BDE-99, BDE-153, and BDE-154. Only BDE-47 was tested in all the articles analyzed. Acute and chronic effects were observed in four marine species, including two microalgae, one fish, and one crustacean species (Table V). The LOECs for BDE-47 ranged from 1.6 mg/L, for the fish *Psetta maxima* (Mhadhbi et al. 2012b), to 5.1 mg/L for the microalgae *Isochrysis galbana* (Mhadhbi et al. 2012a). For the BDE-99, the respective LOECs for both species were 3.2 mg/L (Mhadhbi et al. 2012b) and 6.9 mg/L (Mhadhbi et al. 2012a). The LOEC of BDE-154 was 24.6 mg/L for *I. galbana* (Mhadhbi et al. 2012a), whereas for the BDE-153 the EC50 to *Platymonas subcordiformis* was 14.6 μg/L (Zhao et al. 2019). The environmental concentrations of PBDEs around the world range from non-detectable to 343 ng/L, with the highest concentration found near an industrial area in Korea (Lee et al. 2018, Kim et al. 2012). As the toxic of PBDEs range on the order of micrograms per liter and milligrams per liter, there little or no environmental risks for marine organisms due to PBDEs.

PBDEs are widely employed as brominated flame retardants in the electrical equipment, construction, textiles, and plastic industries (Alaee et al. 2003, Ohgaki et al. 2021). Its molecular structure is similar to that of polychlorinated biphenyls (PCBs), and different brominations of diphenyl ether molecules can generate 209 possible PBDE congeners (Alaee et al. 2003). Due to their widespread use in various industries, even though they have been banned in several countries, PBDEs continue to reach the oceans mainly in sewage systems or associated with

Table V. Comparison of studies on the toxicity of polybrominated diphenyl ethers (PBDEs) to marine species, considering exposure and types of effects.

Species (Taxonomic group)	Type of effect	Duration	Compound	LOEC	EC50/LC50	Reference
Isochrysis galbana (Microalgae)	Chronic growth inhibition	72 h	BDE-47 BDE-99 BDE-154	5.1 mg/L 6.9 mg/L 24.6 mg/L	EC50 25.7 mg/L 30.9 mg/L 243.7 mg/L	Mhadhbi et al. (2012a)
Platymonas subcordiformis (Microalgae)	Acute swimming behavior	2 h	BDE-47 BDE-99 BDE-153	no data	EC50 5.4 μg/L 7.7 μg/L 14.6 μg/L	Zhao et al. (2019)
Psetta maxima (Fish)	Acute Hatching success of eggs	48 h	BDE-47 BDE-99	4.1 mg/L 5.1 mg/L	LC50 27.3 mg/L 38.3 mg/L	Mhadhbi et al. (2012b)
Psetta maxima (Fish)	Acute Larval Survival	72 h	BDE-47 BDE-99	1.6 mg/L 3.2 mg/L	LC50 14.1 mg/L 29.6 mg/L	Mhadhbi et al. (2012b)
Palaemonetes pugio (Crustacea)	Acute Larval mortality	96 h	BDE-47	no data	LC50 23.6 μg/L	Key et al. (2008)
Palaemonetes pugio (Crustacea)	Acute Adult mortality	96 h	BDE-47	no data	LC50 78.1 μg/L	Key et al. (2008)

plastics. Once in the marine environment, PBDEs can reach high concentrations in seawater and sediments, from which they can be resorbed and concentrated in plastic polymers due to their hydrophobicity (Ohgaki et al. 2021). Adverse effects of PBDE exposure have already been demonstrated in mice, neurotoxic (Eriksson et al. 2001), and marine mammals, immunotoxic (Frouin et al. 2010), and PBDEs have also been found in human breast milk (Schecter et al. 2003).

Per- and polyfluoroalkyl substances (PFAS)

Regarding per- and polyfluoroalkyl substances (PFAS), only four articles were found (Fabbri et al. 2014, Gebreab et al. 2022, Hayman et al. 2021, Mhadhbi et al. 2012c), mostly analyzing the toxicity of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) in different marine species (Table VI). Other analyzed compounds included hexafluoropropylene oxide-dimer acid (HFPO-DA), 4-(heptafluoroisopropoxy) hexafluorobutanoic acid (PFDMMOBA), perfluoro-3,6-dioxadecanoic acid (PFO2DA), and perfluoro-3,6,9-trioxadecanoic acid (PFO3TDA), which toxicities were tested for the embryonic development of the fish *Coryphaena hippurus* (Gebreab et al. 2022). The literature reports the effects to nine marine species (two microalgae, two fish, two sea urchins, two crustaceans, and one bivalve), including acute effects on five of them and chronic effects on 13 species (Table VI).

The LOECs of PFOA were exhibited wide variations, and ranged between 0.1 µg/L (for the embryonic development of *M. galloprovincialis*) and 50 mg/L (for the growth of *I. galbana*) (Fabbri et al. 2014, Mhadhbi et al. 2012c). The LOEC of PFOS was also calculated as 0.1 µg/L (Fabbri et al. 2014). The EC50 and LC50 values also varied greatly between species. For the other PFAS, although only one study was found (Gebreab et al. 2022), the lowest observed adverse effect levels (LOAEL) for *C. hippurus* embryos was proposed by the authors as 100 mg/L for HFPO-DA, 10 mg/L for PFDMMOBA, 1 mg/L for PFO2DA, and 5 mg/L for PFO3TDA. Maximum concentrations of total PFAS in marine waters have been reported up to 7400 pg/L (Wang et al. 2025), thus potential environmental risks could occur to embryos of *M. galloprovincialis*.

PFAS includes more than 1000 compounds that have been used in a wide variety of industrial applications (USEPA 2020). PFAS consist of organofluorine compounds with fluorine atoms bonded to the carbon chain instead of hydrogen atoms (Buck et al. 2011), or at least one fully fluorinated methyl or methylene carbon atom (Bilela et al. 2023). The C-F bond is strong and stable providing these compounds with thermal stability characteristics and hydrophobic and lipophobic nature (Smart 1994, O’Hagan 2008, Buck et al. 2011, Zhao et al. 2016). These characteristics make PFAS widely used in industry as stain and water repellents, personal care products, pesticides, fire-suppressors, and emulsifiers (Zushi et al. 2012, Brunn et al. 2023). They are used in plastic food contact materials (food packaging) because of their efficiency in repelling water and oil (Barhoumi et al. 2022). PFAS have been called “*forever chemicals*” because of their innate chemical stability (Evich et al. 2022) and low degradability. PFAS have been used as plastic additives (Llorca et al. 2014, Barhoumi et al. 2022), and their association with microplastics has been reported to increase their persistence in the environment (Scott et al. 2021, Dai et al. 2022). Considering that more than 50% of all plastic packaging is used for food (Groh et al. 2019), PFAS have become an environmental concern due to the plastic waste problem. Moreover, PFAS can be carried by plastic polymers as persistent organic pollutants

Table VI. **Comparison of studies on the toxicity of per- and polyfluoroalkyl substances (PFAS) to marine species, considering exposure and types of effects.**

Species (Taxonomic group)	Type of effect	Duration	Compound	LOEC	EC50/LC50	Reference
Coryphaena hippurus (Fish)	Chronic Embryonic development	24 h	PFOA HFPO-DA PFDMMOBA PFO2DA PFO3TDA	LOAEL* 20 mg/L 100 mg/L 10 mg/L 10 mg/L 10 mg/L	LC50 55 mg/L 84 mg/L 17 mg/L 34 mg/L 19 mg/L	Gebreab et al. (2022)
Coryphaena hippurus (Fish)	Chronic Embryonic development	48 h	PFOA HFPO-DA PFDMMOBA PFO2DA PFO3TDA	LOAEL* 5 mg/L 100 mg/L 10 mg/L 1 mg/L 5 mg/L	LC50 4 mg/L 20 mg/L 10 mg/L 1.1 mg/L 7 mg/L	Gebreab et al. (2022)
Stronglycentrotus purpuratus (Sea urchin)	Chronic Embryonic development	96 h	PFOS PFOA	1.6 mg/L 11 mg/L	EC50 1.7 mg/L 19 mg/L	Hayman et al. (2021)
Mytilus galloprovincialis (Bivalve)	Acute Embryonic mortality	48 h	PFOS PFOA	1.1 mg/L 4.7 mg/L	EC50 1.1 mg/L 9.9 mg/L	Hayman et al. (2021)
Mytilus galloprovincialis (Bivalve)	Chronic Embryonic development	96 h	PFOS PFOA	1.1 mg/L 1.5 mg/L	EC50 1.1 mg/L 12 mg/L	Hayman et al. (2021)
Americamysis bahia (Crustacea)	Acute Adult mortality	96 h	PFOS PFOA	3 mg/L 29 mg/L	EC50 5.1 mg/L 24 mg/L	Hayman et al. (2021)
Pyrocystis lunula (Microalgae)	Acute Light output	24 h	PFOS PFOA	10 mg/L 11 mg/L	EC50 4.9 mg/L 18 mg/L	Hayman et al. (2021)
Mytillus galloprovincialis (Mollusca)	Acute Embryonic development	48 h	PFOS PFOA	0.1 µg/L 0.1 µg/L	no data	Fabbri et al. (2014)
Isochrysis galbana (Microalgae)	Chronic Embryonic development	72 h	PFOS PFOA	15 mg/L 50 mg/L	EC50 37.5 mg/L 163.6 mg/L	Mhadhbi et al. (2012c)
Paracentrotus lividus (Sea urchin)	Chronic Embryonic development	48 h	PFOS PFOA	2 mg/L 20 mg/L	EC50 20 mg/L 110 mg/L	Mhadhbi et al. (2012c)
Siriella armata (Crustacea)	Acute Adult mortality	96 h	PFOS PFOA	2.5 mg/L 10 mg/L	EC50 6.9 mg/L 15.5 mg/L	Mhadhbi et al. (2012c)
Psetta maxima (Fish)	Chronic Embryonic development	144 h	PFOS PFOA	0.03 mg/L 3 mg/L	EC50 0.11 mg/L 11.9 mg/L	Mhadhbi et al. (2012c)

LOAEL = lowest observed adverse effect level.

(POPs) (Bakir et al. 2014, Llorca et al. 2014, Dai et al. 2022, Zenobio et al. 2022).

This review shows that only a very small number of studies have focused on the toxicity of plastic additives in marine organisms; thus, knowledge on this topic is limited. For most of the chemical groups investigated, the reported toxicities were variable and depended on the compound, species tested, and exposure type and duration; however, most threshold effects have been reported in the range of micrograms per liter, and environmental risks could occur for many of the analyzed chemical groups, as discussed above. Most of the chemical compounds used as plastic additives can be considered as very toxic to marine organisms, according to the criteria established in the European Union (EU 2008). The only exception were PFAS, whose toxicities were mostly in the range of milligrams per liter, which were considered toxic (EU 2008); however, because of the persistence of PFASs, they have been known as forever chemicals and are listed as priority pollutants (Brunn et al. 2023).

Furthermore, these plastic additives generally present high partition coefficients (such log K_{oc} and log K_{ow}) and tend to accumulate in the bottom sediments or bioaccumulate (Wang et al. 2025, Khan et al. 2023, Turner 2022, Yogui & Sericano, 2009, Gong et al. 2021, Pittinger & Pecquet 2018, Abdallah, 2016). Thus the possibility of long-term effects of plastic additives is not negligible and should be further studied, as well as their effects on benthic marine species. Moreover, plastic polymers normally have multiple additives (França et al. 2022, Liu et al. 2019), they can be a source of a wide range of chemicals for the marine biota. As consequence, toxicity could occur due to the combined effects of such contaminants.

In this sense, the result of combined effects of plastic additives would depend greatly on the mode of action of such substances. BPA could elicit an endocrine-disrupting capacity, and its effects rely on several and diverse mechanisms that converge upon endocrine and reproductive systems (Acconcia et al 2015). Similarly, alkylphenols are considered endocrine disruptors as well (Regan & Fogarty 2005). Both nonylphenol and octylphenol have been identified as estrogen mimics using vitellogenin gene expression in trout hepatocytes, gene transcription in transfected cells, and by the growth of breast cancer cell lines (Regan & Fogarty 2005). In turn, TBBPA is an endocrine disruptor as well, which acts on T4 production (Lai et al. 2015). Phthalates modify the membrane receptors and protein kinases in signaling pathways, producing endocrine disruption, apoptosis signaling, and carcinogenesis (Hlisníková et al. 2020). The mechanisms involved in the developmental neurotoxic effects of PBDEs are not known, though one general mode of action relates to the ability of PBDEs to impair thyroid hormone homeostasis, indirectly affecting the developing brain. The cAMP pathway is mainly stimulated, affecting critical physiological processes such as metabolism, secretion, calcium homeostasis, muscle contraction, and gene transcription (Costa et al, 2014). Finally, Nguyen et al. (2024) found that PFAS modes of action included increased stem cell self-renewal, altered transcriptomes, and enriched cancer-associated signaling pathways, suggesting a potential association between chronic PFAS exposure and elevated cancer risk. Low-dose PFOA induced male endocrine disruption, revealing significant regulation of proteins and metabolites associated with lipid and fatty acid metabolism, highlighting the stimulation of steroid hormone synthesis.

This review also demonstrates that more research is needed regarding the toxicity of plastic additives to marine organisms, as well as the interactions between plastics and chemical additives. Other relevant features requiring further study involve comparisons between different plastic polymers and their respective chemical additives, as well as the composition and toxicity of plastic leachates. Moreover, due to the hydrophobic nature of most plastic additives and their tendencies of bioaccumulating or accumulating in sediments, there is a critical need for studies covering these topics, including throphic transference and biomagnification. This information is necessary to regulate the use of plastic additives and to establish actions to reduce their impacts on marine ecosystems.

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