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Microplastic pollution in commercially important edible marine bivalves: A comprehensive review

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ABSTRACT

Microplastics have become major pollutants in the marine environment and can accumulate in high concentrations, especially in the gut of marine organisms. Unlike other seafood, bivalves are consumed whole, along with their digestive systems, resulting in the transfer of microplastics to humans. Therefore, there is an urgent need to review the status of microplastic pollution in marine bivalves. In this context, this article provides a comprehensive review of the status of microplastic pollution in marine bivalves and the impact of microplastics on the physiology and immunology of marine bivalves. In general, marine bivalves can accumulate high levels of microplastics in a tissue-specific manner. Although microplastic pollution does not cause mortality in bivalves, it can adversely affects bivalves' immunity, byssus production, and reproduction, potentially affecting bivalve populations. This article provides important information that will aid establishing management measures and determining the direction of future research.

1. Introduction

Plastics are synthetic materials that use fossil fuel-based polymers as the main ingredients. The competitive properties of plastics, such as high plasticity, durability, light weight, and low production cost, enable their wide application and play an important role in economic growth. Unfortunately, improper disposal of plastic waste results in an estimated 75–199 million tons of plastics ending up in our oceans, posing a significant threat to the marine environment (Eriksen et al., 2023). Large plastics gradually degrade into microplastics (MPs) (size <5 mm) through biological, photolytic, or mechanical mechanisms, which will remain in marine systems for thousands of years before further degradation (Arthur et al., 2009; Fu et al., 2020).

These MPs can be accidentally consumed by marine animals, including bivalves, accumulate in the gills and digestive tract, and might cause blockages (Khan & Prezant, 2018; Kinjo et al., 2019). Furthermore, these MPs are absorbed and transported to different tissues through the endosomal pathway (Faggio et al., 2018; Scanes et al., 2019). Marine bivalves are high quality animal proteins (Song, Luo, et al., 2024) rich in polyunsaturated fatty acids (Tan, Huang, et al., 2023; Tan, Lim, et al., 2023; Tan, Ransangan, et al., 2023; Yan et al., 2024) and bioactive compounds that have multiple beneficial health effects (Tan, Lu, et al., 2023). Unlike finfish, bivalves such as mussels, oysters, clams, and scallops are often eaten together with their gills and digestive tract (main organs where MP accumulate), increasing the exposure of consumers to MPs through the food chain (Farrell & Nelson, 2013; Watts et al., 2014).

MPs in bivalves were recently reviewed by Wang, Mou, et al. (2021) and Ding et al. (2022). However, these reviews mainly focus on methods for the extraction and detection of microplastic in bivalves. There is very little information on the status of microplastic pollution in marine bivalves. In this context, this article provides an overview of the latest status of MP pollution in marine bivalves and reviews the impact of MP pollution on the physiology and immunology of marine bivalves. The

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information in this article not only fills the knowledge gap on the status of MP pollution in marine bivalves and the impact of microplastic pollution on marine bivalves but also provides guidance for the development of aquaculture and fisheries management plans for implementation in commercial fisheries and natural conservation.

2. Literature search and data collection

Scientific articles were gathered from Google Scholar, Web of Science, and PubMed (up to July 2024) using a combination of the following keywords: “microplastics”, “bivalves”, “physiology”, “immunology” and “reproduction”. To ensure thorough coverage, relevant articles from the reference lists of each retrieved article were downloaded. This process was repeated until no additional articles were identified. In total, 1620 articles were retrieved from the literature search.

The obtained articles were further screened to identify those describing MPs in marine bivalves or the effects of MPs on marine bivalves. After screening, only 650 articles met the criteria, with 75% of the articles published in the past 5 years (2020 and onward) (Fig. 1). The keywords of publications related to MPs in marine bivalves were analyzed using VOSviewer and are illustrated in Fig. 2. In general, most publications related to MPs in marine bivalves focus on environmental monitoring, ecosystems and seafood.

3. Status of microplastic pollution

Plastics are artificial hydrocarbon polymeric materials that are highly stable, durable, inexpensive, and lightweight. Since the 1950s, plastics have been increasingly used in our daily lives (Carpenter & Smith, 1972). The annual production of plastics has substantially increased from 1.5 million tons in 1950 to 240–280 million tons in 2008 and onward. In 2018, the total annual production of plastics was 360 million tons, with China being the largest producer of plastic materials (26%), followed by Europe (20%) and NAFTA (North American Free Trade Agreement) countries (19%). Plastic production is expected to grow, reaching 1.1 billion tons by 2050 (Geyer, 2020). Since about 40% of plastic production is used in single-use packaging (*e.g.* food and industrial packaging materials), the increase in plastic production and usage has drawn public attention, and is considered to be beyond the safe planetary boundaries (Persson et al., 2022).

Over the past few decades, due to poor management of plastic waste, a huge amount of plastic waste has been deposited into the ocean, in which plastic wastes in the ocean mainly comes from various anthropogenic activities, including fisheries, shipping, agriculture, tourism, industries *etc.* (Naji et al., 2017; Robin et al., 2020). To date, it is estimated that the amount of plastic particles floating on the ocean surface is about 50–75 trillion plastics, weighting 75–199 million tons, with 8–10 million tones of plastic entering the ocean every year. Asia is the main source (80%) of marine plastic pollution, with the Philippines is the main contributor (36.4%), followed by India (12.9%), Malaysia (7.5%), China (7.2%) and Indonesia (5.8%) (Meijer et al., 2021). About 10% of this plastic waste deposited in the oceans is degraded by mechanical abrasion, microorganisms, and/or sunlight into MP,s which are defined as plastic particles with a diameter smaller then 5 mm (Arthur et al., 2009; Fu et al., 2020). In addition, some plastics in the ocean are directly deposited as MPs from electronic equipments, cosmetic products, synthetic textiles, *etc.* These MPs are distributed throughout water column and sediments, with the highest accumulation in ocean gyres, fjords, estuaries, bays and coastlines (Wessel et al., 2016). It is estimated that the amount of MPs floating on the ocean surface is about 171 trillion particles, weighting 2.3 million tones, accounting for about 85% of the total marine debris (Eriksen et al., 2023).

Based on shape, MPs can be classified into fragments, fibres, filaments, pellets, flakes, and foams, with fibres accounting for more than half of the total MPs (Wang, Wu, et al., 2021). Pakhomova et al. (2022) studied the microplastic variability in subsurface water from the Arctic East-Siberian Sea, across the Atlantic Ocean, and into the Antarctic Peninsula. The results revealed that the abundance of MP fibres in the Northern Hemisphere was significantly higher (about 2 fold) than that in the Southern Hemisphere, consistent with the distribution of the global human population. In the Northern Hemisphere, the weight concentrations of MPs are highest in the Barents Sea and the Central Atlantic ($7–7.5\ \mu\ g/m^3$), which is >10 fold higher than in other areas such as the Siberian Arctic and North Atlantic ($0.6\ \mu\ g/m^3$). Major MP polymers in the ocean include polyethylene terephthalate (PET), polystyrene (PS), polypropylene (PP), polyethylene (PE), and polyvinylchloride (PVC), which are also the most produced plastics (accounting for about 90% of

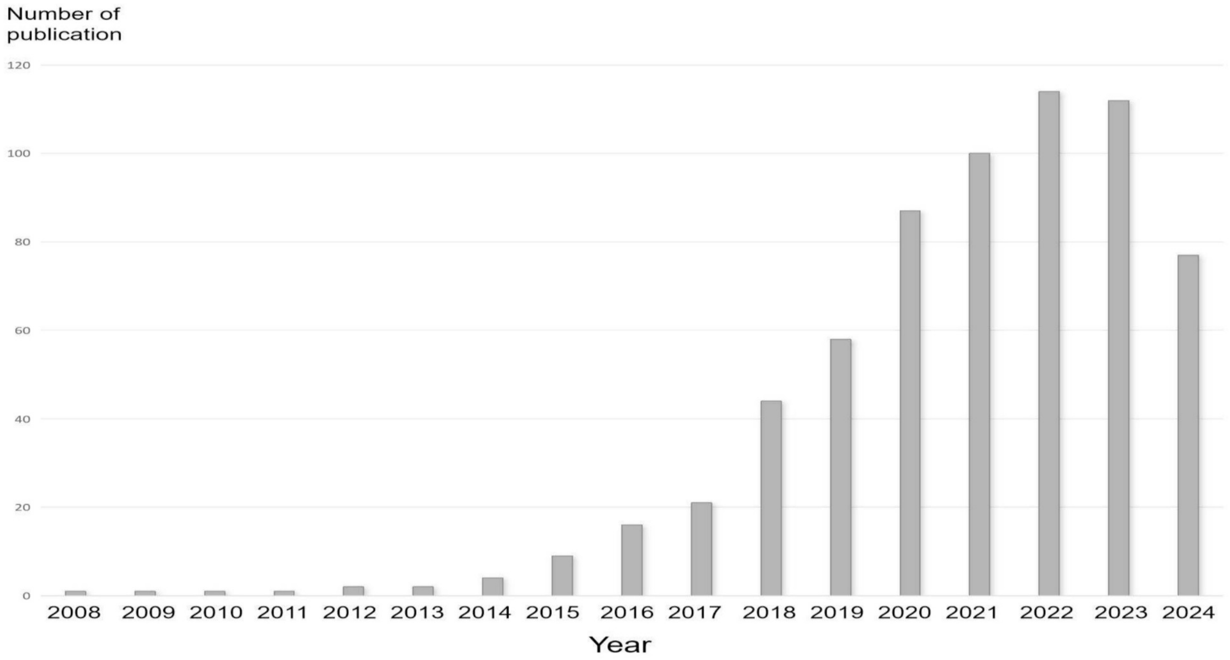

Fig. 1. number of publications related to microplastics and bivalves from year 2008 to 2024 (up to July 2024).

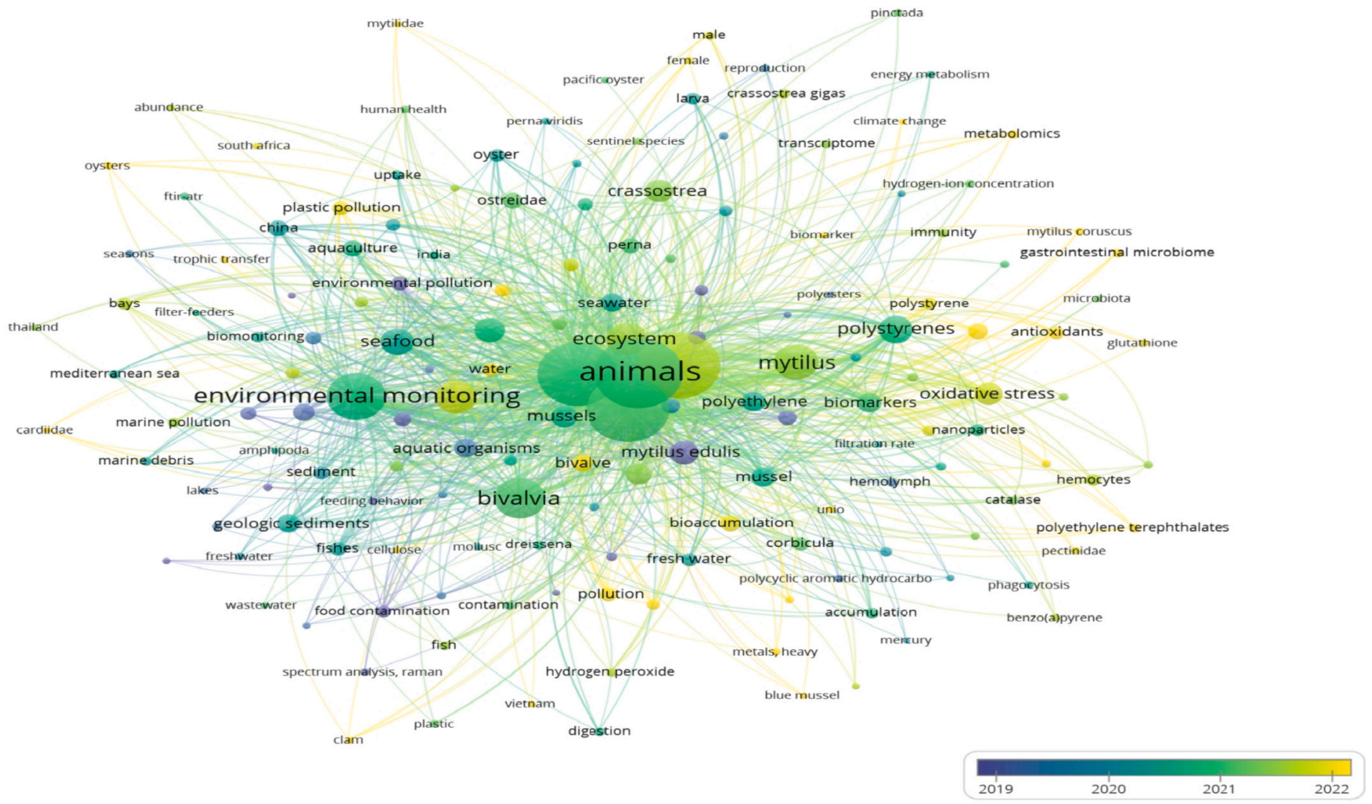

Fig. 2. Main keywords of published literature on microplastics in marine bivalves.

total plastic production) (Avio et al., 2017; Hantoro et al., 2019). Among them, the density of PET, PVC and PS is higher than seawater and thus tends to settle on the sediment, while the density of PP and PE is lower than that of seawater,and tends to float in the water column (Avio et al., 2017).

4. Status of microplastic pollution in marine bivalves

In general, filter-feeders, especially bivalves, accumulate 3 to 5 fold more MPs than other animals (Sfriso et al., 2020). This is due to the fact that bivalves are readily exposed to MPs in the water column and bivalves have been shown to ingest MPs ranging in size from 5 to 300 μm (*e.g.*, Cole & Galloway, 2015; Khan & Prezant, 2018; Kinjo et al., 2019; Van Cauwenberghe et al., 2013). In bivalves, gills and digestive glands are the major tissues that accumulate MP, with higher concentrations in gills (Joshy et al., 2022), but a longer retention time in digestive glands (Ribeiro et al., 2017; Sendra et al., 2019). In the digestive gland, MPs are taken up by lysosomes and transported to hemolymph and other tissues through the endosomal pathway (Faggio et al., 2018; Scanes et al., 2019). In fact, MPs have been reported present in the lining of the digestive tract of *Mytilus edulis* (Wang et al., 2016). In hemocytes, larger MP particles enter the immune cells through phagocytosis, becoming vacuoles that fuse with lysosomes (Ribeiro et al., 2017). Sendra et al. (2019) provided further evidence that inhibition of the clathrin and caveolae endocytosis pathways significantly reduced the internalization rate of MPs, whereas inhibition of phagocytosis significantly reduced the internalization rate of larger MPs (1 μm). It is worth noting that in addition to ingestion, Kolandhasamy et al. (2018) discovered a novel pathway for MP absorption by *Mytilus edulis*, which is through direct absorption through soft tissues.

Among the bivalves, the highest MP levels were recorded in scallops *Patinopecten yessoensis* (55 particles/ind) and cockles *Scapharca subcrenata* (40 particles/ind) collected from Shanghai, China (Li et al., 2015) (Table 1). This is not surprising as Shanghai is a megacity, and the Yangtze River is the largest source of MPs to the ocean (Mai et al., 2020). It is worth noting that the MPs in scallops and cockles living in muddy areas were significantly higher than those in other bivalve species living in the water column and sandy areas in the same region, including mussels *Mytilus galloprovincialis* (5 particles/ind), oysters *Alectryonella plicatula* (10 particles/ind), clams *Sinonovacula constricta* (15 particles/ind), *Ruditapes philippinarum* (7 particles/ind), *Meretrix lusoria* (10 particles/ind) and *Cyclina sinensis* (5 particles/ind). Given that MPs can accumulate in high levels in mud, bivalves inhabiting in muddy areas are exposed to higher levels of MPs (Cho et al., 2019; Khuyen et al., 2021). Similar observations were made in South Korea, where the MP concentration in scallops *Patinopecten yessoensis* was significantly higher than that in *Crassostrea gigas* and *Mytilus edulis* (Cho et al., 2019).

In sedentary (mussels and oysters) and sand-burrowing (clams) bivalves, there is no general agreement on the trend in MP accumulation. Most studies have shown that mussels accumulate higher levels of MPs than oysters and clams (Chinfak et al., 2021; Dowarah et al., 2020; McGrath, 2020; Miller et al., 2019; Murphy, 2018; Piarulli et al., 2020; Ruairuen et al., 2022). On one hand, the higher concentration of MPs in mussels compared to oysters is attributed to oysters having a more efficient selective feeding system consisting of two sites for particle selection (labial palps and gills), whereas labial pals are the only site for particle selection in other bivalves (Ward et al., 2019). On the other hand, the higher concentration of MPs in mussels compared to clams is attributed to the gut retention time and tissue accumulation of MPs in bivalves being negatively associated with the particle size of MPs (Browne et al., 2008; Ward & Kach, 2009). Since the proportion of small MP particles in water is significantly higher than that in sediments (Ding et al., 2019; Tang et al., 2022; Zhang et al., 2021), mussels living in the water column are expected to have a higher gut retention time and tissue accumulation of MPs than clams. We also do not rule out the possibility that the higher concentration of MPs in mussels compared to clams may be due to the used of plastic infrastructure and materials in mussel farmed, while clams are grown in sediment (Mathalon & Hill, 2014; Zhu

Table 1
Status of microplastic pollution in marine bivalves.

Species	Wild/ farmed	Bivalve size (cm)	Extraction method	Major type of microplastics	Polymer types	Concentration (per ind)	Concentration (per g)	Location	References
Mussels									
Perna perna	Wild	4.75 to 6.16	10%KOH	Fibres	Polymethyl methacrylate	–	0.80 to 28.10	Estuarine system of Brazil	Ribeiro et al., 2023
Perna viridis	Wild	2.00 to 9.00	30%H2O2	Fibres	PET	0.15 to 0.22	–	Sri Racha Bay, Thailand	Phaksopa et al., 2023
Perna viridis	Wild	5.29 ± 0.48	10% KOH	Fibres	Polyamides	1.31	–	Pasir Putih Estuary, Malaysia	Zahid et al., 2022
Perna viridis	Wild	6.54 ± 0.29	10% KOH	Fibres	Polyamides	1.05	–	Pasir Putih Estuary, Malaysia	Zahid et al., 2022
Perna viridis	Wild	7.62 ± 0.40	10% KOH	Fibres	Polyamides	0.79	–	Pasir Putih Estuary, Malaysia	Zahid et al., 2022
Perna viridis	Wild	–	10% KOH	Fragment	PET and PP	2.23 ± 1.04	0.4 ± 0.24	Pasir Putih Estuary, Malaysia	Zin et al., 2022
Perna viridis	Farmed	–	10% KOH	Fragment	PET and PP	1.29 ± 1.19	0.44 ± 0.34	Pasir Putih Estuary, Malaysia	Zin et al., 2022
Perna viridis	Wild	8.28 ± 0.82	10% KOH	Fiber	–	3.43 ± 0.21	–	Badon Bay, Thailand	Ruairuen et al., 2022
Perna viridis	Wild	8.30 ± 0.86	10% KOH	Fiber	–	0.75 ± 0.09	–	Badon Bay, Thailand	Ruairuen et al., 2022
Perna viridis	Wild	8.15 ± 0.80	10% KOH	Fiber	–	0.92 ± 0.23	–	Badon Bay, Thailand	Ruairuen et al., 2022
Perna viridis	Wild	8.70 ± 0.73	10% KOH	Fiber	–	0.75 ± 0.12	–	Badon Bay, Thailand	Ruairuen et al., 2022
Perna viridis	Wild	8.77 ± 0.97	10% KOH	Fiber	–	0.65 ± 0.13	–	Badon Bay, Thailand	Ruairuen et al., 2022
Perna perna	Wild	–	10% KOH	Fiber	–	8.30 ± 1.00	1.40 ± 0.30	Espírito Santo, Brazil	Bom et al., 2022
Perna viridis	Farmed	9.39 ± 6.42	30%H2O2	Filament	Polyester	8.40 ± 3.50	–	Koh Phee Canal, Thailand	Cherdsukjai et al., 2022
Perna viridis	Farmed	9.68 ± 5.69	30%H2O2	Filament	Polyester	5.50 ± 2.50	–	Koh Phee Canal, Thailand	Cherdsukjai et al., 2022
Perna viridis	Farmed	10.03 ± 3.58	30%H2O2	Filament	Polyester	6.10 ± 3.50	–	Koh Phee Canal, Thailand	Cherdsukjai et al., 2022
Mytillus galloprovincialis	Wild	5.57 ± 1.18	10% KOH	Fibres	Polyester and PET	0.45 ± 0.67	0.18 ± 0.31	Coast of Portugal	Pequeno et al., 2021
Perna viridis	Farmed	5.16 ± 0.92	30%H2O2	Fibres	–	–	0.41	Inner Bacoor Bay, Philippines	Bilugan et al., 2021
Perna viridis	Farmed	5.39 ± 0.9	30%H2O2	Fibres	–	–	0.40	Middle Bacoor Bay, Philippines	Bilugan et al., 2021
Perna viridis	Farmed	5.43 ± 1.46	30%H2O2	Fibres	–	–	0.27	Outer Bacoor Bay, Philippines	Bilugan et al., 2021
Mytilus spp.	Wild	5.40 to 5.90	10%KOH	Fibres	PP	–	0.54 to 3.0	Portuguese coast	Marques et al., 2021
Perna viridis	Wild	7.74 ± 0.07	30%H2O2	Fibres	Royan, PP and PET	5.70 ± 0.49	0.86 ± 0.08	Bandon Bay, Thailand	Chinfak et al., 2021
Perna viridis	Wild	10.49 ± 0.07	30%H2O2	Fibres	Royan, PP and PET	1.77 ± 0.30	0.14 ± 0.02	Bandon Bay, Thailand	Chinfak et al., 2021
Mytilus galloprovincialis	Farmed	–	10%KOH	Fibres	Rayon	0.80 to 2.10	1.60 to 2.60	Qingdao, China	Ding et al., 2021
Mytilus edulis	Farmed	5.77 ± 0.5	10% KOH	Fragment, fiber	PS	–	0.41 to 2.76	Marine coastal, France	Kazour & Amara, 2020
Mytilus edulis	Wild	–	Lipase, protease	Fragment, fiber	PET	–	1.43 ± 1.45	Southern part of South Korea	Jang et al., 2020
Mytilus galloprovincialis	Wild	–	30%H2O2	Fragment	PET	0.60	2.30	Turkish coasts	Gedik & Eryasar, 2020
Mytilus edulis	Wild	–	30% H 2 O2	–	–	9.88	–	Southern Gulf of St. Lawrence	McGrath, 2020
Mytilus galloprovincialis	Wild	–	1 M KOH	Fragment	Polyester	0.25 ± 0.12	–	Italy	Piarulli et al., 2020
Perna viridis	Wild	–	10% KOH	–	–	3.28 ± 0.87	1.8 ± 0.54	India	Dowarah et al., 2020
Mytilus galloprovincialis	Wild	–	10%KOH	Fibres	–	2.80	3.40	Cape Town, South Africa	Sparks, 2020
Choromytilus meridionalis	Wild	–	10%KOH	Fibres	–	1.80	5.60	Cape Town, South Africa	Sparks, 2020
Aulacomya ater	Wild	–	10%KOH	Fibres	–	2.30	2.90	Cape Town, South Africa	Sparks, 2020
Mytilus edulis	Wild	4.16 ± 1.27	10%KOH	Fibres	PP and PET	1.43 to 7.64	–	South West of England	Scott et al., 2019

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Table 1 (*continued*)

Species	Wild/ farmed	Bivalve size (cm)	Extraction method	Major type of microplastics	Polymer types	Concentration (per ind)	Concentration (per g)	Location	References
Perna perna	Wild	4.67 ± 0.51	30% H 2 O2	Fibres	Polyamide	31.20 ± 17.80	–	Guanabara Bay, Brazil	Brinstiel et al., 2019
Perna perna	Farmed	4.67 ± 0.51	30% H 2 O2	Fibres	Polyamide	25.00 ± 13.00	–	Guanabara Bay, Brazil	Brinstiel et al., 2019
Perna perna	Wild	>8.00	10%KOH	–	PP	2.60 ± 1.14	0.29 ± 0.14	Tinh Gia, Vietnam	Nam et al., 2019
Perna canaliculus	Wild	–	Concentrated HNO3	Fragment	PET	0.20 ± 0.20	0.00 to 0.48	New Zealand	Webb et al., 2019
Mytilus edulis	–	8.95 ± 0.39	10% KOH	Fiber	PET and Polyacrylonitrile	1.40 ± 0.30	0.10 ± 0.03	Fuzhou, China	Fang et al., 2019
Perna viridis	–	7.93 ± 0.48	10% KOH	Fiber	PET	1.40 ± 0.30	0.30 ± 0.10	Xiamen, China	Fang et al., 2019
Mytilus spp.	Wild	–	10%KOH	Fibres	–	2.81 ± 2.80	2.55 ± 2.80	Cantabrian Sea, Spain	Reguera et al., 2019
Mytilus spp.	Wild	–	10%KOH	Fibres	–	2.19 ± 1.57	1.59 ± 1.28	Ria of Vigo, Spain	Reguera et al., 2019
Mytilus galloprovincialis	–	6.29 ± 0.28	10%KOH	Fiber	PET and PP	–	0.80 ± 0.01	Bizerte, Tnisia	Abidli et al., 2019
Mytilus edulis	Farmed	–	10%KOH	Fragment	Acrylic and PP	0.68	0.12	South Korea	Cho et al., 2019
Mytilus edulis	Wild	4.73 ± 0.12	10%KOH	Fiber	PET	0.76 ± 0.40	0.15 ± 0.06	Channel coastline, France	Hermabessiere et al., 2019
Mytilus spp.	Wild	2.00 to 8.90	10%KOH	Fiber	Cellulosic	1.50 ± 2.30	0.97 ± 2.61	Norwegian coas	Brate et al., 2018
Mytilus galloprovincialis	Farmed	5.84 ± 0.35	10% KOH	Fiber and fragment	PP	1.90	3.17	Qingdao and Dongying, China	Ding et al., 2018
Mytilus galloprovincialis	Wild	3.96 ± 0.23	10% KOH	Fiber and fragment	Cellophane	0.53	2.00	Qingdao and Dongying, China	Ding et al., 2018
Mytilus galloprovincialis	Wild	1.24 ± 0.14	30% H 2 O2	Filament, fragment	–	–	0.05	Gulf of La Spezia, Italy	Bonello et al., 2018
Perna viridis	Wild	4.00 to 5.00	30%H2O2	–	–	–	20.00	Java Sea	Khoironi & Anggoro, 2018
Perna viridis	Wild	4.00 to 5.00	30%H2O2	–	–	–	8.00	Java Sea	Khoironi & Anggoro, 2018
Perna viridis	Wild	4.00 to 5.00	30%H2O2	–	–	–	4.00	Java Sea	Khoironi & Anggoro, 2018
Mytilus trossulus	Wild	2.00 to 3.00	Enzyme	Fiber	–	0.04 ± 0.19	0.26 ± 1.3	Baltic Sea, UK	Railo et al., 2018
Mytilus edulis	Wild	–	30%H2O2	Fiber	Polyester	3.23 ± 0.95	2.17 ± 0.62	Yantai, China	Qu et al., 2018
Mytilus edulis	Wild	–	30%H2O2	Fiber	Polyester	1.60 ± 0.43	2.18 ± 0.85	Qingdao, China	Qu et al., 2018
Mytilus edulis	Wild	–	30%H2O2	Fiber	Polyester	5.00 ± 2.03	3.18 ± 1.26	Zhoushan, China	Qu et al., 2018
Perna viridis	Wild	–	30%H2O2	Fiber	Polyester	3.17 ± 0.85	2.33 ± 1.04	Xiamen, China	Qu et al., 2018
Perna viridis	Wild	–	30%H2O2	Fiber	Polyester	4.13 ± 0.30	2.45 ± 0.55	Shenzhen, China	Qu et al., 2018
Perna viridis	Wild	–	30%H2O2	Fiber	Polyester	4.93 ± 1.49	3.15 ± 1.07	Qingzhou, China	Qu et al., 2018
Mytilus spp.	Wild	5.20 ± 1.50	10%KOH	Fiber	PET	1.50	0.97	Norway	Bråte et al., 2018
Mytilus galloprovincialis	Farmed	6.50	30%H2O2	Filament	–	12.40	9.20	Cesenatico, Italy	Renzi et al., 2018
Mytilus galloprovincialis	Farmed	5.00	30%H2O2	Filament	–	6.20	11.40	La Spezia, Italy	Renzi et al., 2018
Mytilus galloprovincialis	Farmed	6.00	30%H2O2	Filament	–	3.60	4.40	Olbia, Italy	Renzi et al., 2018
Mytilus galloprovincialis	Wild	4.50	30%H2O2	Filament	–	3.00	7.20	Talamone, Italy	Renzi et al., 2018
Mytilus sp.	Wild	4.00 ± 0.27	30%H2O2		–	3.2 ± 0.52	3.0 ± 0.9	Scotland, UK	Catarino et al., 2018
Modiolus modiolus	Wild	9.20 ± 0.22	30%H2O2		–	3.5 ± 1.29	0.086 ± 0.031	Scotland, UK	Catarino et al., 2018
Mytilus edulis	Wild	–	30%H2O2	Fiber	–	1.10–6.40	0.70–2.90	United Kingdom	Li, Green, et al., 2018
Mytilus edulis	Farmed	–	30%H2O2	Fiber	–	5.50	0.90	United Kingdom	Li, Green, et al., 2018
Mytilus galloprovincialis	Wild	4.67 ± 0.72	30%H2O2	Fragment	PET	0.80 ± 0.20	5.30 ± 0.50	Greece	Digka et al., 2018
Mytilus edulis	–	–	HNO3	Pellet	–	–	138.00	–	Murphy, 2018
Perna perna	–	–	HNO3	Pellet	–	–	77.12	–	Murphy, 2018
Mytilus edulis	Wild	–	10%KOH	Fragment	PET and PP	0.61 ± 0.56	–	French Atlantic coasts	Phuong et al., 2018a
Mytilus edulis	–	–	Enzyme	Fiber	–	–	1.05–4.44	UK	Courtene-Jones et al., 2017

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Table 1 (*continued*)

Species	Wild/ farmed	Bivalve size (cm)	Extraction method	Major type of microplastics	Polymer types	Concentration (per ind)	Concentration (per g)	Location	References
Perna perna	Wild	4.30 ± 0.99	69%HNO3	Fibres	–	Present	Present	Santos estuary, Brazil	Santana et al., 2016
Mytilus edulis	Wild	–	30%H2O2	Fiber	–	2.70	4.60	China	Li et al., 2016
Mytilus edulis	Farmed	–	30%H2O2	Fiber	–	1.60	3.30	China	Li et al., 2016
Mytilus galloprovincialis	Farmed	4.65 ± 0.25	30%H2O2	Fiber and fragment	–	5.00	2.50 ± 1.50	Shanghai, China	Li et al., 2015
Mytillus galloprovincialis	Wild	4.80 to 7.10	69% HNO3	Fiber, particle	–	–	0.12 ± 0.04	Italy, Portugal, Spain	Vandermeersch et al., 2015
Mytilus edulis	Wild	4.00 to 4.50	69%HNO3	–	–	–	0.20 ± 0.30	French, Belgian and Dutch North Sea coast	Van Cauwenberghe et al., 2015
Mytilus edulis	Farmed	5.20 ± 0.40	69%HNO3	Particles	–	–	0.36 ± 0.07	North Sea, German	Van Cauwenberghe & Janssen, 2014
Mytilus edulis	Farmed	7.00	30%H2O2	Fibres	–	178.00	–	Nova Scotia's Eastern Shore	Mathalon & Hill, 2014
Mytilus edulis	Wild	7.00	30%H2O2	Fibres	–	126.00	–	Nova Scotia's Eastern Shore	Mathalon & Hill, 2014

Species	**Wild/ farmed**	**Bivalve size (cm)**	**Extraction method**	**Major type of microplastics**	**Polymer types**	**Concentration (per ind)**	**Concentration (per g)**	**Location**	**References**
Oysters									
Crassostrea virginica	Wild	6.50 to 8.80	10% KOH	Fragment	PET, PS, and PP	0.13	0.01	New York	Minder et al., 2023
Crassostrea brasiliana	Wild	5.70 to 6.60	10%KOH	Fibres	Polymethyl methacrylate	–	0.80 to 44.10	estuary system in Brazil	Ribeiro et al., 2023
Crassostrea tulipa	Wild	4.60 to 10.60	10%KOH	Fibres	PET	1.40 to 3.40	0.34 to 1.70	Gulf of Guinea, Ghana	Addo et al., 2022
Crassostrea gigas	Farmed	–	10%KOH	Fibres	Polyester and PVC	1.20 to 3.30	0.30 to 3.00	Qingdao, China	Ding et al., 2021
Crassostrea gigas	Farmed	–	30% H 2 O2	Fiber, shard, irregular, spheroid	–	0.69 to 3.00	0.02 to 0.30	Salish Sea, USA	Martinelli et al., 2020
Ostrea denselamellosa	Farmed	–	10% KOH, 30%H 2 O 2	Fiber	Cellulose and PP	1.67 ± 0.44	0.31 ± 0.10	Xiangshan Bay, China	Wu et al., 2020
Crassostrea virginica	Wild	–	30% H 2 O2	–	–	8.75	–	Southern Gulf of St. Lawrence	McGrath, 2020
Crassostrea gigas	Wild	12.54	10% KOH	Fiber	–	10.95 ± 0.77	0.35 ± 0.04	Oregon, USA	Baechler et al., 2020
Magallana bilineata	Wild	2.00 to 16.00	10% KOH	Fiber	PET and PP	6.90 ± 3.80	0.81 ± 0.45	Gulf of Mannar, India	Patterson et al., 2019
Crassostrea gigas	Farmed	10.65 ± 1.36	10% KOH	Fiber, fragment, spherule	–	0.22 ± 0.28	0.04 ± 0.06 (items/ g. dw)	Canada	Covernton et al., 2019
Crassostrea gigas	Wild	–	Lipase, protease	Fragment, fiber	PET	–	1.13 ± 0.84	Southern part of South Korea	Jang et al., 2020
Crassostrea hongkongensis	Wild	–	10%KOH	Fiber, flake, foam, fragment	Rayon and polyester	4.70 ± 0.30	0.80 ± 0.20	Maowei Sea, China	Zhu et al., 2019
Crassostrea spp.	Farmed	6.12 ± 0.97	10%KOH	Fibres	PET	1.52 ± 1.06	0.26 ± 0.29	Dandong, China	Teng et al., 2019
Crassostrea spp.	Farmed	9.88 ± 0.68	10%KOH	Fibres	PET	4.12 ± 6.05	0.83 ± 1.29	Dalian, China	Teng et al., 2019
Crassostrea spp.	Farmed	11.26 ± 1.31	10%KOH	Fibres	PET	1.95 ± 1.84	0.14 ± 0.16	Jinzhou, China	Teng et al., 2019
Crassostrea spp.	Farmed	8.20 ± 0.90	10%KOH	Fibres	PET	4.00 ± 2.25	0.33 ± 0.21	Qinhuangdao, China	Teng et al., 2019
Crassostrea spp.	Farmed	9.43 ± 2.59	10%KOH	Fibres	PET	1.46 ± 1.41	0.19 ± 0.22	Tianjin, China	Teng et al., 2019
Crassostrea spp.	Farmed	6.94 ± 1.10	10%KOH	Fibres	PET	1.67 ± 1.24	0.21 ± 0.20	Changdao, China	Teng et al., 2019
Crassostrea spp.	Farmed	5.80 ± 0.99	10%KOH	Fibres	PET	1.96 ± 1.43	0.42 ± 0.40	Qingdao, China	Teng et al., 2019
Crassostrea spp.	Farmed	8.61 ± 0.94	10%KOH	Fibres	PET	2.63 ± 2.28	0.25 ± 0.24	Lianyungang, China	Teng et al., 2019
Crassostrea spp.	Farmed	4.45 ± 1.33	10%KOH	Fibres	PET	1.67 ± 1.17	0.77 ± 0.91	Nantong, China	Teng et al., 2019
Crassostrea spp.	Farmed	–	10%KOH	Fibres	PET	1.50 ± 1.25	0.19 ± 0.19	Ningbo, China	Teng et al., 2019
Crassostrea spp.	Farmed	4.50 ± 0.91	10%KOH	Fibres	PET	3.12 ± 2.33	1.32 ± 1.22	Wenzhou, China	Teng et al., 2019
Crassostrea spp.	Farmed	5.91 ± 0.55	10%KOH	Fibres	PET	5.19 ± 2.59	1.42 ± 0.68	Putian, China	Teng et al., 2019
Crassostrea spp.	Farmed	4.44 ± 0.67	10%KOH	Fibres	PET	5.63 ± 2.45	2.35 ± 1.39	Xiamen, China	Teng et al., 2019
Crassostrea spp.	Farmed	8.24 ± 0.71	10%KOH	Fibres	PET	1.05 ± 1.03	0.12 ± 0.11	Shantou, China	Teng et al., 2019

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Table 1 (*continued*)

Species	Wild/ farmed	Bivalve size (cm)	Extraction method	Major type of microplastics	Polymer types	Concentration (per ind)	Concentration (per g)	Location	References
Crassostrea spp.	Farmed	6.74 ± 0.87	10%KOH	Fibres	PET	9.08 ± 5.70	1.00 ± 0.72	Shenzhen, China	Teng et al., 2019
Crassostrea spp.	Farmed	10.02 ± 1.07	10%KOH	Fibres	PET	1.50 ± 1.22	0.11 ± 0.10	Zhanjiang, China	Teng et al., 2019
Crassostrea spp.	Farmed	4.67 ± 0.90	10%KOH	Fibres	PET	1.84 ± 1.75	0.70 ± 1.05	Beihai, China	Teng et al., 2019
Crassostrea gigas	–	8.68 ± 0.14	10%KOH	Fiber	PET	–	1.48 ± 0.02	Bizerte, Tnisia	Abidli et al., 2019
Crassostrea gigas	Farmed	–	10%KOH	Fragment	Acrylic and PET	0.77	0.07	South Korea	Cho et al., 2019
Crassostrea virginica	Wild	6.33 ± 1.74	30%H2O2	Fiber	PET	16.50	3.84 ± 3.39	Florida estuary	Waite et al., 2018
Crassostrea gigas	Wild	8.30 ± 0.45	30% H 2 O2	Filament, fragment	–	–	0.11	Gulf of La Spezia, Italy	Bonello et al., 2018
Saccostrea cucullata	Wild	–	10%KOH	Fiber	PET	1.4–70	1.50 to 7.20	Pearl River Delta, China	Li et al., 2018b
Crassostrea gigas	–	–	HNO3	Pellet	–	–	39.20	–	Murphy, 2018
Pinctada radiata	–	6.90 ± 0.65	30%H2O2	Fiber	PET, PS and nylon	3.9 ± 0.8	0.10	Bandar lengeh, Persian Gulf	Naji et al., 2018
Saccostrea forskalii	Wild	–	69%HNO3	Fiber	Polyamide Nylon	–	0.37–0.57	Chonburi, Thailand	Thushari et al., 2017
Crassostrea gigas	Wild	–	10%KOH	Fragment	PET and PP	2.10 ± 1.70	–	French Atlantic coasts	Phuong et al., 2018a
Alectryonella plicatula	Farmed	8.40 ± 0.58	30%H2O2	Pellet and fiber	–	10.00	6.00 ± 1.50	Shanghai, China	Li et al., 2015
Crassostrea gigas	Farmed	–	10%KOH	Fibres	–	0.60 ± 0.90	–	Half Moon Bay, California, USA	Rochman et al., 2015
Crassostrea gigas	Farmed	9.00 ± 0.50	69%HNO3	Particles	–	–	0.47 ± 0.16	Brittany, France	Van Cauwenberghe & Janssen, 2014
Species	**Wild/ farmed**	**Bivalve size (cm)**	**Extraction method**	**Major type of microplastics**	**Polymer types**	**Concentration (per ind)**	**Concentration (per g)**	**Location**	**References**
Clams									
Mercenaria mercenaria	Wild	6.50 to 8.80	10% KOH	–	–	undetectable	undetectable	New York	Minder et al., 2023
Anomalocardia flexuosa	Wild	2.54 ± 0.31	10% KOH	Fiber	Polyolefins	0.79 ± 0.90	1.20 ± 2.00	Hong Kong	Lam et al., 2023
Anomalocardia squamosa	Wild	2.63 ± 0.28	10% KOH	Film	Polyolefins	1.89 ± 2.93	1.51 ± 1.71	Hong Kong	Lam et al., 2023
Atactodea striata	Wild	3.19 ± 0.18	10% KOH	Fiber	Polyolefins	0.90 ± 0.30	0.80 ± 2.0	Hong Kong	Lam et al., 2023
Meretrix lyrata	Wild	3.18 ± 0.42	10% KOH	Fiber	Polyolefins	0.79 ± 0.90	0.80 ± 1.10	Hong Kong	Lam et al., 2023
Venerupis philippinarum	Wild	2.89 ± 0.21	10% KOH	Fiber	Polyolefins	0.79 ± 0.90	1.30 ± 1.50	Hong Kong	Lam et al., 2023
Meretrix lyrata	Wild	3.60 ± 0.40	10% KOH	Fiber	Polyester, PET and PP	12.73 ± 4.49	4.71 ± 2.15	Han River Estuary, Vietnam	Tran-Nguyen et al., 2023
Meretrix lyrata	Wild	3.80 ± 0.40	10% KOH	Fiber	Polyester, PET and PP	13.20 ± 7.66	5.36 ± 2.69	Cu De River Estuary, Vietnam	Tran-Nguyen et al., 2023
Paratapes undulatus	Wild	3.80 ± 0.50	10% KOH	Fiber	Polyester, PET and PP	3.43 ± 0.98	2.17 ± 0.43	Han River Estuary, Vietnam	Tran-Nguyen et al., 2023
Paratapes undulatus	Wild	3.50 ± 0.70	10% KOH	Fiber	Polyester, PET and PP	3.30 ± 0.94	2.38 ± 1.28	Cu De River Estuary, Vietnam	Tran-Nguyen et al., 2023
Ruditapes philippinarum	Farmed	4.07 ± 0.40	10% KOH	Circularity	PS	2.70 ± 1.66	15.64 ± 9.25	South Korea	de Guzman et al., 2022
Ruditapes philippinarum	Farmed	5.12 ± 0.29	10% KOH	Circularity	PS	3.65 ± 1.95	41.63 ± 16.90	South Korea	de Guzman et al., 2022
Meretrix lyrata	Wild	2.00 to 6.00	10% KOH	Fiber	–	3.60 ± 2.10	2.70 ± 2.40	Ho Chi Minh, Vietnam	Kieu-Le et al., 2022
Mactra veneriformis	Wild	3.29 ± 0.46	10% KOH	Fiber	Rayon	7.50 ± 4.00	2.50 ± 1.00	Nantong, China	Tang et al., 2022
Mactra veneriformis	Wild	3.53 ± 0.25	10% KOH	Fiber	Rayon	5.50 ± 3.50	1.00 ± 0.50	Yancheng,China	Tang et al., 2022
Mactra veneriformis	Wild	3.66 ± 0.30	10% KOH	Fiber	Rayon	8.50 ± 3.50	5.00 ± 4.00	Lianyungang, China	Tang et al., 2022
Ruditapes philippinarum	Wild	3.69 ± 0.21	10% KOH	Fiber	Rayon	4.50 ± 1.00	2.00 ± 0.60	Nantong, China	Tang et al., 2022
Ruditapes philippinarum	Wild	3.91 ± 0.43	10% KOH	Fiber	Rayon	5.00 ± 1.00	2.10 ± 0.50	Yancheng,China	Tang et al., 2022

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Species	Wild/ farmed	Bivalve size (cm)	Extraction method	Major type of microplastics	Polymer types	Concentration (per ind)	Concentration (per g)	Location	References
Ruditapes philippinarum	Wild	3.72 ± 0.20	10% KOH	Fiber	Rayon	7.00 ± 1.50	4.00 ± 1.50	Lianyungang, China	Tang et al., 2022
Meretrix pethechialis	Wild	3.98 ± 0.58	10% KOH	Fiber	Rayon	4.50 ± 2.00	0.80 ± 0.50	Nantong, China	Tang et al., 2022
Meretrix pethechialis	Wild	4.39 ± 0.43	10% KOH	Fiber	Rayon	4.40 ± 2.00	0.50 ± 0.30	Yancheng,China	Tang et al., 2022
Meretrix pethechialis	Wild	4.41 ± 0.47	10% KOH	Fiber	Rayon	7.30 ± 2.50	4.00 ± 3.50	Lianyungang, China	Tang et al., 2022
Cyclina sinensis	Wild	4.09 ± 0.76	10% KOH	Fiber	Rayon	4.50 ± 1.50	0.50 ± 0.10	Nantong, China	Tang et al., 2022
Cyclina sinensis	Wild	4.01 ± 0.73	10% KOH	Fiber	Rayon	4.30 ± 1.00	0.60 ± 0.10	Yancheng,China	Tang et al., 2022
Cyclina sinensis	Wild	3.99 ± 0.73	10% KOH	Fiber	Rayon	6.00 ± 2.00	1.50 ± 0.30	Lianyungang, China	Tang et al., 2022
Katelysia hiantina	Wild	–	69%HNO3	Filament/fiber	PP and rayon	5.89 ± 4.23	–	Panguil Bay, Philippines	Bonifacio et al., 2022
Meretrix meretrix	Wild	–	69%HNO3	Filament/fiber	PP and rayon	4.16 ± 2.86	–	Panguil Bay, Philippines	Bonifacio et al., 2022
Donax sp.	Wild	–	69%HNO3	Filament/fiber	Polypropylene and rayon	2.41 ± 1.47	–	Panguil Bay, Philippines	Bonifacio et al., 2022
Scrobicularia plana	Wild	4.50 ± 0.33	10% KOH	Fiber	Polyester and PP	0.30 ± 0.63	0.07 ± 0.15	Coast of Portugal	Pequeno et al., 2021
Meretrix meretrix	Wild	2.75 to 3.4	10% KOH	Fiber and fragmen	–	–	4.60	Lemo Beach, South Sulawesi	Tamrin et al., 2021
Meretrix meretrix	Wild	3.41 to 4.21	10% KOH	Fiber and fragmen	–	–	2.46	Lemo Beach, South Sulawesi	Tamrin et al., 2021
Meretrix meretrix	Wild	4.22 to 5.24	10% KOH	Fiber and fragmen	–	–	1.53	Lemo Beach, South Sulawesi	Tamrin et al., 2021
Hiatella arctica	Wild	2.36 ± 0.21	30%H2O2	Fragment	PET	8.10 ± 1.80	–	Spitsbergen, Svalbard archipelago	Teichert et al., 2021
Ruditapes philippinarum	Farmed	–	10%KOH	Fibres	Polyester and PVC	1.20 to 3.20	4.50 to 20.10	Qingdao, China	Ding et al., 2021
Polititapes spp.	–	–	10%KOH	Fiber	PP and PS	–	10.40	Ria Formosa lagoon, southern Portugal	Cozzolino et al., 2021
Cerastoderma spp.	–	–	10%KOH	Fiber	PP and PS	–	11.90	Ria Formosa lagoon, southern Portugal	Cozzolino et al., 2021
Ruditapes decussatus	–	–	10%KOH	Fiber	PP and PS	–	18.40	Ria Formosa lagoon, southern Portugal	Cozzolino et al., 2021
Meretrix lyrata	Wild	2.65 ± 0.03	30%H2O2	Fibres	Royan, PP and PET	0.67 ± 0.15	0.28 ± 0.06	Bandon Bay, Thailand	Chinfak et al., 2021
Meretrix lyrata	Wild	4.81 ± 0.05	30%H2O2	Fibres	Royan, PP and PET	0.23 ± 0.09	0.03 ± 0.01	Bandon Bay, Thailand	Chinfak et al., 2021
Siliqua patula	Wild	11.39	10% KOH	Fiber	–	8.84 ± 0.45	0.16 ± 0.02	Oregon, USA	Baechler et al., 2020
Limecola balthica	Wild	–	1 M KOH	Fiber	Polyester	0.03 ± 0.03	–	Italy	Piarulli et al., 2020
Scrobicularia plana	Wild	–	1 M KOH	Fiber	Polyacrylonitrile	0.05 ± 0.05	–	Italy	Piarulli et al., 2020
Sinonovacula constricta	Farmed	–	10% KOH, 30%H 2 O 2	Fiber	PP	1.8 0 ± 0.34	0.21 ± 0.05	Xiangshan Bay, China	Wu et al., 2020
Meretrix meretrix	Wild	–	10% KOH	–	–	0.50 ± 0.11	0.18 ± 0.04	India	Dowarah et al., 2020
Donax cuneatus	Wild	1.00 to 2.00	10%KOH	Fibres	PET	1.08 ± 0.61	1.38 ± 0.49	Gulf of Mannar, India	Sathish et al., 2020
Donax cuneatus	Wild	2.00 to 3.00	10%KOH	Fibres	PET	0.89 ± 0.68	0.75 ± 0.18	Gulf of Mannar, India	Sathish et al., 2020
Donax cuneatus	Wild	>3.00	10%KOH	Fibres	PET	0.96 ± 0.63	0.60 ± 0.18	Gulf of Mannar, India	Sathish et al., 2020
Cyamiocardium denticulatum	Wild	–	1% NaOH	–	Polyphthalamide and polyarylamide	0.50	0.10 (DW)	Ross Sea	Sfriso et al., 2020
Thyasira debilis	Wild	–	1% NaOH	–	Polyphthalamide and polyarylamide	2.50	0.50 to 2.00 (DW)	Ross Sea	Sfriso et al., 2020
Meretrix meretrix		4.09 ± 0.21	10% KOH	Fiber	PET and Polyacrylonitrile	1.20 ± 0.40	0.30 ± 0.10	Xiamen, China	Fang et al., 2019
Meretrix meretrix		4.20 ± 0.17	10% KOH	Fiber	Polyacrylonitrile	0.50 ± 0.10	0.15 ± 0.05	Fuzhou, China	Fang et al., 2019
Venerupis philippinarum	Farmed	3.74 ± 3.99	10% KOH	Fiber, fragment, spherule	–	0.16 ± 0.22	0.22 ± 0.31 (items/ g. dw)	Canada	Covernton et al., 2019
Siliqua radiata	Wild	7.12 ± 0.92	30%H2O2	Fiber	–	5.00 ± 4.00	–	Hat Laem Son, Thailand	Rangseethapanya et al., 2019
Siliqua radiata	Wild	6.28 ± 0.61	30%H2O2	Fiber	–	8.00 ± 4.00	–	Hat Pakmeng, Thailand	Rangseethapanya et al., 2019
Ruditapes decussatus	–	2.51 ± 0.16	10%KOH	Fiber	Cellophane and PET	–	1.40 ± 0.20	Bizerte, Tnisia	Abidli et al., 2019
Tapes philippinarum	Farmed	–	10%KOH	Fragment	PET, PP and polyester	1.15	0.34	South Korea	Cho et al., 2019
Anomia ephippium	Wild	3.25 ± 0.54	30% H 2 O2	Filament, fragment	–	–	0.12	Gulf of La Spezia, Italy	Bonello et al., 2018

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Table 1 (*continued*)

Species	Wild/ farmed	Bivalve size (cm)	Extraction method	Major type of microplastics	Polymer types	Concentration (per ind)	Concentration (per g)	Location	References
Amiantis purpuratus	–	4.40 ± 0.24	30%H2O2	Fiber	PET, PP and nylon	6.90 ± 1.90	1.50 ± 0.15	Gelkan, Persian Gulf	Naji et al., 2018
Amiantis umbonella	–	4.40 ± 0.24	30%H2O2	Fiber	PET, PP and nylon	7.10 ± 1.60	2.90 ± 0.20	Gelkan, Persian Gulf	Naji et al., 2018
Venerupis philippinarum	Wild	44.60 ± 5.20	HNO3	Fiber	–	–	0.90 ± 0.90	Baynes Sound, British Columbia	Davidson & Dudas, 2016
Venerupis philippinarum	Farmed	40.70 ± 2.80	HNO3	Fiber	–	–	1.70 ± 1.20	Baynes Sound, British Columbia	Davidson & Dudas, 2016
Sinonovacula constricta	Farmed	6.21 ± 0.45	30%H2O2	Fiber	–	15.00	2.00 ± 1.50	Shanghai, China	Li et al., 2015
Ruditapes philippinarum	Farmed	3.36 ± 0.21	30%H2O2	Fiber and pellet	–	7.00	2.50 ± 1.50	Shanghai, China	Li et al., 2015
Meretrix lusoria	Farmed	3.49 ± 0.18	30%H2O2	Fiber	–	10.00	4.50 ± 1.50	Shanghai, China	Li et al., 2015
Cyclina sinensis	Farmed	2.82 ± 0.16	30%H2O2	Fiber and fragment	–	5.00	4.00 ± 1.50	Shanghai, China	Li et al., 2015
Species	**Wild/ farmed**	**Bivalve size (cm)**	**Extraction method**	**Major type of microplastics**	**Polymer types**	**Concentration (per ind)**	**Concentration (per g)**	**Location**	**References**
Scallops									
Chlamys farreri	Farmed	–	10%KOH	Fibres	Rayon	0.50–2.90	0.40 to 3.40	Qingdao, China	Ding et al., 2021
Argopecten purpuratus	–	7.74 ± 0.23	10%KOH	Fibres	Polyester and PP	2.25 ± 0.54	0.13 ± 0.03	Lima, Peru	De-la-Torre et al., 2019
Patinopecten yessoensis	Farmed	–	10%KOH	Fragment	PS, Polyester and PP	1.21	0.08	South Korea	Cho et al., 2019
Chlamys farreri	Farmed	6.45 ± 0.24	10% KOH	Fiber and fragment	PP	5.20 to 19.40	3.20 to 7.10	Qingdao and Dongying, China	Ding et al., 2018
Patinopecten yessoensis	Farmed	8.92 ± 0.23	30%H2O2	Fibres	–	55.00	–	Shanghai, China	Li et al., 2015
Species	**Wild/ farmed**	**Bivalve size (cm)**	**Extraction method**	**Major type of microplastics**	**Polymer types**	**Concentration (per ind)**	**Concentration (per g)**	**Location**	**References**
Cockles									
Gafrarium pectinatum	Wild	2.39 ± 0.21	10% KOH	Fiber	Polyolefins	0.79 ± 0.90	1.45 ± 2.00	Hong Kong	Lam et al., 2023
Tegillarca granosa	Wild	4.53 ± 0.42	10% KOH	Fiber	–	2.14 ± 0.36	–	Badon Bay, Thailand	Ruairuen et al., 2022
Tegillarca granosa	Wild	3.94 ± 0.34	10% KOH	Fiber	–	0.29 ± 0.06	–	Badon Bay, Thailand	Ruairuen et al., 2022
Tegillarca granosa	Wild	4.14 ± 0.61	10% KOH	Fiber	–	0.33 ± 0.04	–	Badon Bay, Thailand	Ruairuen et al., 2022
Tegillarca granosa	Wild	4.03 ± 0.07	10% KOH	Fiber	–	0.28 ± 0.05	–	Badon Bay, Thailand	Ruairuen et al., 2022
Tegillarca granosa	Wild	4.74 ± 0.26	10% KOH	Fiber	–	0.36 ± 0.06	–	Badon Bay, Thailand	Ruairuen et al., 2022
Cerastoderma glaucum	Wild	–	1 M KOH	Fragment	PP	0.01 ± 0.01	–	Italy	Piarulli et al., 2020
Cerastoderma edulis	Wild	3.52 ± 0.04	10%KOH	Fiber	PET	2.46 ± 1.16	0.74 ± 0.35	Channel coastline, France	Hermabessiere et al., 2019
Tegillarca granosa	Wild	–	10%KOH	Fragment	–	9.87–23.17	–	Semarang, Indonesia	Suprayogi, 2018
Scapharca subcrenata	Farmed	3.64 ± 0.16	30%H2O2	Fiber and fragment	–	40.00	–	Shanghai, China	Li et al., 2015
Tegillarca granosa	Farmed	2.62 ± 0.21	30%H2O2	Fiber and fragment	–	7.00	–	Shanghai, China	Li et al., 2015

PET = polyethylene terephthalate; PS = polystyrene; PP = polypropylene; – = no data.

et al., 2019). However, contradictory results have been documented in some studies, where significantly higher MP concentrations were reported in oysters (Abidli et al., 2019; Phuong et al., 2018; Van Cauwenberghe & Janssen, 2014) or clams (Ding et al., 2021; Naji et al., 2018) than in mussels. Therefore, more studies are required to confirm MP accumulation trends in different bivalves.

Many studies have shown that smaller bivalves accumulate higher concentrations of MPs than larger bivalves (Bom et al., 2022; Chinfak et al., 2021; Sathish et al., 2020; Tamrin et al., 2021; Zahid et al., 2022). For example, in the Pasir Putih Estuary, Malaysia, the MP content in small *P. viridis* (5.29 ± 0.48 cm) was 25% and 66% higher than that in medium (6.54 ± 0.29 cm) and large *P. viridis* (7.62 ± 0.40 cm) (Zahid et al., 2022). On the southeastern Brazilian coast, Bom et al. (2022) recorded a clear negative relationship between the size of *Perna perna* and the concentration of MP.s In the Tapi-Phumduang River system and Bandon Bay, Thailand, the MPs in smaller *Perna viridis* (7.74 ± 0.07 cm) and *Meretrix lyrata* (2.65 ± 0.03 cm) were 1.9 to 8.3 fold higher than that in larger one (10.49 ± 0.07 cm and 4.81 ± 0.05 cm for *Perna viridis* and *Meretrix lyrata*, respectively) (Chinfak et al., 2021). In Lemo Beach, South Sulawesi, the MP concentration (2.75–3.4 cm) in smaller *Meretrix meretrix* were 1.87 and 2.46 fold higher than those in the medium (3.41–4.21 cm) and large clams (4.22–5.24 cm) (Tamrin et al., 2021). In the Gulf of Mannar, India, Sathish et al. (2020) showed that smaller *Donax cuneatus* (1.00 to 2.00 cm) contain 1.21 to 1.84 fold higher MP content than larger one (2.00 to 3.00 cm). The higher MP content in smaller bivalves may be attributed to the fact that smaller bivalves feed more actively (higher clearance rate) to meet the higher energy demand for higher metabolisms and higher growth rate (Kreeger et al., 2018). However, some other studies did not find significant differences in MP concentrations among bivalve age groups (Cherdsukjai et al., 2022; Joshy et al., 2022), and some even documented that larger bivalves tend to accumulate more microparticles than smaller bivalves (Brate et al., 2018; de Guzman et al., 2022; Ding et al., 2018; Patterson et al., 2019). The lower MP concentration in smaller bivalves is believed to be due to smaller bivalves being unable to ingest larger MPs and therefore being exposed to a narrower range of MP sizes than larger bivalves (Patterson et al., 2019).

Many studies have shown that farmed bivalves contain much higher levels of MPs than wild ones (Anderson et al., 2016; Covernton et al., 2019; Ding et al., 2018; Mathalon & Hill, 2014; Phuong et al., 2018). For example, in Columbia, Canada, Covernton et al. (2019) reported that farmed *Venerupis philippinarum* and *Crassostrea gigas* had about 60% higher MP concentrations than their wild counterparts. In Qingdao, China, MP concentrations in farmed *Mytilus galloprovincialis* were 60–250% higher than those in the wild (Ding et al., 2018). In Halifax Harbor, Nova Scotia, Mathalon and Hill (2014) reported that farmed *Mytilus edulis* had 40% higher MP than wild *Mytilus edulis* collected from the most polluted areas. This may be due to the extensive use of plastic infrastructure and materials in bivalve farms, mainly made of polyethylene, polypropylene, polystyrene, or PVC, which potentially become a source of MP pollution (Mathalon & Hill, 2014; Zhu et al., 2019). However, some other studies did not record significant differences between wild and farmed bivalves, such as *M. edulis* on the Belgian coast (De Witte et al., 2014), *Venerupis philippinarum* in British Columbia (Davidson & Dudas, 2016), *Perna perna* in Guanabara Bay, Brazil (Brinstiel et al., 2019), *C. gigas*, *O. cucullata* and *Mytilus edulis* in Yellow Sea, China (Zhang et al., 2022), *P. viridis* in Pasir Putih Estuary, Malaysia (Zin et al., 2022). It is worth noting that a few studies reported higher MP content in wild bivalves than in farmed bivalves (Li et al., 2016). For example, in a field study covering 2/3 of the coastline of China, Li et al. (2016) reported that the concentration of MP in wild *M. edulis* was 1.69 fold higher than in farmed mussels. The authors attribute this observation to the fact that mussel farms in China are generally less affected by human activities and have high water quality.

Among MP shapes, fibres were the dominant MP shapes found in various bivalves, with MP fibres accounting for >80% of the total microplastics in *Perna viridis* collected from Sri Racha Bay, Thailand (Phaksopa et al., 2023), *Mytillus galloprovincialis* collected from Coast of Portugal (Pequeno et al., 2021), *Perna viridis* and *Mytilus edulis* collected from the coastal waters of China (Qu et al., 2018), *Venerupis philippinarum* collected from Baynes Sound, British Columbia (Davidson & Dudas, 2016) *etc.* The proportion of MP fibres in bivalves is much higher than the estimated MP fibres (around 48.5%) in ambient water and sediments (Burn and Boxall, 2018), indicating selective accumulation of MP fibres in bivalves. This observation may be attributed to the difficulty of fiber elimination from the digestive tract. The dominant polymer types of MPs in bivalves were polyester (PET), polyethylene (PE), and polypropylene (PP), with these 3 polymer types accounting for >80% of the total MPs in *Perna viridis* collected from Sri Racha Bay, Thailand (Phaksopa et al., 2023), *Mytillus galloprovincialis* and *Scrobicularia plana* collected from Portuguese coast (Pequeno et al., 2021), *Mytilus spp.* collected from Portuguese coast (Marques et al., 2021) *etc.* This is not surprising since PET, PE, and PP have been mostly produced and used in plastic bottles, food wraps and bags *etc.* over the past few decades (Suaria et al., 2020), and these polymers have also been documented as the most common MPs in aquatic environments (Browne et al., 2011a; Gago et al., 2018; White et al., 2018).

5. Impact of microplastic on marine bivalves

5.1. Impact of MPs on immunity of marine bivalves

In general, hemocytes are the main components of the innate immunity of bivalves and play an important role in phagocytosis. MP exposure has been shown to impair innate immunity of bivalves (Table 2) (*e.g.* Paul-Pont et al., 2016; Pavicic-Hamer et al., 2022; Sendra et al., 2019). For example, in *Mytilus spp.*, exposure to polymethylmethacrylate (10 and 50 μm; 0.1–10 mg/L) (Pavicic-Hamer et al., 2022) and polystyrene (2 and 6 μm; 30 mg/L) (Paul-Pont et al., 2016) has been shown to cause a significant increase in the mortality rate of hemocytes. Moreover, exposure of *Mytilus spp.* to polystyrene (50 nm, 100 nm and 1 μm; 10 mg/L) has been shown to decrease the phagocytosis capacity of hemocytes (Sendra et al., 2019). Similar observations have been documented in a laboratory experiments, where exposure of *M. galloprovincialis* hemolymph to amino polystyrene (50 nm) at concentrations ranging from 1 to 50 μg/mL for 30 min to 4 h induced a dose-dependent reduction of phagocytic activity (Canesi et al., 2015). In addition, exposure of *Mytilus spp.* to polyethylene and polystyrene MPs have been shown to cause lysosome dysfunctional through inducing lysosomal membrane destabilization (Avio et al., 2015; von Moos et al., 2012). Similar observations have been recorded in oyster *C. brasiliana* (Nobre et al., 2020) and *M. edulis* (von Moos et al., 2012), where polyethylene exposure disrupted the stability of lysosomal membranes and increased granulocytoma formation indicative of cellular damage.

Besides hemocytes, exposure to MPs also affects the antioxidant system of bivalves (Avio et al., 2015; Canesi et al., 2015; Cole et al., 2020; Nobre et al., 2020; Paul-Pont et al., 2016; Pittura et al., 2018; Revel et al., 2019; Ribeiro et al., 2017). In *Mytilus sp.*, exposure to polystyrene (Cole et al., 2020; Paul-Pont et al., 2016), polyethylene (Pittura et al., 2018), and polypropylene (Revel et al., 2019) MPs caused a dose-dependent increase in superoxide dismutase (SOD) and catalase (CAT) activity, a means of modulating cellular oxidative balance in response to increased production of reactive oxygen species (ROS) (Canesi et al., 2015). Similar observations have been documented in clam *Scrobicularia plana*, where 2 weeks of polystryrene exposure (20 μm; 1 mg/L) triggered substantial modulation of cellular oxidative balance (elevation of SOD in gills), indicative of oxidative damage, DNA damage, and neurotoxicity (Ribeiro et al., 2017). However, these results differ from those reported by Nobre et al. (2020), where exposure of oyster *C. brasiliana* to polyethylene MP (150–250 μm; 250 mg/L) did not cause significant changes in oxidative stress and induced inhibition of antioxidant enzymes, especially glutathione S-transferase (GST) and

Table 2
Impact of microplastics on the immunity of marine bivalves.

Species	Size (cm)	Exposure time (day)	Concentration (MP/L)	MP (type)	MP (μm)	Type of polymers	Observation	References
Mussels								
Mytilus galloprovincialis	–	3	0.1–10 mg/L	–	10 and 50	Polymethylmethacrylate	Increase the total haemocytes count in haemolymph, and significantly reduce cell viability	Pavicic-Hamer et al., 2022
Mytilus sp.	~1.00	294	15 to 15,000 particles/ individual/week	Microbeads	40	PVC	Microplastics pose only a minor threat to blue mussel	Hamm & Lenz, 2021
Mytilus edulis	~5.00	7	20 particles/mL	Microbeads	1 to 75	PVC	No significant effects on CAT, neutral red retention, lysosomal membrane stability, Metallothionein isoform 20 and pyruvate kinase	Li et al., 2020
Mytilus sp.	~6.00	7	500 ng/mL	Microfibres	20	PS	Alter granulocyte/hyalinocyte ratios and increased SOD activity, dicative of a heightened immune response.	Cole et al., 2020
Mytilus edulis	–	52	25 mg/L	Fragments	65.6 and 102.6	PLA and PET	Filtration ability decreased, byssal threads and attachment strength impaired; hemolymph proteome changed.	Green et al., 2019
Mytilus galloprovincialis immune cells	3.63 ± 0.33	3 h	10 mg/L	–	50 nm, 100 nm and 1 μm	PS	Reduced phagocytic capacity of hemocytes	Sendra et al., 2019
Mytilus spp.	5.00 to 6.00	10	0.008, 10 and 100 μg/L	–	<400	PET and PP	Significant increases in superoxide dismutase (SOD) and catalase (CAT) activities	Revel et al., 2019
Perna perna	–	90	0.125	Microbeads	0.1 to 1	PVC	No significant effects.	Santana et al., 2018
Mytilus galloprovincialis	6.00 ± 1.00	28	10 mg/L	Micro powders	20–25	PET	Nagetively affect immune system but less effect on oxidative system	Pittura et al., 2018
Mytilus galloprovincialis	4.10 ± 0.90	18	460 MP/ml	Microbeads	–	–	Disruption of mussel global homeostasis resulting in the production of stress and immune-related proteins and as a consequence, a diminution of energy allocated to growth.	Detree & Gallardo-Escarate, 2018
Mytilus edulis	4.82 ± 0.83	52	800 μg/L	Fragments	65.6 and 102.6	PLA and PET	Alteration of immunological profiles (up-regulation of C1qDC protein family, galectin-2 and apextrin) of haemolymph	Green et al., 2018
Dreissena polymorpha	–	6	5 × 105 and 2.0 × 106 items/L	–	1 and 10	PS	Accumulation of microplastic in the gut lumen and hemolymph; dopamine concentration increased	Magni et al., 2018
Mytilus spp.	5.86 ± 0.96	7	30 mg/L	Microbeads	2 and 6	PS	Increase in hemocyte mortality and triggered substantial modulation of cellular oxidative balance: increase in reactive oxygen species production in hemocytes and enhancement of anti-oxidant and glutathione-related enzymes in mussel tissues.	Paul-Pont et al., 2016
Mytilus galloprovincialis	4.00 to 5.00	30 min to 4 h (hemolyph)	1 to 50 μg/ml	–	50 nm	Amino polystyrene	Dose dependent decrease in phagocytic activity and increase in lysozyme activity, but increase in extracellular ROS and NO production.	Canesi et al., 2015
Mytilus galloprovincialis	5.00 ± 1.00	6	0.5 to 50 μg/ L		<100	PET and PS	Decrase granulocytes: hyalinocytes ratio, hemocytes lysosomal membrane stability, but increase DNA tail, nucrlear alteration	Avio et al., 2015
Mytilus edulis	–	4	2.5 g/ L	Grains	<80	PET	Formation of granulocytomas after 6 h and lysosomal membrane destabilization	von Moos et al., 2012
Species	**Size (cm)**	**Exposure time (day)**	**Concentration (MP/L)**	**MP (type)**	**MP (μm)**	**Type of polymers**	**Observation**	**References**
Oysters								

(*continued on next page*)

Table 2 (*continued*)

Species	Size (cm)	Exposure time (day)	Concentration (MP/L)	MP (type)	MP (μm)	Type of polymers	Observation	References
Crassostrea brasiliana	–	7	250 mg/L	Microspheres	150–250	PET	Significantly decrease the level of GST, GPx, DNA damage,	Nobre et al., 2020
Crassostrea virginica	–	2	50 μg/L	Microbeads	0.5 and 3	PS	Microplastic accumulated in hepatopancreas cells; nanoparticles showed potential for bioreactivity and sublethal impacts.	Gaspar et al., 2018
Crassostrea virginica	–	2	50 ppb	Microbeads	0.5 and 3 μm	PS	did not cause any significant toxicity (acute or sublethal)	Gaspar et al., 2018
Clams								
Scrobicularia plana	3.80 ± 0.50	14	1 mg/L	Microspheres	20	PS	Induce effects on antioxidant capacity, DNA damage, neurotoxicity and oxidative damage.	Ribeiro et al., 2017
Scrobicularia plana	3.80 ± 0.50	14	1 mg/L	–	20	–	Microplastics induce effects on antioxidant capacity, DNA damage, neurotoxicity and oxidative damage	Ribeiro et al., 2017

PET = polyethylene terephthalate; PS = polystyrene; PP = polypropylene; PVC = polyvinylchloride; PLA = Polylactic acid; – = no data.

glutathione peroxidase (GPx). The discrepancy may be due to the size of MP particles used in this study (150–250 μm) being much larger than that in other studies (0.5–25 μm), or the ability of bivalves to tolerate MP is species-specific.

At the molecular level, a number of transcriptional and gene expression studies provide evidence that MPs negatively affects the immunity of bivalves (Capolupo et al., 2018; Detree & Gallardo-Escarate, 2018; Green et al., 2019). For example, Capolupo et al. (2018) exposed *M. galloprovincialis* larvae to polystyrene (3 μm; 50–10,000 particles/mL) for 24 h. Upregulation of genes involved in immunomodulation indicating a modulation of redox balance to counteract the increased ROS production. Similar observations have been documented in *M. edulis*, where exposure to polyethylene MP (102.6 μm; 800 μg/L) for 52 days resulted in up-regulation of genes related in immunity, especially the C1q-domain-containing (C1qDC) protein family, galectin-2, and apextrin (Green et al., 2019). However, these results differ from those reported by Pittura et al. (2018) and Gaspar et al. (2018), where transcriptional studies revealed that polyethylene (20–25 μm; 10 mg/L) and polystyrene MP (0.5–3 μm) exposure for 28 days induced only mild cellular toxicity to *M. galloprovincialis* and *Crassostrea virginica*, respectively. We do not rule out the possibility that the contrasting responses may be related to the acclimation of bivalves to MPs, depending on exposure history. In fact, Detree and Gallardo-Escarate (2018) have shown that after a second exposure of *M. galloprovincialis* to microbeads (460 MP/mL), the expression of genes related to immune and stress responses was down-regulated in the digestive gland, indicative of bivalves being able to acclimate to MPs.

5.2. *Impact of MPs on feeding behaviour and reproduction of marine bivalves*

There is no general agreement on the effects of MP exposure on the feeding behaviour of bivalves (Table 3). Many studies have shown decreased clearance rate in bivalves in response to MP exposure (Alexander et al., 1994; Bacon et al., 1998; Grant & Thorpe, 1991; Green et al., 2017, 2019; Rist et al., 2016; Ward & Macdonald, 1996; Wegner et al., 2012; Xu et al., 2017). For example, Green et al. (2019) and Green et al. (2017) documented that exposure of *M. edulis* to polylatic acid and high density polyethylene (65.6 and 102.6 μm; 25 mg/L) caused a significant reduction in filtration rate. Similar observations have also been reported by Xu et al. (2017) and Rist et al. (2016), in which exposure of *Atactodea striata* and *Perna perna* to polystyrene (up to 500 μm; 1000 items/L) and polyvinylchloride (1–50 μm; 2160 mg/L) caused more than a 2 fold reduction in clearance rate. However, a few studies have not recorded significant changes in the clearance rate of bivalves when exposed to MPs (Cole & Galloway, 2015; Gardon et al., 2018; Green, 2016; Hamm et al., 2022; Revel et al., 2019; Walkinshaw et al., 2023). It is worth noting that Green et al. (2017) reported that exposure of *Ostra edulis* to polylactic acid and polyethylene MPs (65.6–102.6 μm; 2.5–25 μg/L) caused an increase in filtration rate and pseudofaeces production.

In terms of nutrient absorption and assimilation, most studies have demonstrated that MP exposure reduces the efficiency of nutrient assimilation and reduces the overall energy budget (*e.g.* Bour et al., 2018; Gardon et al., 2018; Shang et al., 2021). For example, Shang et al. (2021) have shown that exposure of *M. corucus* to (10^4–10^6 particles/L) caused increased cellular energy demands and depleted carbohydrates, lipids, and proteins stores. Gardon et al. (2018) found that although the present of polystyrene (6 and 10 μm; 0.25–25 μg/L) did not affect the ingestion rate of *Pinctada margaritifera*, it caused a significant negative effect on the assimilative efficiency of oyster in a dose-dependent manner. Similar observations have also been documented by Bour et al. (2018), in which large MPs entangled in the digestive tracts of *Ennucula tenius* and *Abra nitida*, and significantly reduced the efficiency of nutrient absorption. However, these results differ from those reported by Sussarellu et al. (2016), in which two months exposure of *Crassostrea gigas* to polystyrene microspheres (2 and 6 μm; 0.023 mg/L) increased nutrient assimilation efficiency, indicative of a compensatory effect in response to digestive interference caused by MPs. Surprisingly, mussels have high toleration to MPs, with exposure to high concentrations of MPs (up to 150 mg/L) not significantly affecting the overall energy budget (Gonçalves et al., 2018; Hamm & Lenz, 2021; Li et al., 2020; Van Cauwenberghe et al., 2015; Yap et al., 2020).

Decreased feeding rates and assimilation efficiency in most bivalves result in disruption of energy flow, reducing energy allocation for reproduction to maintain normal maintenance and growth (Bour et al., 2018; Gardon et al., 2018; Pandey et al., 2022; Sussarellu et al., 2016; Xu et al., 2017). For example, in *C. gigas*, exposure to polystyrene has been shown to negatively affect the quality of oocytes, quantity of egg production, and the motility of sperm (Pandey et al., 2022). In *Abra nitida*, exposure to MPs has been shown to impair clam reproduction by causing alterations in energy reserve, especially a reduction in protein content (Bour et al., 2018). In *Pinctada margaritifera* (Gardon et al., 2018) and *Atactodea striata* (Xu et al., 2017), exposure to polystyrene MPs caused a dose dependent negative impact on reproduction through reducing nutrient intake or absorption. Similarly, in *Crassostrea gigas*, results from dynamic energy budget modeling revealed that exposure of oysters to

Table 3
Impact of microplastics on the physiology of marine bivalves.

Species	Size (cm)	Exposure time (day)	Concentration (MP/L)	MP (type)	MP (μm)	Type of polymers	Observation	References
Mussels								
Mytilus sp.	~1.00	94	8 and 80 items/L	Microfibres	149	Polyester	Decreased in growth rate by 35.6%, but has no significant impact on mortality, respiration rates or clearance rates	Walkinshaw et al., 2023
Mytilidae	–	42	1.5, 15 and 150 mg/L	–	–	Polymethyl Methacrylate and PVC	Significantly affect respiration rate, byssus production and condition index of the animals, but no effects on clearance rate and survival	Hamm et al., 2022
Mytilus sp.	~1.00	294	15 to 15,000 particles/individual/week	Microbeads	40	PVC	Microplastics pose only a minor threat to blue mussel	Hamm & Lenz, 2021
Mytilus corucus	7.95 ± 0.32	14	5.69 × 109 particles/mL	Microspheres	2	PS	Increased cellular energy demand and depleted carbohydrates, lipids and proteins stores	Shang et al., 2021
Mytilus galloprovincialis	–	35	1.5, 15, 150 mg/L	Microbeads	12–14	PVC	No difference in byssus production, respiration and survival rates	Yap et al., 2020
Mytilus edulis	–	52	25 mg/L	Fragments	65.6 and 102.6	PLA and PET	Filtration ability decreased, byssal threads and attachment strength impaired; hemolymph proteome changed.	Green et al., 2019
Mytilus galloprovincialis	larvae	1	50–10,000 particles /mL	Microspheres	3	PS	Upregulation of genes involved in shell biogenesis and immunomodulation and inhibition of lysosomal enzymes	Capolupo et al., 2018
Mytilus edulis	4.82 ± 0.83	52	800 μg/L	Fragments	102.6	PET	Reduced the number of byssal threads produced and the attachment strength (tenacity) by ~50%.	Green et al., 2018
Perna perna	–	90	0.125	Microbeads	0.1 to 1	PVC	No significant effects.	Santana et al., 2018
Mytilus edulis	4.79 ± 0.06	50	2.5 and 25 μg/L	–	65.6 and 102.6	PLA and PET	Decreased filtration rate	Green et al., 2017
Perna perna	3.50 to 4.00	44	up to 2160 mg/L	–	1–50	PVC	Impairment of the mussels' physiological performance (clearance rates, respiration rates and byssus production)	Rist et al., 2016
Mytilus edulis		14	10 items/L	Microbeads	10 to 90	PS	Respiration increased; no significant effects on overall energy budget.	Van Cauwenberghe et al., 2015
Mytilus edulis	–	8 h	0.1 to 0.3 g/L	Microbeads	30	PS	Production of pseudo-faeces; filtering activity reduced	Wegner et al., 2012
Species	**Size (cm)**	**Exposure time (day)**	**Concentration (MP/L)**	**MP (type)**	**MP (μm)**	**Type of polymers**	**Observation**	**References**
Oysters								
Pinctada margaritifera	–	60	0.25, 2.5, 25 μg/L	Microbeads	6 and 10	PS	Significant dose-dependent negative impact on the assimilation efficiency and more broadly the energy balance, with negative repercussions on reproduction	Gardon et al., 2018
Ostrea edulis	7.41	60	0.8 and 80 μg/L	–	65.6 and 102.6	PLA and PET	Increased respiration rate but do not affect filtration rate and shell growth.	Green, 2016
Crassostrea gigas	–	8	1000 MP/ml	Microbeads	1 to 10	PS	No measurable effects on the development or feeding capacity of the larvae	Cole & Galloway, 2015
Crassostrea gigas	–	60	0.023 mg/L	Microbeads	2 and 6 μm	PS	Increased clearance rate and absorption efficiency, but decreased in oocyte number (−38%), diameter (−5%), and sperm velocity (−23%), as well as lower D-larval yield (−41%) and larval development (−18%)	Sussarellu et al., 2016
Ostra edulis	6.30 ± 0.16	50	2.5 and 25 μg/L	–	65.6 and 102.6	PLA and PET	Increased filtration rate and pseudofaeces production	Green et al., 2017
Ostra edulis	–	60	0.8 and 80 μg/L	–	65.6	PLA	Respiration rates increased; effects on the oysters were minimal	Green, 2016
Crassostrea gigas	–	60	0.023 mg/L	Microspheres	2 and 6	PS	Significant decreases in oocyte number (−38%), diameter (−5%), and sperm velocity (−23%). The D-larval yield and larval development of offspring derived from exposed parents decreased by 41% and 18%, respectively	Sussarellu et al., 2016
Clams								
Ennucula tenuis	–	28	1; 10 and 25 mg/kg of sediment	–	4–6; 20–25 and 125–500	–	Decreased energy reserves	Bour et al., 2018
Abra nitida	–	28	1; 10 and 25 mg/kg of sediment	–	4–6; 20–25 and 125–500	–	Decreased in protein content	Bour et al., 2018

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Table 3 (*continued*)

Species	Size (cm)	Exposure time (day)	Concentration (MP/L)	MP (type)	MP (μm)	Type of polymers	Observation	References
Abra nitida	–	21	1, 10 and 25 mg/kg	Microbeads	–	–	Energy reserves significantly changed; protein content decreased under exposure of the largest particles	Bour et al., 2018
Atactodea striata	–	10	10 and 1000 items/L	Microbeads	up to 500	PS	Clearance rate decreased at high concentrations; energy allocation to growth and reproduction was affected.	Xu et al., 2017
Scallops								
Pinctada margaritifera	–	60	0.25, 2.5 and 25 μg/L	Microbeads	6 and 10	PS	Assimilation efficiency inhibited; negative repercussions on reproduction	Gardon et al., 2018

PET = polyethylene terephthalate; PS = polystyrene; PP = polypropylene; PVC = polyvinylchloride; PLA = Polylactic acid; – = no data.

polystyrene microspheres (2 and 6 μm; 23 μg/L) for 8 weeks caused alteration of proteins in oocytes and expression of genes involved in gamete differentiation and manuturation, reducing sperm mobility by 23%, as well as decreasing fertility, oocyte number, and diameter by 41%, 38% and 5%, respectively (Sussarellu et al., 2016). As a result, the survival of oyster D-larvae and the growth of oyster larvae decreased by about 41% and 18%, respectively (Sussarellu et al., 2016).

5.3. *Impact of MPs on survival and burrowing behaviour and byssus production of marine bivalves*

In general, most studies revealed that exposure of bivalves to MPs did not significantly affect the growth and survival of bivalves (*e.g.* Bour et al., 2018; Hamm et al., 2022; Hamm & Lenz, 2021; Santana et al., 2018) (Table 3), with the exception of Walkinshaw et al. (2023), who reported that exposure of *Mytilus sp.* to polyester (149 μm; 80 items/L) caused a 35.6% reduction in growth rate but did not cause mortality. Caution through, these data were derived from laboratory experiments which may underestimate the impact of MPs on the survival of bivalves in natural environments. In the natural environment, the survival of mussels largely depends on their ability to hide from predators through burrowing in the sediment, as well as to form firm attachments (byssus threads) to withstand waves and currents.

Burrowing behaviour is an important avoidance response in bivalves to evade predators. Despite the importance of bivalve burrowing behaviour, the effects of MPs on burrowing behaviour of bivalves have not been well studied. To date, there is only one report on the effect of MPs on burrowing behaviour of bivalves, in which the authors did not observe any significant changes in burrowing behaviour of *Ennucula tenuis* and *Abra nitida* exposed to three sizes (4–6; 20–25 and 125–500 μm) of polyethylene MPs for four weeks (Bour et al., 2018). Similar observations have been documented in other shellfish, where environmentally relevant levels of MPs did not affect the burrowing behaviour of gastropod *Littorina littorea* (Doyle et al., 2020). It is obvious that more studies are required to confirm the effect of MP exposure on the burrowing behaviour of shellfish, especially bivalves.

In addition to burrowing behaviour, the production of byssus threads is another important indicator of the ability of bivalves, especially mussels, to survive in their natural environment. In general, many studies have demonstrated negative effects of MPs on the production of byssus threads (Green et al., 2019; Hamm et al., 2022; Rist et al., 2016). For example, Hamm et al. (2022) conducted a 6 weeks laboratory experiment to evaluate the impact of polymethyl methacrylate and polyvinyl chloride MPs (1.5–150 mg/L) on *M. galloprovincialis*, *M. trossulus* and *M. edulis*. It was found that the byssus production of mussels was reduced by 6–34% in a dose dependent manner. Similar observations were documented by Green et al. (2019), in which exposure of *Mytilus edulis* to fragmented polylatic acid (65.6 μm; 25 mg/L) and polyethylene (102.6 μm; 25 μg/L) for 52 days caused a reduction of the production and strength of byssal threads. When exposed to high concentrations of polylactic acid (65.6 μm; 800 μg/L) and polyethylene (102.6 μm; 800 μg/L), the strength and production of *M. edulis* byssal threads decreased by ~50% (Green et al., 2018). In the Asian green mussel *P. viridis*, exposure to polyvinylchloride MPs (21.6–2160 mg/L) for 44 days had a dose-dependent negative effect on byssus production (Rist et al., 2016). These negative effects may be attributed to the energy allocation for byssus production being used to maintain growth and essential functions of cells.

6. Discussion

Exposure of bivalves to MP particles has been shown to alter the feeding behaviour of marine bivalves, especially by reducing filtration and clearance rate, as well as reducing the energy fraction of synthesis due to reduced food uptake (*e.g.* Green et al., 2017, 2019; Rist et al., 2016; Xu et al., 2017). At the same time, MPs also induce stress and activate the immune response (release of hydrolytic enzymes and nitrogen based reactive species) in marine bivalves, thereby increasing energy demands under toxicity and stress (*e.g.* Paul-Pont et al., 2016; Pavicic-Hamer et al., 2022; Sendra et al., 2019). As the results, energy allocation is diverted from reproduction to maintain essential functions, impairing the reproduction of bivalves (*e.g.* Bour et al., 2018; Gardon et al., 2018; Pandey et al., 2022), and potentially causing a negative impact on the population dynamics of marine bivalves.

From the perspective of food security, among seafood, bivalves are an important route for human exposure to MPs, mainly due to bivalves are consumed whole. In the human body, MPs can cause health issues through physical and chemical pathways, including genotoxicity, oxidative stress, apoptosis *etc.* (Schirinzi et al., 2017; Smith et al., 2018; Wright & Kelly, 2017). Laboratory studies have shown that MPs can cause cytotoxicity to cerebral and epithelial human cells through inducing oxidative stress (Schirinzi et al., 2017). Fortunately, increased public awareness of plastic pollution has improved waste management and reduced the use of disposable plastic items, especially shopping bags (Xu et al., 2022). However, the amount of MP in the ocean will inevitably increase, as the degradation of large plastic waste will generate millions of MPs.

In the marine environment, MPs are exposed to a variety of organic pollutants, especially persistent-type polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB), which accumulate and transfer to marine life through accidental ingestion (Avio et al., 2015; Semysim et al., 2024). This is due to the fact that these organic pollutants are hydrophobic, thus selectively absorbed by compounds with similar hydrophobic nature (Avio et al., 2015; Gonzalez-Soto et al., 2019; Heskett et al., 2012; Mato et al., 2001; Pittura et al., 2018). For example, Mato et al. (2001) reported that the absorption rate of polychlorinated biphenyl on the surface of plastic particles was significantly higher than that of the surrounding seawater. This aligns with the observations of Heskett et al. (2012), who reported the presence of PAHs and PCBs in plastics found on various remote islands around the world. Another good example is provided by Avio et al. (2015), who showed that polyethylene and polystyrene MPs increase the bioavailability of organic pollutants to bivalves by transferring pyrene (a model of PAH) to the gills, digestive tissues, and haemolymph of *M. galloprovincialis*, causing genotoxic effects and inducing immunological responses. Likewise, Pittura et al. (2018) demonstrated that MPs can absorb and transfer benzo(*a*)pyrene to the tissues of *M. galloprovincialis*. Therefore, there is increasing concern about MPs in bivalves reaching humans through food chain.

Since MPs can be transferred through the food chain to consumers, depuration is an important step to reduce MP levels in marine bivalves before they are marketed. In general, bivalves have a rapid depuration efficiency for MPs, where a short depuration time of only 3 days is sufficient to reduce the MP content in the gut of bivalves by 90–100% (Christo et al., 2021; Kinjo et al., 2019; Stamataki et al., 2020) (Table 4). In fact, Woods et al. (2018) demonstrated that a 3 h depuration time could eliminate 65% of MP (0.2 μm) in the digestive tract of *Mytilus edulis*, and a 24 h depuration could completely remove MPs from *Crassostrea brasiliana* (Christo et al., 2021). However, several studies have shown that the MP depuration efficiency of bivalves is relatively low, where a 3 days depuration time can only remove <50% of the total MPs in the gut of bivalves (Al-Sid-Cheikh et al., 2018; Brinstiel et al., 2019; Van Cauwenberghe & Janssen, 2014). In scallop *Pecten maximus*, 14 and 48 days were required to completely remove 24 nm and 250 nm MPs, respectively (Al-Sid-Cheikh et al., 2018).

On the other hand, larger MP particles generally retain longer in the digestive tract than smaller MP particles, thus requiring longer depuration time to eliminate larger MP particles (Al-Sid-Cheikh et al., 2018; Brillant & MacDonald, 2000; Fernández & Albentosa, 2019; Kinjo et al., 2019). For example, in a 40 days depuration experiment of *M. galloprovincialis* ingesting MPs of 3 different sizes (1, 10, and 90 μm), Kinjo et al. (2019) recorded a clear size-dependent elimination rate of MPs, where the elimination rate of larger MPs of 10 μm and 90 μm took 4 and 7 fold longer time, respectively. In studies on sea scallops, *Pecten maximus* (Al-Sid-Cheikh et al., 2018) and *Placopecten magellanicus* (Brillant & MacDonald, 2000), larger MP particles were retained in the gut longer than smaller MP particles. However, these results differ from those reported by Fernández and Albentosa (2019), who found that in *M. galloprovincialis*, a 6 days MP depuration also showed a size-dependent elimination rate, with larger MP particles (> 10 μm) being eliminated faster than smaller ones (<10 μm). It is worth noting that many marine bivalve species have not been well studied concerning MP pollution and food security. Therefore, future surveys of MPs in these bivalves species, especially those edible species with commercial value, are highly recommended. In recent years, there is increasing evidence showing that climate change affects the physiology of marine bivalves

Table 4
Depuration efficiency of microplastics in marine bivalves.

Species	Size	Concentration (MP/L)	Depuration time (day)	MP (type)	MP (μm)	Type of polymers	Observation	References
Crassostrea brasiliana	7.25 ± 0.70	3 mg/L	1	Fibres	17.35 ± 4.17	–	Reduced by 100%	Christo et al., 2021
Mytilus edulis	4.00 ± 0.50	0.28 particles g − 1 w.w.	2.5	–	–	–	Reduced by 90%	Stamataki et al., 2020
M. galloprovincialis	5.00 ± 0.30	0.27 particles g − 1 w.w.	12	–	–	–	Reduced by 90%	Stamataki et al., 2020
Mytilus edulis	5.77 ± 0.50	Collected from wild	7	Fragments	–	PS	Reduced by 97.6%	Kazour & Amara, 2020
Mytilus galloprovincialis	–	250/ml	40	sphere	1, 10 and 90	PS	Larger MPs were slowly excreted in bulk	Kinjo et al., 2019
Perna perna	4.67 ± 0.51	Collected from wild	4	Fibres	–	Polyamide	Reduced by 46.79%	Brinstiel et al., 2019
Mytilus galloprovincialis	4.00	2 and 4 mm 3/L	7	–	4 to 6	PET	Reduced by 85%	Fernández & Albentosa, 2019
Pecten maximus	11.50 ± 1.60	15 μg/L	48	–	0.024 and 0.250	PS	24 nm and 250 nm MP were completely removed after 14 and 48 days, respectively	Al-Sid-Cheikh et al., 2018
Mytilus edulis	–	30 MP/L	0.125	Fibres	0.2	PET	Reduced by 65%	Woods et al., 2018
Atactodea striata	3.50 to 4.00	10 and 1000	7	–	63 to 250	PS	Amount of MP was reduced by 50% and 85% at a concentration of 10 and 1000 MP/L, respectively	Xu et al., 2017
Mytilus edulis	–	–	3	–	–	–	Reduced by 33%	Van Cauwenberghe & Janssen, 2014

PET = polyethylene terephthalate; PS = polystyrene.

(Liu et al., 2024; Song, Farhadi, et al., 2024; Song, Wang, et al., 2024; Tan et al., 2024; Tan, Yan, et al., 2023). Therefore, it is also very interesting to explore the effects of climate change drivers on the accumulation of MPs in bivalves.

7. Conclusion

In a nutshell, plastic pollution is a major threat to our oceans. Bivalves can accumulate high levels of MPs, especially in their gills and digestive glands, with smaller and farmed bivalves accumulating higher concentrations of MPs than larger and wild bivalves. Exposure to MPs may adversely affect immunity and energy budgets, resulting in the reallocation of energy from reproduction to maintaining essential functions, which could negatively affect the reproduction and population of marine bivalves. This study provides detailed information on the status of MP pollution in marine bivalves and the impact of MP pollution on marine bivalves. The information in this review is very useful for formulating management plans for sustainable commercial fisheries and natural conservation. For future studies, it is highly recommended to conduct more surveys of MPs in edible marine bivalves around the world, especially those of commercially important species.

CRediT authorship contribution statement

Zhixiong Xu: Writing – review & editing, Project administration, Funding acquisition. **Leiheng Huang:** Project administration. **Peng Xu:** Project administration. **Leongseng Lim:** Conceptualization. **Kit-Leong Cheong:** Supervision, Project administration, Conceptualization. **Youji Wang:** Supervision, Software. **Karsoon Tan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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