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Review

Risk assessment of natural and synthetic fibers in aquatic environment: A critical review

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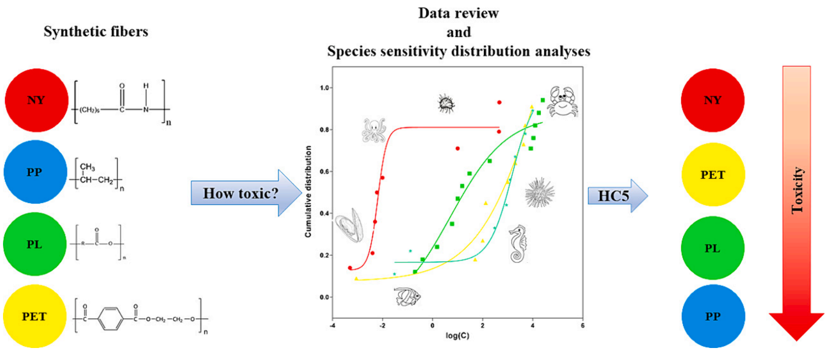
HIGHLIGHTS

- Mollusks are significantly impacted by Nylon, PL, and PET compared to Arthropods.
- Chordata and Arthropoda show the highest and lowest sensitivity to PP, respectively.
- Nylon poses the greatest risk, followed by PET, PL, and PP.
- Risk Quotient (RQ) Analysis reveals notable risks associated with Nylon.

GRAPHICAL ABSTRACT



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ABSTRACT

Marine microplastics, categorized as primary and secondary, including synthetic microfibers like polyethylene terephthalate (PET), polypropylene (PP) and acrylic (PC), represent a potential environmental concern. The complex classification of these fibers, originating from diverse sources such as textiles and many others commercial goods, prompts a need for understanding their impact on aquatic organisms. This study assesses the ecological risks associated with both natural and synthetic fibers in aquatic ecosystems, focusing on toxicity data and their effects on taxonomic groups like Mollusca, Arthropoda, Echinodermata, Cnidaria, and Chordata. To carry out species sensitivity distribution (SSD) curves, a comprehensive analysis of scientific literature was conducted, collecting toxicity data related to various fibers. The resulting SSDs provide insights into the relative sensitivity of different taxonomic groups. The potential ecological risks were evaluated by comparing measured concentrations in diverse aquatic environments with Predicted No-Effect Concentration (PNEC) values. The

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Aquatic ecosystems
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calculation of Risk Quotient (RQ) allowed to indicate areas where fibers abundance poses a potential threat to aquatic organisms. The study reveals that nylon fibers can pose the highest toxicity risk, especially in Atlantic and Pacific Ocean, Arabian Gulf and VietNam river. Mollusca emerged as particularly sensitive to different fiber types, likely due to their body structure facilitating the accumulation of microfibers. The research emphasizes the urgent need for further studies to get data to human health risk analysis and to address comprehensive environmental management strategies to address the global issue of microfiber pollution.

1. Introduction

Marine microplastics can be distinguished as primary, when distinct particles such as fibers and cosmetic microbeads enter into the environment directly, and secondary, when small particles are formed *in situ* through the disintegration of larger plastics (Barrows et al., 2018; Efimova et al., 2018; Multisanti et al., 2022; Watts et al., 2015). Although synthetic fibers, including polyethylene terephthalate (PET), polypropylene (PP), and acrylic, typically fall under the category of microplastics, their classification is complex, as some particles are of secondary origin (such as fragments of fishing rope), while others results from *ex situ* wear through consumer and industrial usage (Barrows et al., 2018; Watts et al., 2015). Belzagui et al. (2019) estimated that the laundering of clothes and other textile products were the most significant source of both synthetic microfibers and processed microfibers (mainly cotton), with a detachment rates range from 175 to 560 fibers per gram or from 30,000 to 465,000 fibers per square meter of garment during washing. Due to the size and density of these particles, it is likely that the majority will evade water treatment processes, ending up in the oceans and potentially entering the food chain (Salvador Cesa et al., 2017). Additionally, due to their significant surface area and hydrophobic properties, microplastics can effectively absorb and adhere to both organic and inorganic contaminants in water, leading to an increase in the toxic effects on non-target organisms (Gholamhosseini et al., 2023; Zeidi et al., 2023). The continuous release of natural and synthetic fibers into aquatic environments raises concerns about potential ecological and human health risks (Schirinzi et al., 2020).

To the best of our knowledge, no studies assessing the risk of fibers on the species living in both freshwater and seawater using the species sensitivity distribution (SSD) have been published yet.

The aim of this study was to assess the risks associated with both natural and synthetic fibers in aquatic ecosystems, focusing on toxicity data and their effects on different taxonomic groups. Specifically, we conducted a comprehensive analysis of scientific literature to collect toxicity data related to natural and synthetic fibers. The collected data allowed the construction of Species Sensitivity Distribution (SSD) curves for each type of fiber, providing insights into the relative sensitivity of different taxonomic groups, such as Mollusca, Arthropoda, Echinodermata, Cnidaria, and Chordata.

The potential ecological risks of different fibers were evaluated by comparing measured concentrations in different aquatic environments with the PNEC values. The Risk Quotient (RQ) was calculated to assess the ecological risk. Results allowed to indicate the areas where the abundance of fibers poses a potential threat to aquatic organisms. We addressed this issue reported in literature and based on field observations and laboratory analysis of water samples from sea, ocean, lakes, canals and river.

2. Toxicity data collection

Scientific literature was searched for toxic effect data concerning natural and synthetic (micro-)fibers by using Google Scholar, National Center for Biotechnology Information (NCBI), Web of Science (WoS), and Scopus (last update January 2024). Only papers reporting original experimental data were considered. The following exclusion criteria were adopted: i) papers investigating only terrestrial species and human or mammal toxicity (*i.e.*, an *ad hoc* review will be specifically provided); ii) papers did not show NFs/SFs acute or chronic effects on species concerned.

After the elimination of duplications, a total of 99 papers was identified and pre-reviewed according to the abovementioned selection criteria. After the pre-revision phase, only 39 were shortlisted, including toxicity data on species from freshwater and saltwater (last update January 2024). The toxicity effects of MFs were evaluated in 4 (12.1 %) and 29 (87.9 %) papers for natural and synthetic fibers, respectively.

Considering all type of fibers, the relative abundance of papers for each group of species was reported in Fig. 1A. Most studies focused on Arthropoda (53.2 %) and in sequence on Echinodermata (21.3 %), Chordata (12.8 %), Mollusca (8.5 %), and Cnidaria (4.2 %). Respect to the species, the most investigated species were: *Daphnia magna* (17.02 %), *Artemia franciscana* (6.38 %), from *Aiptasia pallida* to *Thyonella gemmata* (4.25 %), and from *Achatina fulica* to *Rana sylvatica* (2.13 %), as shown in Fig. 1B.

The systematic review of papers included the collection of the following information: i) fiber type (*i.e.*, nylon, polyesters, polyethylene terephthalate, polypropylene, polystyrene, polyethylene, polyvinyl chloride, cellulose, cotton and linen), ii) fiber size, iii) taxonomy, iv) biological endpoints tested (*i.e.*, acute and chronic LC_{50} or EC_{50}s), v) exposure time, and vi) concentrations (mg/l). Data points expressed in items/volume (*e.g.*, fibers/ml) were conveyed in mass/volume (mg/l) using the fiber size and the formula for cylinder volume as done by Cohen et al., 2001; Lavoie et al., 2022. The results are reported in Table 1.

As shown in Table 1, four taxonomy groups have been tested (*i.e.*, 9 species in total: Mollusca, Cnidaria, Arthropoda and Echinodermata represented with 1, 1, 2 and 5 species, respectively) focusing on toxic effects of nylon fibers. Respect to the effects of polyester fibers, 12 testing species belonging to 5 taxonomic groups (Mollusca, Cnidaria, Arthropoda, Echinodermata and Chordata were represented with 1, 1, 6, 1 and 3 species, respectively; see Table 1) were identified. 7 species including 3 taxonomic groups (Mollusca, (n = 2), Arthropoda (n = 4) and Chordata, (n = 1); Table 1) were tested respect to the exposure to polyethylene terephthalate fibers. About Polypropylene fibers, 6 species including 2 taxonomic groups (Arthropoda (n = 4) and Chordata, (n = 2); Table 1) were tested. About Polyvinyl chloride and Cellulose fibers, only one taxonomic group (Echinodermata, (n = 4) and Arthropoda (n = 2), respectively) was considered. Likewise, only one specie including 1 taxonomic (Arthropoda, n = 1) was used to test the effects of cotton and linen fibers. Due to the limited number of toxicity data about polystyrene, polyethylene, polyvinyl chloride, cellulose, cotton and linen fibers, the related SSDs curves could not be carried out.

3. Organization and treatment of data and statistical analysis

Toxicity data of fibers were sometimes duplicated that is the same species and endpoints. In that event, their geometric mean was used for the relative evaluations (Kooijman, 1987) and in particular for *D. magna*. SSD curves have been constructed considering the seawater and freshwater species in their totality. Toxicity data related to cellulose, cotton and linen was so limited that the related SSDs were not constructed. Data point was first log-transformed and the associated risk was visualized as cumulative distribution function using log-logistic model according to previous studies (Albarano et al., 2021; Burmaster and Hull, 1997; Newman et al., 2000; Posthuma et al., 2002). The hazard concentration affecting the 5 % (HC$_5$) of species was calculated according to (Aldenberg and Slob, 1993). All details were reported in Appendix S1 (Supplementary Materials. The predicted no-effect concentration (PNEC) value was calculated by dividing HC$_5$ value by an assessment factor (AF) whose value is in the range 1–5 (Parvin et al., 2022; Zhang et al., 2020). Due to limited number of taxonomic groups and the current lack of standard toxicity test methods, the highest AF was selected to derive PNEC. Using risk quotient (RQ), the water fibers potential ecological risks has been evaluated according to Eq. (1).

$$RQ = \frac{FEC}{PNEC} \tag{1}$$

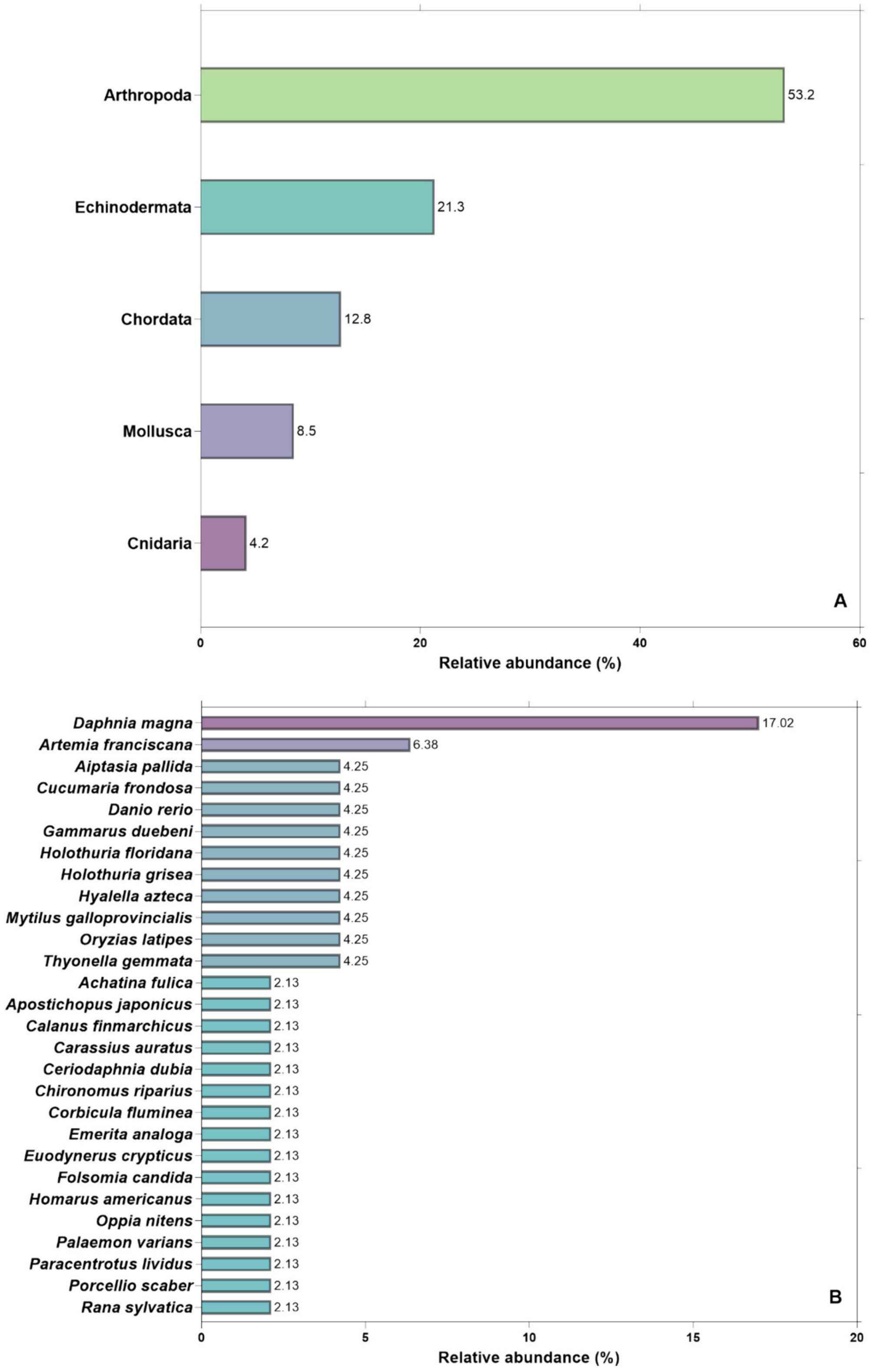

Fig. 1. Comparison of the relative abundance (%) of papers for A) each taxonomic groups and B) species studied in response to natural and synthetic fibers.

where, FEC is the measured fiber environmental concentrations at surface of different aquatic environments (see Table S1). If, RQ < 1 it indicates the measured microplastics in the site has negligible ecological risk and if RQ > 1 it indicates high potential ecological risk.

4. Discussion

The collected toxicity data passed the Anderson–Darling test, D'Agostino & Pearson test, Kolmogorov–Smirnov Test and Shapiro-Wilk test normality (Parvin et al., 2022; Zhang et al., 2020).

4.1. Toxicity comparison of four types of fibers on species-by-species basis

As shown in Fig. 2, considering the sensibility of all species groups to fibers, the Mollusca and Arthropoda exhibited the higher and lower sensitivity, respectively.

Specifically, regarding nylon fibers data (Fig. 2a), toxicity data of the mollusk species *Mytilus* spp., demonstrated high sensitivity respect to all species, whereas the Arthropoda with *Calanus finmarchicus* exhibited the lowest sensitivity. In the case of polyester fibers data (Fig. 2b), the mollusk *Corbicula fluminea* and the arthropod *Euodynerus crypticus*, showed the higher and the lower sensitivity, respectively. For

Table 1
Types of fibers, phylum, species, time of exposure, concentrations and dimension of fibers, endpoints, effects, and references of negative impact of natural and synthetic fibers.

Type of fibers	Phylum	Species	Exposure time (days)	Length × width (μm)	Endpoints	Concentrations (mg/l)	Reference
Nylon	Mollusca	*Mytilus* spp.	1	10 × 30	EC50	0.0005	(Cole et al., 2020)
	Cnidaria	*Aiptasia pallida*	3	30 × 50	EC50	10	(Romanó de Orte et al., 2019)
	Arthropoda	*Artemia* sp.	0.08	10 × 40	EC50	450	(Cole, 2016)
	Arthropoda	*Calanus finmarchicus*	6	10 × 30	EC50	467	(Cole et al., 2019)
	Echinodermata	*Thyonella gemmata*	1	270 × 810	EC50	0.006	(Graham and Thompson, 2009)
	Echinodermata	*Holothuria floridana*	1	270 × 810	EC50	0.004	(Graham and Thompson, 2009)
	Echinodermata	*Holothuria grisea*	1	270 × 810	EC50	0.005	(Graham and Thompson, 2009)
	Echinodermata	*Cucumaria frondosa*	1	270 × 810	EC50	0.005	(Graham and Thompson, 2009)
	Echinodermata	*Paracentrotus lividus*	1	n.a.	EC50	0.01	(Di Natale et al., 2022)
Polyester	Mollusca	*Corbicula fluminea*	2	100 × 250	EC50	0.2	(Li et al., 2019)
	Cnidaria	*Aiptasia pallida*	3	30 × 50	EC50	10	(Romanó de Orte et al., 2019)
	Arthropoda	*Ceriodaphnia dubia*	2	25.7 × 280	LC50	1.5	(Ziajahromi et al., 2017)
	Arthropoda	*Gammarus duebeni*	4	17 × 60	EC50	192	(Mateos-Cárdenas et al., 2021)
	Arthropoda	*Porcellio scaber*	21	14.7 × 710	EC50	17,441	(Selonen et al., 2020)
	Arthropoda	*Folsomia candida*	21	14.7 × 710	LC50	12,500	(Selonen et al., 2020)
	Arthropoda	Euodynerus crypticus	21	14.7 × 710	LC50	25,000	(Selonen et al., 2020)
	Arthropoda	*Oppia nitens*	21	14.7 × 710	EC50	8333	(Selonen et al., 2020)
	Echinodermata	*Apostichopus japonicus*	3	50 × 1000	EC50	6	(Mohsen et al., 2021, 2020)
	Chordata	*Oryzias latipes*	21	10 × 350	EC50	0.4	(Hu et al., 2020)
	Chordata	*Carassius auratus*	6	50–500	EC50	4.1	(Grigorakis et al., 2017)
	Chordata	*Rana sylvatica*	1	20 × 86	EC50	30	(Buss et al., 2022)
Polyethylene terephthalate	Mollusca	*Mytilus galloprovincialis*	4	13 × 100	LC50	100	(Auguste et al., 2023; Choi et al., 2021)
	Mollusca	*Achatina fulica*	28	76.3 × 1257.8	EC50	0.0009	(Song et al., 2019)
	Arthropoda	*Homarus americanus*	10	20 × 459	LC50	5000	(Woods et al., 2020)
	Arthropoda	*Daphnia Magna*	2	21.5 × 530	LC50	31	(Jemec et al., 2016)
	Arthropoda	*Daphnia Magna*	2	10 × 120.5	LC50	4000	(D. Kim et al., 2021)
	Arthropoda	*Artemia franciscana*	2	22.4 × 234	LC50	1000	(L. Kim et al., 2021)
	Arthropoda	*Chironomus riparius*	28	14 × 50	LC50	9140	(Setyorini et al., 2021)
	Chordata	*Danio rerio*	3	20 × 300	EC50	133	(Cheng et al., 2021)
Polypropylene	Arthropoda	*Daphnia Magna*	2	10 × 134.8	LC50	1250	(D. Kim et al., 2021)
	Arthropoda	*Hyalella azteca*	10	20 × 20	LC50	300	(Au et al., 2015)
	Arthropoda	*Artemia franciscana*	2	19.3 × 182.8	LC50	2000	(L. Kim et al., 2021)
	Arthropoda	*Emerita analoga*	71	30 × 6000	LC50	0.13	(Horn et al., 2020)
	Chordata	*Danio rerio*	21	20 × 200	EC50	10,000	(Zhao et al., 2021)
	Chordata	*Oryzias latipes*	21	50 × 380	EC50	0.03	(Hu et al., 2020)
Polystyrene	Arthropoda	*Palaemon varians*	2	30 × 236	LC50	89.3	(Saborowski et al., 2019)
Polyethylene	Arthropoda	*Hyalella azteca*	10	10 × 20	LC50	380	(Au et al., 2015)
Polyvinyl chloride	Echinodermata	*Thyonella gemmata*	1	270 × 810	EC50	0.011	(Graham and Thompson, 2009)
	Echinodermata	*Holothuria floridana*	1	270 × 810	EC50	0.045	(Graham and Thompson, 2009)
	Echinodermata	*Holothuria grisea*	1	270 × 810	EC50	0.025	(Graham and Thompson, 2009)
	Echinodermata	*Cucumaria frondosa*	1	270 × 810	EC50	0.024	(Graham and Thompson, 2009)
Cellulose	Arthropoda	*Daphnia Magna*	21	0.6 × 22	EC50	34.3	(Ogonowski et al., 2018)
	Arthropoda	*Daphnia Magna*	2	n.a.	EC50	52	(Dave and Aspegren, 2010)
	Arthropoda	*Daphnia magna*	2	100 × 2000	LC50	0.001	(Belzagui et al., 2021)
	Arthropoda	*Gammarus duebeni*	4	15 × 60	EC50	50,000	(Mateos-Cárdenas et al., 2021)
Cotton	Arthropoda	*Daphnia Magna*	2	n.a.	EC50	29.2	(Dave and Aspegren, 2010)
Linen	Arthropoda	*Daphnia Magna*	2	n.a.	EC50	32	(Dave and Aspegren, 2010)

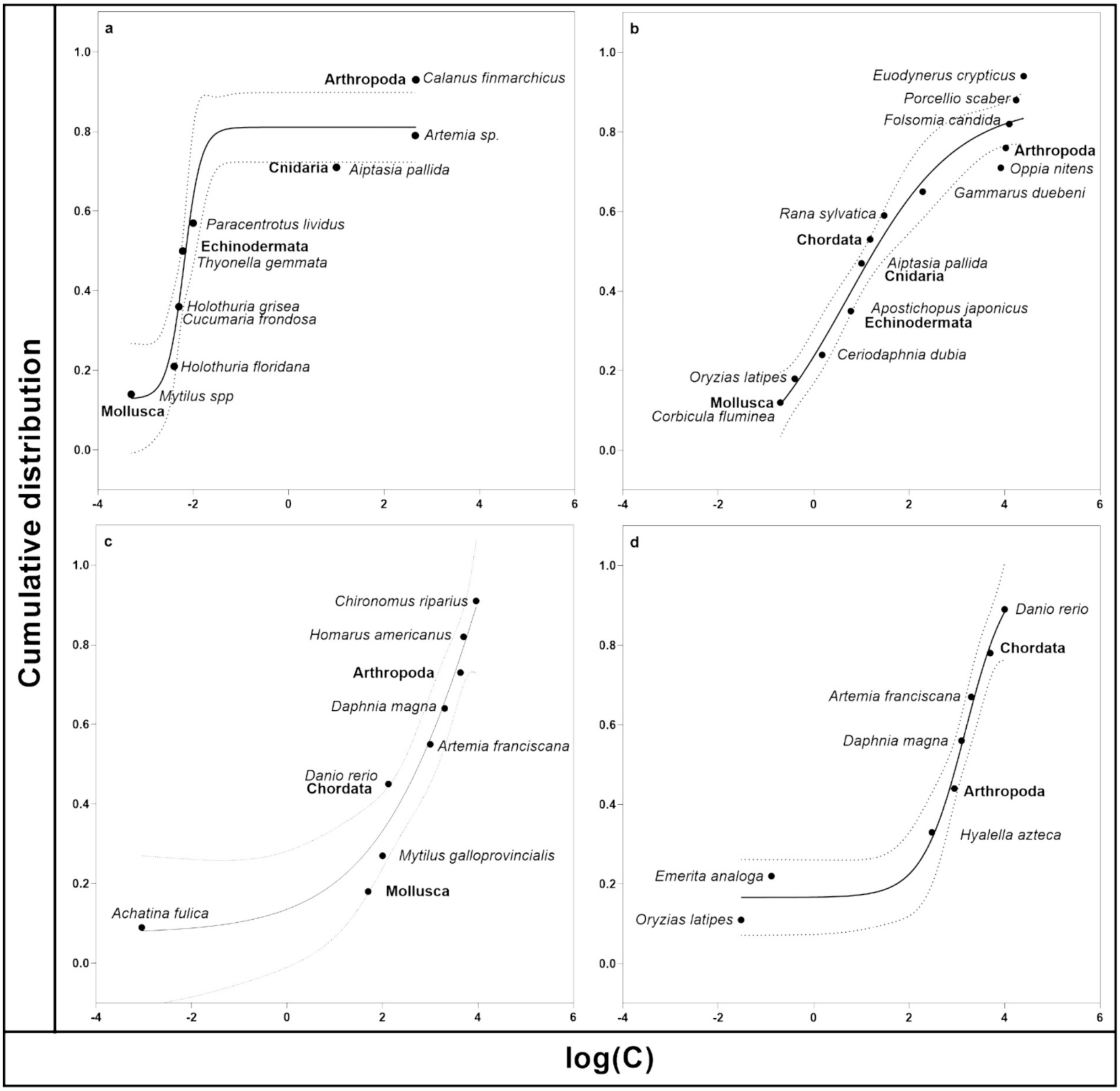

Fig. 2. Species sensitivity distribution including all phylum to a) nylon; b) polyester; c) polyethylene terephthalate; and d) polypropylene.

polyethylene terephthalate fibers (Fig. 2c), the mollusk *Achatina fulica* was the most sensitive species, while the arthropod *Chironomus riparius* displayed the lowest sensitivity. Finally, in Fig. 2d, the chordate *Oryzias latipes* followed by the arthropod *Emerita analoga*, emerged as the most sensitive organisms, whereas collectively, the chordate *Danio rerio* exhibited the highest resistance when exposed to Polypropylene.

Based on these finding, Mollusca are notably sensitive to various types of fibers (Fig. 2). This sensitivity may be attributed to their body structure, which potentially facilitates the accumulation and retention of microfibers. Indeed, many mollusks, such as mussels and clams, filter water to feed on suspended particles, and during this filtration process, microfibers can become ensnared in their feeding systems (Expósito et al., 2022; Li et al., 2021; Pinheiro et al., 2020).

4.2. Overall toxicity comparison of four types of fibers

As illustrated in Fig. 3, Species Sensitivity Distributions (SSDs) were constructed for four types of fibers across all species, and the relationship of sensitivity among total species was examined for each fiber type.

The curves representing polyethylene terephthalate and polypropylene shifted to the right side of the graph (Fig. 3), indicating relatively lower toxicity, whereas the toxicity curves of nylon shifted to the left, suggesting higher toxicity compared to the other fiber types. The toxicity curve of polyester was located in the middle among all fiber types. Notably, when the concentrations were below 0.001 mg/l, discernible differences in toxicity were observed between polyethylene terephthalate and polypropylene fibers, but as concentrations increased to 0.01 mg/l, the ecological risks associated with nylon escalated rapidly (Fig. 3).

Based on the calculated HC_5 (refer to Table 2), Mollusca consistently emerged as the most sensitive phylum, while Arthropoda exhibited the lowest sensitivity across almost all cases.

For instance, nylon fibers were found to be particularly toxic for Mollusca, with an HC_5 of 0.0003 mg/l (CI = 0.0001–0.0004; Table 2) which was significantly lower than the HC_5 values for the other analyzed phyla, namely Echinodermata, Cnidaria and Arthropoda. The HC_5 value of Arthropoda was found to be more than about 1500 times higher (HC_5 = 442 mg/l, CI = 393–453; Table 2) than that measured in Mollusca. The sensitivity ranking across phyla decreased as follows: Mollusca > Echinodermata > Cnidaria > Arthropoda.

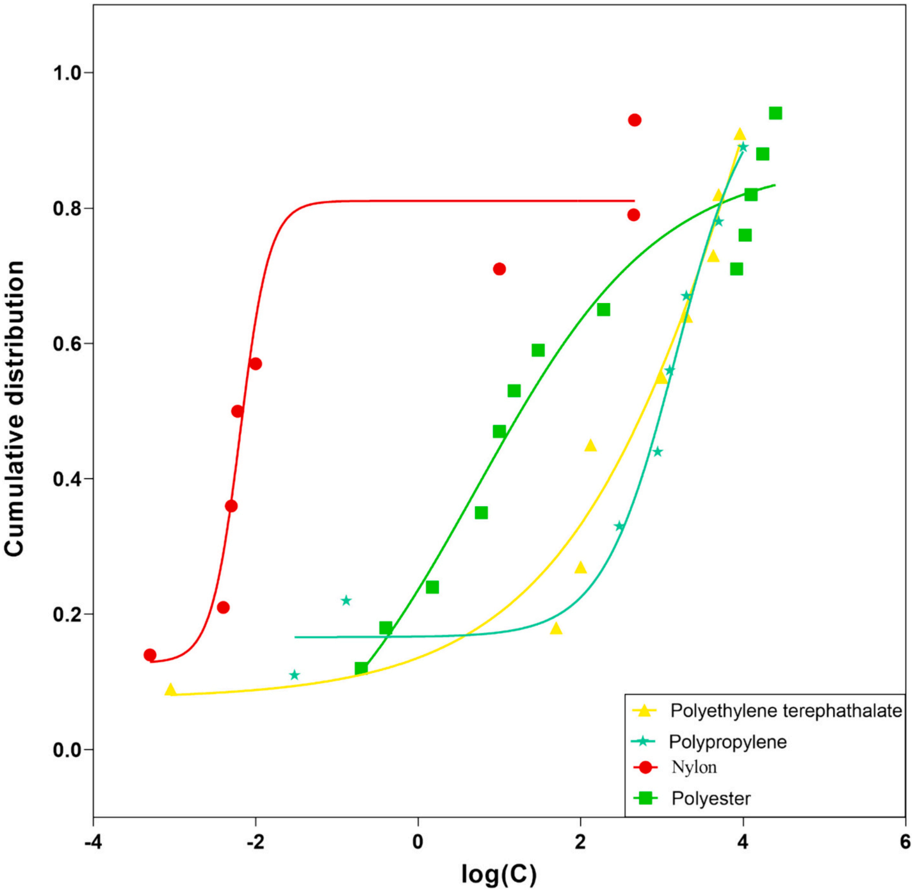

Fig. 3. SSD curves for total species exposed to different types of fibers.

Table 2
The calculated HC_5 values of groups (Cnidaria, Mollusca, Arthropoda, Echinodermata and Chordata) and total species for four types of fibers. The values were expressed in mg/l. CI = confidence interval; n.a. = not available.

		HC_5	CI
Nylon	Cnidaria	9.8	8.1–9.9
	Mollusca	0.0003	0.0001–0.0004
	Arthropoda	442	393–453
	Echinodermata	0.0023	0.0018–0.0042
	Chordata	n.a.	n.a.
Polyester	Cnidaria	9.8	8.1–9.9
	Mollusca	0.18	0.0093–0.19
	Arthropoda	4969	941–6315
	Echinodermata	5.8	4.1–5.9
	Chordata	14	10–16
Polyethylene terephthalate	Cnidaria	n.a.	n.a.
	Mollusca	4.7	3.3–18
	Arthropoda	1750	870–2083
	Echinodermata	n.a.	n.a.
	Chordata	131	114–132
Polypropylene	Cnidaria	n.a.	n.a.
	Mollusca	n.a.	n.a.
	Arthropoda	52	24–241
	Echinodermata	n.a.	n.a.
	Chordata	4690	1800–5280

Only for Chordata, the HC_5 values were not calculated because toxicity data about on this phylum was not available in literature. Polyester fibers determined a highest impact on Mollusca (0.18 mg/l, CI = 0.0093–0.19, Table 2) respect to Echinodermata, Cnidaria, Arthropoda and Chordata, probably due to their general role of non-selective filter feeders. The HC_5 value of Arthropoda was found to be more than twenty-seven thousand times higher than that of Mollusca. The sensitivity resulted decreasing according to the following order: Mollusca > Echinodermata > Cnidaria > Chordata > Arthropoda. Similarly, about Polyethylene terephthalate fibers, Mollusca the most affected phylum (4.5 mg/l, CI = 3.3–18, Table 2). HC_5 of Arthropoda group results to be >372 times higher than that of Mollusca (see Table 2). The HC_5 values were not calculated for Cnidaria and Echinodermata because toxicity data about on this phylum was not available in literature.

Polypropylene fibers determined a highest impact on Arthropoda (52 mg/l, CI = 24–241, Table 2) respect to Chordata. HC_5 of Chordata group resulted to be >90 times higher than that of Arthropoda (with HC_5 value of 4690, CI = 1800–5280; see Table 2).

When considered the impact of four fiber types on total species (see also Table 3), the nylon fibers was the most toxic with the acute HC_5 value of 24 mg/l (CI = 5.1–97 mg/l), followed by polyethylene terephthalate (330 mg/l; CI = 88.2–782 mg/l), polyester (928 mg/l; CI = 922–3470 mg/l) and polypropylene fibers (4520 mg/l; CI = 1130–12,300 mg/l).

The decreasing risk is: Nylon > Polyethylene terephthalate > Polyester > Polypropylene (Table 3). Specifically, the HC_5 value of Polypropylene (4520 mg/l) is 99.5 % higher than Nylon HC_5. The resulting PNEC for Nylon, Polyester, Polyethylene terephthalate and

Table 3
The calculated HC_5 values and PNEC of total species for four types of fibers. The values were expressed in mg/l; CI = confidence interval.

	HC_5	CI	PNEC
Nylon	24	5.1–97	4.8
Polyester	928	922–3470	186
Polyethylene terephthalate	330	88.2–782	66
Polypropylene	4520	1130–12,300	905

Polypropylene fibers in surface water 4.8 mg/l, 186 mg/l, 66 mg/l and 905 mg/l, respectively (Table 3).

The potential risk levels of Nylon, Polyester, Polyethylene terephthalate and Polypropylene fibers in Mediterranean sea (S1), Ross Sea (S2), Southern Sea (Korea; S3), Bohai Sea (S4), Jiaozhou Bay (S5), Indian, Atlantic, Arctic and Pacific Ocean (from S6 to S9), Arabian Gulf (S10), Chabahar Bay (S11), Hong Kong Bay (S12), Northern European Lake (S13), Victoria Lake (S14), Guaíba Lake (S15), VietNam Lake (S16), Awano River (S17), Ayaragi River (S18), Asa River (S19), Majime River (S20) and VietNam River (S21) were quantified by RQs which were derived from the measured abundances of microfibers and the PNEC values obtained in this study. The RQ for each type of fibers is shown in Fig. 4. In the same figure, Nylon fibers represent the type of fiber with the highest toxicological risk for all considered aquatic environments. Specifically, nylon RQs values in all studied area ranged from 0.0041 to 207.45. The potential risks of nylon fibers resulted high (RQ > 1) at sampling site S1, S5, S7, S9, S10, S17, S18, S19 and S21 water samples (Fig. 4).

Nylon fibers in S5, S7, S9, S10 and S21 water samples posed significantly high risks (RQ ~ 18–207) to seawater and freshwater species. The potential risks of polyester fibers were high (RQ > 1) at sampling sites S7, S8, S10 and S16 water samples. Among those, polyester fibers in S8 and S10 water samples posed significantly high risks (RQ ~ 4–5) to seawater and freshwater species (Fig. 4). RQs values of polyethylene terephthalate fibers resulted high (RQ > 1) at sampling site S5, S7, S9, S10 and S13, where in S5 and S10 water samples posed significantly high risks (RQ ~ 15–50) to all species. Finally, the potential risks of polypropylene are high (RQ > 1) only at sampling site S5 and S10 (Fig. 4). On the basis of these results, the potential risks of all fiber types were high (RQ > 1) at Jiaozhou Bay (S5) and Arabian Gulf (S10).

5. Concluding remarks

Based on the results of this study, we can state that: (i) Nylon, Polyester and Polyethylene terephthalate affect Mollusca more than Arthropoda; (ii) Polypropylene sensitivity is highest in Chordata and lowest in Arthropoda; (iii) Nylon represent the highest toxicological risk, followed by Polyethylene terephthalate, Polyester, and Polypropylene fibers; (iv) RQ values indicated significant risks for Nylon, Polyester, Polyethylene terephthalate and Polypropylene fibers in two specific sampling sites (Jiaozhou Bay (S5) and Arabian Gulf (S10)).

In conclusion, this study contributes valuable insights into the ecological risks associated with natural and synthetic fibers in aquatic ecosystems, providing a basis for future environmental management strategies and highlighting the urgency of addressing microfiber pollution. Moreover, the study emphasizes the need for further research and comprehensive strategies for environmental management.

CRediT authorship contribution statement

Luisa Albarano: Writing – original draft, Software, Methodology, Conceptualization. **Chiara Maggio:** Writing – original draft, Data curation. **Annamaria La Marca:** Writing – original draft, Data curation. **Rosalba Iovine:** Writing – original draft, Data curation. **Giusy Lofrano:** Writing – original draft, Data curation. **Marco Guida:** Supervision, Conceptualization. **Vincenzo Vaiano:** Software, Methodology. **Maurizio Carotenuto:** Investigation, Conceptualization. **Silvana Pedatella:** Investigation, Conceptualization. **Vincenzo Romano Spica:** Software, Methodology. **Giovanni Libralato:** Writing – review & editing, Supervision, Conceptualization.

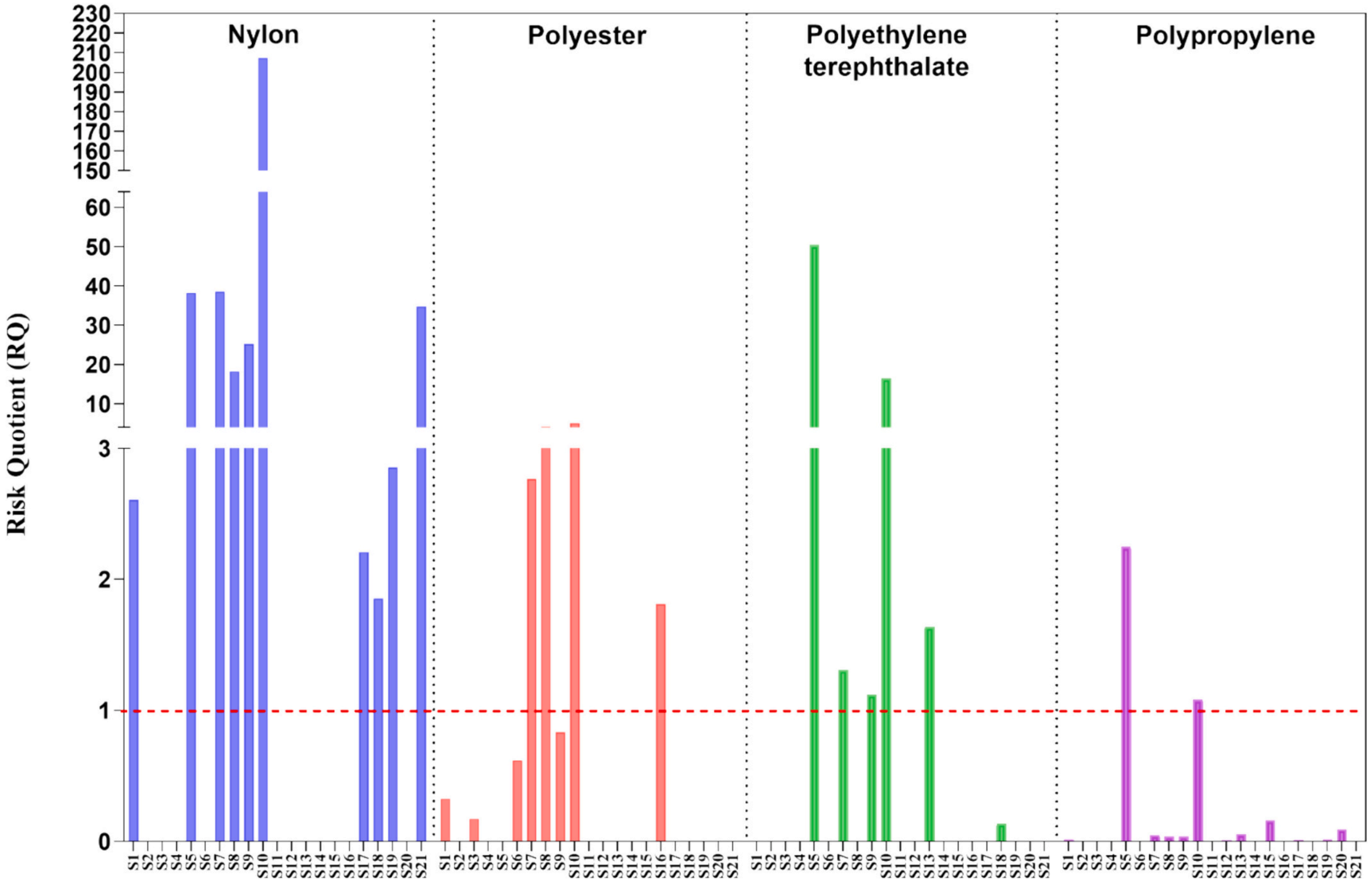

Fig. 4. The risk quotient (RQ) of Nylon, Polyester, Polyethylene terephthalate and Polypropylene fibers for the aquatic organisms in waters of different sites (for more details on sites, see Table S1).

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

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.173398.

References

Albarano, L., Lofrano, G., Costantini, M., Zupo, V., Carraturo, F., Guida, M., Libralato, G., 2021. Comparison of in situ sediment remediation amendments: risk perspectives from species sensitivity distribution. Environ. Pollut. 272, 115995 https://doi.org/10.1016/j.envpol.2020.115995.

Aldenberg, T., Slob, J., 1993. Confidence limits for hazardous concentrations based on logistically distributed NOEC toxicity data. Ecotoxicol. Environ. Saf. 25 (48/63).

Au, S.Y., Bruce, T.F., Bridges, W.C., Klaine, S.J., 2015. Responses of Hyalella azteca to acute and chronic microplastic exposures. Environ. Toxicol. Chem. 34, 2564–2572. https://doi.org/10.1002/etc.3093.

Auguste, M., Leonessi, M., Bozzo, M., Risso, B., Cutroneo, L., Prandi, S., Kokalj, A.J., Drobne, D., Canesi, L., 2023. Multiple responses of Mytilus galloprovincialis to plastic microfibers. Sci. Total Environ. 890, 164318 https://doi.org/10.1016/j.scitotenv.2023.164318.

Barrows, A.P.W., Cathey, S.E., Petersen, C.W., 2018. Marine environment microfiber contamination: global patterns and the diversity of microparticle origins. Environ. Pollut. 237, 275–284. https://doi.org/10.1016/j.envpol.2018.02.062.

Belzagui, F., Crespi, M., Álvarez, A., Gutiérrez-Bouzán, C., Vilaseca, M., 2019. Microplastics’ emissions: microfibers’ detachment from textile garments. Environ. Pollut. 248, 1028–1035. https://doi.org/10.1016/j.envpol.2019.02.059.

Belzagui, F., Buscio, V., Gutiérrez-Bouzán, C., Vilaseca, M., 2021. Cigarette butts as a microfiber source with a microplastic level of concern. Sci. Total Environ. 762, 144165 https://doi.org/10.1016/j.scitotenv.2020.144165.

Burmaster, D.E., Hull, D.A., 1997. Using lognormal distributions and lognormal probability plots in probabilistic risk assessments. Hum. Ecol. Risk. Assess. 3, 235–255. https://doi.org/10.1080/10807039709383683.

Buss, N., Sander, B., Hua, J., 2022. Effects of polyester microplastic fiber contamination on amphibian–trematode interactions. Environ. Toxicol. Chem. 41, 869–879. https://doi.org/10.1002/etc.5035.

Cheng, H., Feng, Y., Duan, Z., Duan, X., Zhao, S., Wang, Y., Gong, Z., Wang, L., 2021. Toxicities of microplastic fibers and granules on the development of zebrafish embryos and their combined effects with cadmium. Chemosphere 269, 128677. https://doi.org/10.1016/j.chemosphere.2020.128677.

Choi, J.S., Kim, K., Hong, S.H., Park, K. Il, Park, J.W., 2021. Impact of polyethylene terephthalate microfiber length on cellular responses in the Mediterranean mussel Mytilus galloprovincialis. Mar. Environ. Res. 168, 105320 https://doi.org/10.1016/j.marenvres.2021.105320.

Cohen, D., Mantell, S.C., Zhao, L., 2001. The effect of fiber volume fraction on filament wound composite pressure vessel strength. Compos. Part B Eng. 32, 413–429. https://doi.org/10.1016/S1359-8368(01)00009-9.

Cole, M., 2016. A novel method for preparing microplastic fibers. Sci. Rep. 6, 1–7. https://doi.org/10.1038/srep34519.

Cole, M., Coppock, R., Lindeque, P.K., Altin, D., Reed, S., Pond, D.W., Sørensen, L., Galloway, T.S., Booth, A.M., 2019. Effects of nylon microplastic on feeding, lipid accumulation, and moulting in a coldwater copepod. Environ. Sci. Technol. 53, 7075–7082. https://doi.org/10.1021/acs.est.9b01853.

Cole, M., Liddle, C., Consolandi, G., Drago, C., Hird, C., Lindeque, P.K., Galloway, T.S., 2020. Microplastics, microfibres and nanoplastics cause variable sub-lethal responses in mussels (Mytilus spp.). Mar. Pollut. Bull. 160, 111552 https://doi.org/10.1016/j.marpolbul.2020.111552.

Dave, G., Aspegren, P., 2010. Comparative toxicity of leachates from 52 textiles to Daphnia magna. Ecotoxicol. Environ. Saf. 73, 1629–1632. https://doi.org/10.1016/j.ecoenv.2010.06.010.

Di Natale, M.V., Carroccio, S.C., Dattilo, S., Cocca, M., Nicosia, A., Torri, M., Bennici, C. D., Musco, M., Masullo, T., Russo, S., Mazzola, A., Cuttitta, A., 2022. Polymer aging affects the bioavailability of microplastics-associated contaminants in sea urchin embryos. Chemosphere 309, 136720. https://doi.org/10.1016/j.chemosphere.2022.136720.

Efimova, I., Bagaeva, M., Bagaev, A., Kileso, A., Chubarenko, I.P., 2018. Secondary microplastics generation in the sea swash zone with coarse bottom sediments: laboratory experiments. Front. Mar. Sci. 5 https://doi.org/10.3389/fmars.2018.00313.

Expósito, N., Rovira, J., Sierra, J., Gimenez, G., Domingo, J.L., Schuhmacher, M., 2022. Levels of microplastics and their characteristics in molluscs from North-West Mediterranean Sea: human intake. Mar. Pollut. Bull. 181 https://doi.org/10.1016/j.marpolbul.2022.113843.

Gholamhosseini, A., Banaee, M., Sureda, A., Timar, N., Zeidi, A., Faggio, C., 2023. Physiological response of freshwater crayfish, Astacus leptodactylus exposed to polyethylene microplastics at different temperature. Comp. Biochem. Physiol. Part - C Toxicol. Pharmacol. 267, 109581 https://doi.org/10.1016/j.cbpc.2023.109581.

Graham, E.R., Thompson, J.T., 2009. Deposit- and suspension-feeding sea cucumbers (Echinodermata) ingest plastic fragments. J. Exp. Mar. Biol. Ecol. 368, 22–29. https://doi.org/10.1016/j.jembe.2008.09.007.

Grigorakis, S., Mason, S.A., Drouillard, K.G., 2017. Determination of the gut retention of plastic microbeads and microfibers in goldfish (Carassius auratus). Chemosphere 169, 233–238. https://doi.org/10.1016/j.chemosphere.2016.11.055.

Horn, D.A., Granek, E.F., Steele, C.L., 2020. Effects of environmentally relevant concentrations of microplastic fibers on Pacific mole crab (Emerita analoga) mortality and reproduction. Limnol. Oceanogr. Lett. 5, 74–83. https://doi.org/10.1002/lol2.10137.

Hu, L., Chernick, M., Lewis, A.M., Lee Ferguson, P., Hinton, D.E., 2020. Chronic microfiber exposure in adult Japanese medaka (Oryzias latipes). PLoS One 15, 5–7. https://doi.org/10.1371/journal.pone.0229962.

Jemec, A., Horvat, P., Kunej, U., Bele, M., Kržan, A., 2016. Uptake and effects of microplastic textile fibers on freshwater crustacean Daphnia magna. Environ. Pollut. 219, 201–209. https://doi.org/10.1016/j.envpol.2016.10.037.

Kim, D., Kim, H., An, Y.J., 2021a. Effects of synthetic and natural microfibers on Daphnia magna–are they dependent on microfiber type? Aquat. Toxicol. 240 https://doi.org/10.1016/j.aquatox.2021.105968.

Kim, L., Kim, S.A., Kim, T.H., Kim, J., An, Y.J., 2021b. Synthetic and natural microfibers induce gut damage in the brine shrimp Artemia franciscana. Aquat. Toxicol. 232, 105748 https://doi.org/10.1016/j.aquatox.2021.105748.

Kooijman, S.A.L.M., 1987. A safety factor for LC50 values allowing for differences in sensitivity among species. Water Res. 21, 269–276. https://doi.org/10.1016/0043-1354(87)90205-3.

Lavoie, J., Boulay, A.M., Bulle, C., 2022. Aquatic micro- and nano-plastics in life cycle assessment: development of an effect factor for the quantification of their physical impact on biota. J. Ind. Ecol. 26, 2123–2135. https://doi.org/10.1111/jiec.13140.

Li, L., Su, L., Cai, H., Rochman, C.M., Li, Q., Kolandhasamy, P., Peng, J., Shi, H., 2019. The uptake of microfibers by freshwater Asian clams (Corbicula fluminea) varies based upon physicochemical properties. Chemosphere 221, 107–114. https://doi.org/10.1016/j.chemosphere.2019.01.024.

Li, J., Wang, Z., Rotchell, J.M., Shen, X., Li, Q., Zhu, J., 2021. Where are we? Towards an understanding of the selective accumulation of microplastics in mussels. Environ. Pollut. 286, 117543 https://doi.org/10.1016/j.envpol.2021.117543.

Mateos-Cárdenas, A., O’Halloran, J., van Pelt, F.N.A.M., Jansen, M.A.K., 2021. Beyond plastic microbeads – short-term feeding of cellulose and polyester microfibers to the freshwater amphipod Gammarus duebeni. Sci. Total Environ. 753 https://doi.org/10.1016/j.scitotenv.2020.141859.

Mohsen, M., Zhang, L., Sun, L., Lin, C., Wang, Q., Yang, H., 2020. Microplastic fibers transfer from the water to the internal fluid of the sea cucumber Apostichopus japonicus. Environ. Pollut. 257 https://doi.org/10.1016/j.envpol.2019.113606.

Mohsen, M., Zhang, L., Sun, L., Lin, C., Wang, Q., Liu, S., Sun, J., Yang, H., 2021. Effect of chronic exposure to microplastic fibre ingestion in the sea cucumber Apostichopus japonicus. Ecotoxicol. Environ. Saf. 209, 111794 https://doi.org/10.1016/j.ecoenv.2020.111794.

Multisanti, C.R., Merola, C., Perugini, M., Aliko, V., Faggio, C., 2022. Sentinel species selection for monitoring microplastic pollution: a review on one health approach. Ecol. Indic. 145, 109587 https://doi.org/10.1016/j.ecolind.2022.109587.

Newman, M.C., Ownby, D.R., Mézin, L.C.A., Powell, D.C., Christensen, T.R.L., Lerberg, S. B., Anderson, B.A., 2000. Applying species-sensitivity distributions in ecological risk assessment: assumptions of distribution type and sufficient numbers of species. Environ. Toxicol. Chem. 19, 508–515. https://doi.org/10.1002/etc.5620190233.

Ogonowski, M., Edlund, U., Gorokhova, E., Linde, M., Ek, K., Liewenborg, B., Könnecke, O., Navarro, J.R.G., Breitholtz, M., 2018. Multi-level toxicity assessment of engineered cellulose nanofibrils in Daphnia magna. Nanotoxicology 12, 509–521. https://doi.org/10.1080/17435390.2018.1464229.

Parvin, F., Hassan, M.A., Tareq, S.M., 2022. Risk assessment of microplastic pollution in urban lakes and peripheral Rivers of Dhaka, Bangladesh. J. Hazard. Mater. Adv. 8, 100187 https://doi.org/10.1016/j.hazadv.2022.100187.

Pinheiro, L.M., Ivar do Sul, J.A., Costa, M.F., 2020. Uptake and ingestion are the main pathways for microplastics to enter marine benthos: a review. Food Webs 24, e00150. https://doi.org/10.1016/j.fooweb.2020.e00150.

Posthuma, Leo, Suter II, Glenn W., Traas, T.P., 2002. Species Sensitivity Distributions in Ecotoxicology. Lewis, Boca Raton.

Romanó de Orte, M., Clowez, S., Caldeira, K., 2019. Response of bleached and symbiotic sea anemones to plastic microfiber exposure. Environ. Pollut. 249, 512–517. https://doi.org/10.1016/j.envpol.2019.02.100.

Saborowski, R., Paulischkis, E., Gutow, L., 2019. How to get rid of ingested microplastic fibers? A straightforward approach of the Atlantic ditch shrimp Palaemon varians. Environ. Pollut. 254, 113068 https://doi.org/10.1016/j.envpol.2019.113068.

Salvador Cesa, F., Turra, A., Baruque-Ramos, J., 2017. Synthetic fibers as microplastics in the marine environment: a review from textile perspective with a focus on domestic washings. Sci. Total Environ. 598, 1116–1129. https://doi.org/10.1016/j.scitotenv.2017.04.172.

Schirinzi, G.F., Pedà, C., Battaglia, P., Laface, F., Galli, M., Baini, M., Consoli, P., Scotti, G., Esposito, V., Faggio, C., Farré, M., Barceló, D., Fossi, M.C., Andaloro, F., Romeo, T., 2020. A new digestion approach for the extraction of microplastics from gastrointestinal tracts (GITs) of the common dolphinfish (Coryphaena hippurus) from the western Mediterranean Sea. J. Hazard. Mater. 397, 122794 https://doi.org/10.1016/j.jhazmat.2020.122794.

Selonen, S., Dolar, A., Jemec Kokalj, A., Skalar, T., Parramon Dolcet, L., Hurley, R., van Gestel, C.A.M., 2020. Exploring the impacts of plastics in soil – the effects of polyester textile fibers on soil invertebrates. Sci. Total Environ. 700 https://doi.org/10.1016/j.scitotenv.2019.134451.

Setyorini, L., Michler-Kozma, D., Sures, B., Gabel, F., 2021. Transfer and effects of PET microfibers in Chironomus riparius. Sci. Total Environ. 757 https://doi.org/10.1016/j.scitotenv.2020.143735.

Song, Y., Cao, C., Qiu, R., Hu, J., Liu, M., Lu, S., Shi, H., Raley-Susman, K.M., He, D., 2019. Uptake and adverse effects of polyethylene terephthalate microplastics fibers on terrestrial snails (Achatina fulica) after soil exposure. Environ. Pollut. 250, 447–455. https://doi.org/10.1016/j.envpol.2019.04.066.

Watts, A.J.R., Urbina, M.A., Corr, S., Lewis, C., Galloway, T.S., 2015. Ingestion of plastic microfibers by the crab Carcinus maenas and its effect on food consumption and energy balance. Environ. Sci. Technol. 49, 14597–14604. https://doi.org/10.1021/acs.est.5b04026.

Woods, M.N., Hong, T.J., Baughman, D., Andrews, G., Fields, D.M., Matrai, P.A., 2020. Accumulation and effects of microplastic fibers in American lobster larvae (Homarus americanus). Mar. Pollut. Bull. 157, 111280 https://doi.org/10.1016/j.marpolbul.2020.111280.

Zeidi, A., Sayadi, M.H., Rezaei, M.R., Banaee, M., Gholamhosseini, A., Pastorino, P., Multisanti, C.R., Faggio, C., 2023. Single and combined effects of CuSO4 and polyethylene microplastics on biochemical endpoints and physiological impacts on the narrow-clawed crayfish Pontastacus leptodactylus. Chemosphere 345, 140478. https://doi.org/10.1016/j.chemosphere.2023.140478.

Zhang, X., Leng, Y., Liu, X., Huang, K., Wang, J., 2020. Microplastics' pollution and risk assessment in an urban river: a case study in the Yongjiang River, Nanning City, South China. Expo. Heal. 12, 141–151. https://doi.org/10.1007/s12403-018-00296-3.

Zhao, Y., Qiao, R., Zhang, S., Wang, G., 2021. Metabolomic profiling reveals the intestinal toxicity of different length of microplastic fibers on zebrafish (Danio rerio). J. Hazard. Mater. 403, 123663 https://doi.org/10.1016/j.jhazmat.2020.123663.

Ziajahromi, S., Kumar, A., Neale, P.A., Leusch, F.D.L., 2017. Impact of microplastic beads and fibers on waterflea (Ceriodaphnia dubia) survival, growth, and reproduction: implications of single and mixture exposures. Environ. Sci. Technol. 51, 13397–13406. https://doi.org/10.1021/acs.est.7b03574.