frontiers | Frontiers in Environmental Science

TYPE Systematic Review
PUBLISHED 19 September 2022
DOI 10.3389/fenvs.2022.999349

Check for updates

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Freshwater Science,
a section of the journal
Frontiers in Environmental Science

RECEIVED 20 July 2022
ACCEPTED 07 September 2022
PUBLISHED 19 September 2022

CITATION
Moyo S (2022), An enigma: A meta-analysis reveals the effect of ubiquitous microplastics on different taxa in aquatic systems.
Front. Environ. Sci. 10:999349.
doi: 10.3389/fenvs.2022.999349

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An enigma: A meta-analysis reveals the effect of ubiquitous microplastics on different taxa in aquatic systems

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Microplastics are ubiquitous in aquatic ecosystems globally, with tropical freshwater systems underrepresented in the literature. The ubiquity of microplastics may affect the feeding, growth, reproduction, and survival of organisms in aquatic systems; however, the data on the potential effects of microplastics on aquatic organisms is tentative. In the current study, I conducted a meta-analysis using published data to examine the impacts of microplastic exposure on functional traits (i.e., feeding, growth, reproduction, survival) of fish and aquatic invertebrates. The data revealed that while there were within-taxa negative effects on traits such as reproduction and growth some effect sizes were low, suggesting that the exposure to microplastics may vary across taxa. Globally, negative effects on growth, reproduction, and even survival were evident in some taxa (e.g., bivalves, crustaceans). Considering feeding habits, negative effects of microplastic were more pronounced in bacterivores, omnivores, predators, and filter feeders compared to shredders. In tropical freshwater systems, microplastics had no significant effects on the feeding, growth, reproduction, and survival of aquatic organisms. It is worth noting that organisms that are passive feeders (e.g., bivalves) may be particularly susceptible to microplastic pollution, which in turn may have long-lasting effects on the stability of lacustrine and lotic food webs. Because microplastics may impart more chronic effects than acute effects, future works must include understudied regions of the world (e.g., freshwater systems) and must emphasize the subtle role that microplastics may play on the physiology and behavior of organisms in the long term.

KEYWORDS
review, plastics, pollution, climate, tropics, food webs, freshwater, marine

Introduction

Microplastic ubiquity in aquatic environments is widely recognized (Gregory, 1978; Brahney et al., 2020), with much of the data suggesting that microplastics are the most abundant man-made pollutant on Earth (Geyer et al., 2017; Lavers and Bond, 2017). Microplastics originate from the breakdown of large plastic material via prolonged exposure to ultra-violet light and/or physical scuffing (Andrady, 2011). Other sources of microplastics include textile manufacturing industries (Dris et al., 2017; Gasperi et al., 2018), personal care products (e.g., toothpaste; Biginagwa et al., 2016), tire wear plastics and road-wear-associated microplastics (Vogelsang et al., 2018; Rødland et al., 2022), artificial turfs (e.g., playgrounds; van Kleunen et al., 2020), street litter (Haave and Henriksen, 2022), paint (Gaylarde et al., 2021), and wastewater from washing machines (Napper and Thompson, 2016). The ubiquity of microplastics in aquatic systems has been recognized for over four decades, with the effects of microplastics recognized among scientists and non-science audiences. With the effect of microplastics recognized, many researchers and citizens have emphasized the need for studies documenting the effect of microplastics on aquatic animals. To this end, it is not surprising that studies examining the effect of microplastics on aquatic animals have burgeoned in the last two decades (Lusher et al., 2017; Bucci et al., 2020).

Aquatic organisms may consume microplastics via the active or passive ingestion of microplastics attached to algae or sediment, which is a source of food for other animals (Desforges et al., 2015; Tongo and Erhunmwunse, 2022). Because microplastics can persist in the body of organisms for long periods, they can potentially be passed to higher trophic levels (predator species) such as fish, birds, and humans (reviewed comprehensively by Carbery et al., 2018). Microplastics can also be incorporated into an organism's tissues via the gills and gut walls (Watts et al., 2016). To date, several researchers have demonstrated the effects of microplastics on different organisms such as fish (e.g., Tongo and Erhunmwunse, 2022) and aquatic invertebrates (Paul-Pont et al., 2016). Specifically, microplastic exposure has been associated with several detrimental physiological effects, including decreased food consumption in annelid worms (*Arenicola marina*; Besseling et al., 2013), decreased growth in freshwater amphipods (*Gammarus fossarum*; Straub et al., 2017), depletion of energy reserves in African catfish (*Clarias gariepinus*; Karami et al., 2016), negative impacts on the fecundity of oyster (*Crassostrea gigas*; Sussarellu et al., 2016) and death in amphipods (*Hyalella azteca*; Au et al., 2015). Additionally, microplastics can adsorb organic pollutants (e.g., pesticides, polychlorinated biphenyls; PCBs), which subsequently have detrimental health effects such as endocrine disruption and death (Bakir et al., 2014; Horn et al., 2020). While microplastics can adversely affect organisms, some research has shown that microplastics do not affect aquatic organisms (e.g., Green et al., 2016). These data show that conclusions about the effects of microplastics on aquatic organisms may not be consistent across studies. For instance, ingestion of microplastics had not effect on mortality of zooplankton (*Daphnia magna*; Ogonowski et al., 2016) and African sharptooth catfish (*Clarias gariepinus*; Tongo and Erhunmwunse, 2022). Similarly, microplastic ingestion had no effect on the New Zealand mud snails (*Potamopyrgus antipodarum*; Imhof and Laforsch, 2016). Elsewhere, ingestion of microplastics caused death in brine shrimp (*Artemia franciscana*; Eom et al., 2020) and Zebra fish (*Danio rerio*; Dinani et al., 2021). It would seem that some organisms may be resilient to stresses induced by microplastic exposure (Watts et al., 2016) and more importantly microplastic effects may be taxon specific (Yıldız et al., 2022). For example, microplastics do not affect growth, behavior and metabolism of some amphipods (*Gammarus pulex*; Weber et al., 2018) whereas the same plastics decrease reproduction and growth in other groups of amphipods (*Hyalella azteca*; Au et al., 2015). In Japanese rice fish (*Oryzias latipes*), ingestion of fish causes stress and necrosis of single cells, while in other fishes it causes lipid accumulation and oxidative stress (Rochman et al., 2013; Lu et al., 2016). The divergent results on the potential impact of microplastic pollution in aquatic systems and the factors that drive those impacts remain to be extensively addressed.

In aquatic ecosystems, several abiotic factors may influence the effects of microplastics to aquatic consumers, including temperature, pH, ultraviolet radiation, and the presence of other environmental contaminants (Oliveira et al., 2013; Fonte et al., 2016; Cao et al., 2021; Ahechti et al., 2022). Among these factors, temperature is of special relevance because it can influence many biological and ecological processes. Moreover, aquatic communities are under increasing pressure from global warming, with projected increases of at least 1.5°C by the end of the century (IPCC, 2022). The survival of water fleas (*Daphnia magna*) under the presence of microplastics has been noted to decrease sharply with water temperature increases from 18 to 26°C (Jaikumar et al., 2018), indicating that these two stressors acted synergistically when they were combined. The underlying mechanisms of the synergistic effects of temperature and microplastics, may be because higher temperatures increase metabolic rates in organisms, which subsequently increases individual feeding rates and alters consumer-prey interactions (Brown et al., 2004; Rall et al., 2012). In spite of the potential interactions between temperature and microplastics, there is lack of research about the interactive effects of warming and microplastics on metabolic rates (but see Kratina et al., 2019; Serra et al., 2020). This uncertainty about the potential for water temperature to modify the impact of microplastics requires some attention for ecologists to fully understand the current and future risks of microplastic exposure to aquatic fauna.

Microplastic size and length of exposure to microplastics dictate the potential effects of microplastic on aquatic fauna's functional traits (Kögel et al., 2020). For instance, large microplastics can often block guts in aquatic organisms, which often decreases feeding and resource availability as has been documented in zooplankton (Cole et al., 2013). Moreover, microplastics can induce immune and strong inflammatory responses in invertebrates (von Moos et al., 2012; Avio et al., 2015; Ribeiro et al., 2017), which may alter organisms response to disease and parasites and potentially cause organisms to divert energy from other physiological processes (Greven et al., 2016). The concentration and length of microplastic exposure are key factors behind effects of microplastic on aquatic organisms. *Daphnia magna* a non-selective feeder that plays key roles in freshwater food chains and is a food source for many aquatic organisms (Hiltunen et al., 2017), is significantly affected after acute exposure to microplastic concentrations ranging between 75 and 150 mg/L (Mattsson et al., 2017). Similarly, after exposure periods of 24 h, *Daphnia magna* can become immobilized with reduced egg hatching rates and embryo development. Elsewhere, studies have shown that prolonged exposure to plastic particles ranging in size (20 nm to 5 μm) and long-term exposures (21 or 103 days of exposure) show reduced reproduction in crustaceans after exposure to polystyrene particles (Besseling et al., 2014; Kelpsiene et al., 2020).

While there is growing evidence that microplastics have effects on both freshwater and marine ecosystems there is a general paucity of studies from freshwater systems and those in tropical ecosystems (Wagner et al., 2014; Eerkes-Medrano et al., 2015; Scherer et al., 2018). The paucity of studies in freshwater systems and the tropics could be an artefact of biases towards marine research, the underfunding of research in inland waters (Maasri et al., 2022), and the general low research capacity in some of parts of the tropics (Marincola and Kariuki, 2020; Mutapi, 2021). The effects of microplastic on aquatic animals in the tropics are probably more pronounced considering many tropics, as in the whole world, are threatened by land use changes and anthropogenic global climate change (Ramírez et al., 2015; Vitule et al., 2017). In addition, to the threats of global warming and habitat degradation, tropical aquatic ecosystems are under increasing pressure from rapid population and economic growth and with that come the escalating problem of plastic and demand and waste disposal (Scherer et al., 2018; Donoso and Rios-Touma, 2020; Horton and Barnes, 2020; Álvarez-Lopeztello et al., 2021). To understand the full extent of the impacts of microplastics on aquatic animals there is need to include all regions including scanty data from freshwater systems and the aquatic systems in the tropics as a whole (Sarijan et al., 2021; Yardy et al., 2022).

Here I synthesize studies examining microplastics' effects on aquatic fauna using a meta-analysis. I compiled data from empirical studies to test the following hypotheses: 1) microplastic exposure will negatively affect key functional traits (i.e, feeding, growth, reproduction, survival) with effects more pronounced in some taxa (e.g., filter feeders or omnivores), because some taxa are passive feeders and do not select the foods they eat 2) the effect on functional traits will be directly related to temperature, size of plastics and length of exposure. In addressing these hypotheses, I also considered how these findings may relate to tropical freshwater systems (where experiments and mesocosm studies are scanty). In addition, some research needs for freshwater aquatic systems with an emphasis on understudied tropical systems are also considered.

Methods

Literature search

Literature searches were conducted using the free software "Publish or Perish" (Harzing, 2007) to collect articles that could be suitable for data extraction. The search was aimed at collecting articles examining the effects of microplastics on aquatic organisms (fish and other aquatic invertebrates). To search for potential articles the following Boolean phrase was used: [("plastic" OR "microplastic*" OR "micro plastic*" OR "micro-plastic*") AND ("function*" OR "response*" OR "measure*" OR "rate*" OR "Feeding*" OR "Growth*" OR "Reproduction" OR "Survival*") AND ("laborator*" OR "experiment*" OR "treatment*" OR "manipulat*") AND ("benth*" OR "animals*" OR "taxa" OR "invertebrate" OR "fish")]. The results of the search were further refined by choosing the range of publication years from 1900—2021. These publications years were selected to cover the wide range of studies that could potentially be included in the meta-analysis. The literature search yielded 958 results. During the screening, all extracted articles were checked for consistency with inclusion criteria following steps recommended by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA; See Supplementary Table S1 in supplementary materials; Moher et al., 2009). Initially, screening of articles was based on titles, then abstracts, and finally full text screenings of all remaining articles. Using a Population, Intervention, Control, and Outcome framework (PICO; Huang et al., 2006), papers from that used empirical approaches (experiments or mesocosms) to quantify the effects of microplastics on feeding, survival, reproduction, and growth of aquatic organisms were selected for the meta-analyses (*Population*). During the scoping exercise, only the following studies were included: 1) studies that actually measured at least one response of organisms to microplastics with adequate replication (*Intervention*) 2) studies that measured faunal effects (*Outcome*), and included a control group with no exposure to microplastics (*Control*) 3) studies that reported mean, samples sizes and associated variances for controls and treatments. The reason for only including the aforementioned studies is that it would be easier to eliminate the effects of other factors that could affect the physiology of aquatic organisms. After considering the above criteria, 72 studies were included in the final analyses (see

TABLE 1 Summary of the general categories of organism responses to microplastic exposure, and the specific description of response variables that comprise them.

General response variable	Specific response variables
Feeding	foraging (selectivity, giving up time, feeding time)
	Ingestion rate
	Egestion (defecation) rate
	predation (% attacked, % caught, % consumed, number eaten)
Growth	body condition, body size, growth rate, body length
Reproduction	fecundity, gonad size, % of abnormal offspring, pregnancy probability
Survival	longevity, survival number, survival rate

Supplementary for all data included in the final meta-analyses).

Data extraction

After literature sources were compiled, data were extracted from text, tables, or graphs. If the data were not reported in numbers, they were extracted from published diagrams using PlotDigitizer Version 3 (http://plotdigitizer.sourceforge.net/; Rohatgi, 2021). Data that presented the central tendency (mean or median if no mean was presented) in response to microplastic exposure were also extracted. If the study was an experimental manipulation, the data from the treatments containing the manipulation and the control were extracted. If a study tested multiple treatments (e.g., different concentrations of microplastics), all the data contained in that paper were extracted. If the authors described multiple experiments for a given response that were independent of each other, e.g., conducted experiments over two discrete periods, or if the authors reported results of a pilot study as well as the main study, those were included in the final analyses.

The literature search yielded studies with a range of response variables. Only studies including response variables most strongly related to feeding, growth, reproduction, and survival (see Table 1 for descriptions) and grouped different specific response variables into representative general categories were included. Those four responses were selected as they are the commonly measured variables in experiments and mesocosms. Some authors reported behavior but these were not always recorded in all studies, as such behavior could not be included as a measure. For each study, the following were documented: 1) the focal species, 2) the commonly designated functional feeding group of the focal species simplified into broad categories such as predator, omnivore, filter feeder 3) the response variable measured (feeding, growth, reproduction, survival), 4) abiotic and physical conditions of the experiment including microplastic type, size, temperature and length of exposure, and 5) the ecosystem type (freshwater versus marine) food web 6) whether the organism being tested was from the tropics or not.

Data analyses

To account for the differences in variables and reporting of results across all studies considered, effect sizes were measured using a Hedges'g statistic. The Hedges'g statistic is a standardized mean difference (SMD) between control and treatment that accounts for the heterogeneity in variables reported by dividing the SMD by the pooled standard deviation (Hedges, 1981; Buck et al., 2022). Because the sign of Hedges'g tells the direction of the effect, a negative value of Hedges' g indicates that microplastics have a higher effect on impairing the specific trait considered. Hedges'g values of less than 0.2 represent small effects, values between 0.2 and 0.5 represent moderate effects, with values greater than 0.5 suggesting large effects (Borenstein et al., 2010).

All statistical models were performed using the "rma.mv" function of the metafor package in R. The "rma.mv" function uses a Wald-type test to determine statistical difference among tested groups (Viechtbauer, 2010; Saldaña-Vázquez and Munguía-Rosas, 2013). Mixed effects models were performed that included the study identification number (i.e., the ID of the study as reported in my dataset) and the functional traits (feeding, growth, reproduction, survival) as random effects to account for heterogeneity (Viechtbauer, 2007) and non-independence of results (Salerno et al., 2021). Effect sizes for the models including categorical fixed factors were considered to be statistically significant if their 95% confidence interval (CI) did not overlap with zero and if their alpha value (p) values were less than 0.05.

To examine the effects of temperature, and microplastic size a meta-regression was performed using the 'lmer' function from the lme4 library to perform mixed-effect regression analyses (Bates and Maechler, 2009).

All statistical analyses and graphing plotting were performed in R software (R Core Team, 2022, version 4.1.2, Vienna, Austria).

Results

Microplastic exposure to key functional traits (hypothesis 1)

Broadly, results revealed that the effect of microplastic exposure varies by taxonomic groupings (Figure 1).

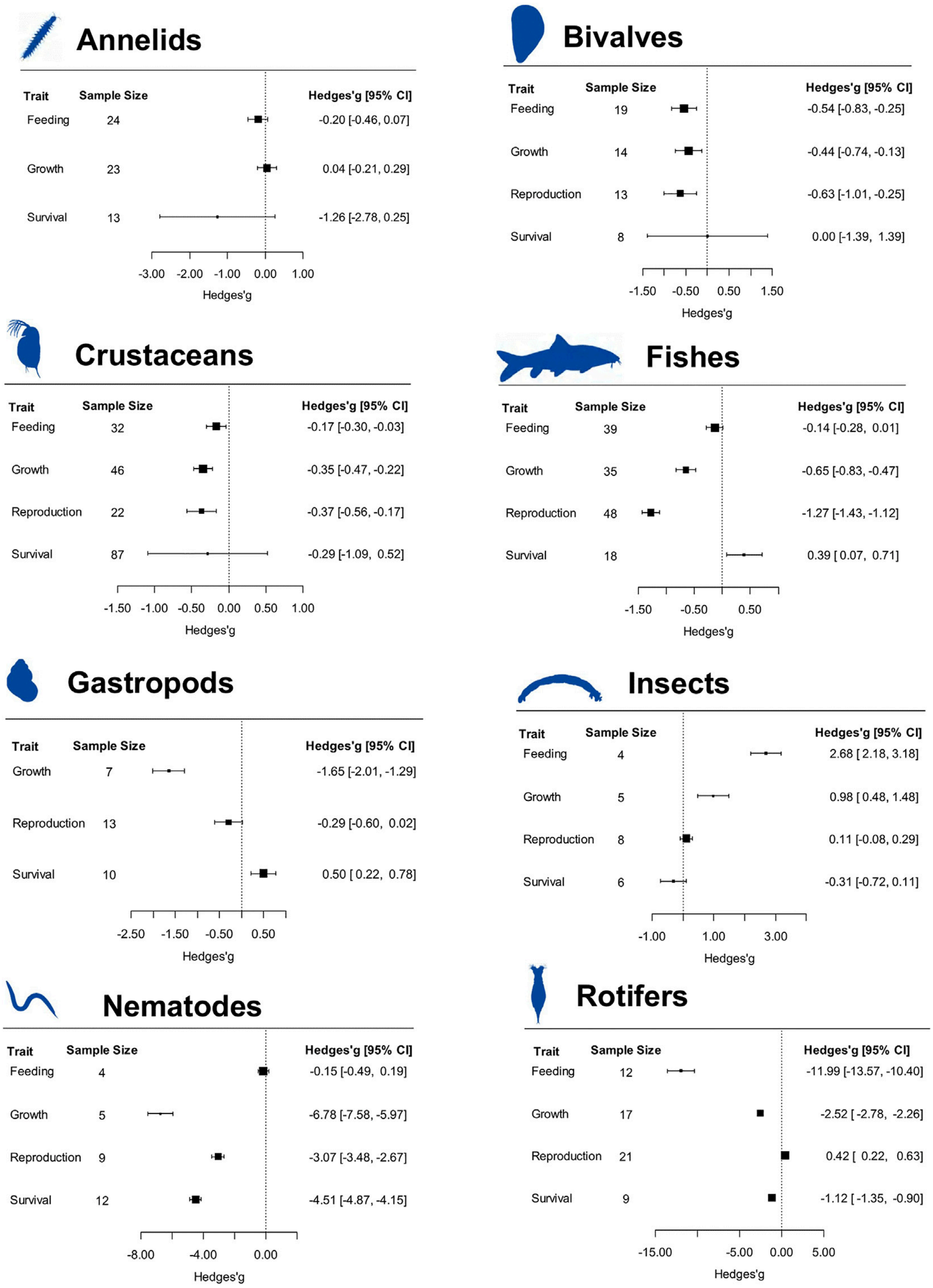

FIGURE 1
Forest plot of effect sizes of response categories based on taxonomic groupings. Analyses were conducted using a mixed-effects model. Black boxes denote the hedges'g value and horizontal lines denote the 95% confidence intervals (CI) for each hedges'g value. Hedges'g values of less than 0.2 represent small effects, values between 0.2 and 0.5 represent moderate effects, with values greater than 0.5 suggesting large effects. The relative size of the black boxes shows the relative effect size of the studies included in each analysis.

TABLE 2 Effect sizes of microplastic responses of aquatic organisms based on their feeding modes included in the meta-analysis. Hedges'g values and associated p-values are also reported. Lower-95 and Upper -95 represent credibility intervals. Asterisks significant effects for each species *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Hedges'g values of less than 0.2 represent small effects, values between 0.2 and 0.5 represent moderate effects, with values greater than 0.5 suggesting large effects.

Functional feeding group	Hedges'g	SE	Lower-95	Upper-95	p-value
Bacterivores	−2.71	0.10	−2.92	−2.51	<.0001***
Deposit Feeders	−0.09	0.09	−0.27	0.09	0.3486
Filter Feeders	−0.36	0.05	−0.45	−0.26	<.0001***
Grazers	−0.10	0.08	−0.25	0.06	0.2205
Omnivores	−0.64	0.04	−0.72	−0.57	<.0001***
Predators	−0.81	0.12	−1.05	−0.57	<.0001***
Shredders	0.16	0.07	0.03	0.29	0.0187*

Nematode growth, reproduction, and survival were all moderately reduced by exposure to microplastics. Contrariwise, feeding had no effect on the feeding of nematodes. Rotifer exposure to microplastics largely affected their feeding, growth and survival, but exposure to microplastics, had a moderately positive effect on reproduction in rotifers. Annelid feeding, growth, and survival were not affected by exposure to microplastics. Exposure to microplastic had a large positive effect on the feeding and growth of aquatic insects while having no effect on reproduction and survival of aquatic insects. Microplastics negatively affected gastropod growth while it conversely had positive effects on gastropod survival. In gastropods, microplastics had no effect on reproduction. Crustacean and bivalve growth and reproduction were all moderately reduced when exposed to microplastics. Similarly, crustacean and bivalve exposure to microplastics reduced feeding. Exposure to microplastics did not affect survival of crustaceans. Fish growth and reproduction were largely negatively affected and marginally affected by exposure to microplastics, respectively. Exposure to microplastics had a marginal negative effect on feeding in fishes. Overall, microplastic exposure did not affect survival in most groups, it actually had positive effects on fishes and gastropods (Figure 1).

Among feeding modes, bacterivores (e.g., nematodes; Hedges'g = -2.71 ± 0.10), Omnivores (Hedges'g = -0.64 ± 0.04), and predators (many fishes; Hedges'g = -0.81 ± 0.12) were negatively affected to a larger extent than filter feeders (Hedges'g = -0.36 ± 0.05). Shredders were marginally affected by microplastics (Table 1). Grazers and deposit feeders were not affected by microplastics (Table 2).

In tropical freshwater systems (Figure 2B), exposure to microplastics had no effect on growth, survival, and feeding. Strikingly, microplastics had large positive effect on reproduction and feeding in tropical aquatic systems.

Summarizing data across all groups (Figure 2C), shows that exposure to microplastics had a significantly negative effect on the feeding, growth, reproduction, and survival of organisms.

Effect of temperature, microplastic size, and length of exposure (hypothesis 2)

In general, temperature, microplastic size, and length of exposure had no effect on different taxonomic groups with a few exceptions (Table 3). Specifically, temperature was positively related to responses in annelids but negatively affected fish traits. Days of microplastic exposure only influenced rotifers (positive relationship) and annelids. Microplastic size only had effects on annelids.

Species specific and habitat effect of microplastics

The effect of microplastics varied by species (Table 4). The extracted data, which covers 47 species shows significant negative effects on 23 of the species considered. The effects of microplastics ranged from moderate to large effects in all organisms considered.

Considering habitat effects, microplastics have a significant negative effect on organisms in both freshwater and marine systems (Figure 2A). Considering the effect size by habitat reveals that the effects of microplastics are greater in freshwater systems than marine systems.

Discussion

Microplastics are ubiquitous and questions remain on the full extent to which they are harmful to organisms (Galloway and Lewis, 2016; Issac and Kandasubramanian, 2021). Here, a global

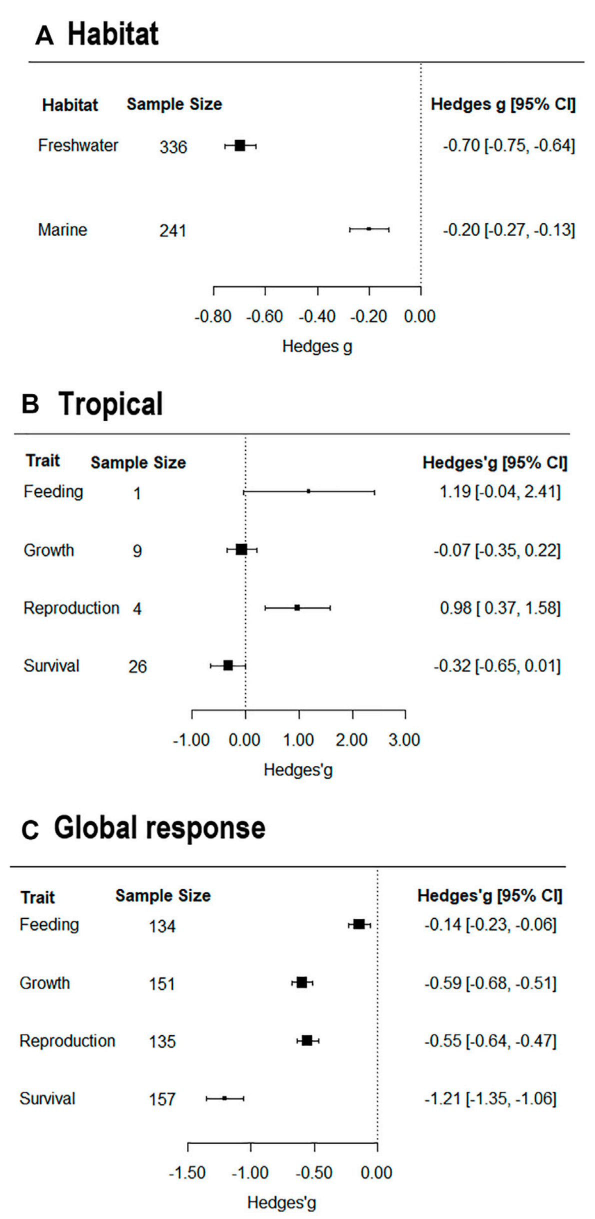

FIGURE 2
Forest plot of effect sizes by **(A)** Habitat **(B)** Tropical freshwater systems functional traits **(C)** Global response traits. Analyses were conducted using a mixed-effects model. Black boxes denote the hedges'g value and horizontal lines denote the 95% confidence intervals (CI) for each hedges'g value. Hedges'g values of less than 0.2 represent small effects, values between 0.2 and 0.5 represent moderate effects, with values greater than 0.5 suggesting large effects. The relative size of the black boxes shows the relative effect size of the studies included in each analysis.

perspective of the potential effects of microplastics was explored using a plethora of data from different aquatic systems. This study revealed substantially negative effects of microplastics on growth, reproduction, survival and feeding regardless of habitat or species as documented in other studies (e.g., Yin et al., 2018; Salerno et al., 2021). One key finding from this work is that the effect of microplastics varies with taxa, and may negatively affect shredders and filter feeders; with the largest negative effects evident in omnivores, predators and bacterivores (**hypothesis 1** partially supported). Congruent to previous research (e.g., Au et al., 2015; Foley et al., 2018; Salerno et al., 2021), the results demonstrate significant impacts of exposure to microplastics on functional traits, and highlight that temperature, microplastics size and length of exposure may not have detrimental effects on aquatic organisms (**hypothesis 2** not supported).

Nematode growth, reproduction and survival was negatively affected by exposure to microplastics. The effects of microplastic on nematodes may be related to their linear digestive systems, and damage to the pharynx (and associated glands) that produce lubricants and digestive enzymes. Studies on nematode anatomy and physiology have shown that the consumption of microplastics causes the accumulation of microplastic in the intestine, damage to small intestine lining, oxidative stress, and increases in calcium levels; which subsequently leads to decreases in reproduction, survival and growth (Jeong et al., 2016; Lei et al., 2018). Researchers have shown that microplastic exposure to nematodes causes the inhibition of Glutathione S-transferase 4 (GST-4), an enzyme that plays roles in the detoxification and excretion of contaminants from cells (Kahn et al., 2008; Lei et al., 2018). The aforementioned factors may explain the negative effects of microplastics on nematodes.

Rotifer feeding was negatively affected by microplastics. Microplastics in rotifers interfere with normal food ingestion, and in addition, the particles function as a non-food item, providing no energy resource. Thus, microplastics effectively occupy space in the digestive tract, decreasing the available space for algal food. A similar study on zooplankton (*Daphnia magna*) determined that chronic exposure to microplastics led to reduction in fitness (number of offspring), because of inactivation of several digestive enzymes, which ultimately interfered with the animal's nutrient supply (Trotter et al., 2021). The uniqueness of the reproduction systems in rotifers may explain why Rotifera reproduction actually increased. Considering that rotifers considered here are monogononts (they essentially reproduce by parthenogenesis) that can produce diploid eggs by mitosis (amictic), haploid eggs (mictic) by meiosis, haploid and diploid eggs simultaneously (amphoteric) or resting eggs (diapause eggs) when conditions are unfavourable (Stelzer, 2005), it is not surprising that their microplastics did not cause negative affect reproduction. The null effects of microplastic on rotifers, could be because rotifers exposed to microplastics may not obtain enough energy resources, thus leading to a significant reduction in reproduction (Van Cauwenberghe et al., 2015; Sun et al., 2019). The weakened overall performances of rotifers may inevitably be the mechanism that causes them to change in reproductive strategies.

TABLE 3 Meta-regression analyses between effect size (dependent variable = Hedges' g of microplastic response) and three independent variables extracted from the literature (temperature in °C, maximum exposure in days, microplastic size in μm). Beta (β) represents the slope of the best fit line. SE represent the standard error of β. Lower-95 and Upper -95 represent credibility intervals. R^2 denotes the proportion of the variance explained by the regression model. p represents statistical significance. Asterisks significant effects for each species *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Fixed effect	β	SE	Lower-95	Upper-95	R^2	p
Annelids						
Temperature	1.01	0.39	0.27	1.74	0.33	0.017*
Exposure	0.06	0.02	0.03	0.09	0.33	0.002**
Size	0.01	0.00	0.00	0.02	0.33	0.009**
Bivalves						
Temperature	0.32	0.17	0.03	0.62	0.62	0.056
Exposure	0.03	0.02	0.00	0.06	0.62	0.049
Size	0.06	0.04	−0.01	0.14	0.62	0.129
Crustaceans						
Temperature	−0.04	0.08	−0.19	0.10	0.19	0.578
Exposure	0.01	0.02	−0.03	0.04	0.19	0.742
Size	0.04	0.03	−0.01	0.10	0.19	0.170
Fish						
Temperature	−0.17	0.08	−0.33	−0.02	0.51	0.039*
Exposure	−0.01	0.02	−0.04	0.02	0.51	0.451
Size	0.00	0.00	0.00	0.01	0.51	0.627
Gastropod						
Temperature	−0.19	0.37	−0.76	0.23	0.32	0.655
Exposure	−0.01	0.02	−0.04	0.02	0.32	0.650
Size	−0.01	0.04	−0.05	0.04	0.32	0.886
Hexapod						
Temperature	−4.41	61.96	−104.83	99.30	0.25	0.944
Exposure	2.82	5.56	−6.11	13.65	0.25	0.946
Size	−0.24	0.62	−1.59	0.75	0.25	0.623
Nematoda						
Temperature	−2.95	14.52	−29.03	23.13	0.31	0.841
Exposure	2.96	2.61	0.28	5.64	0.31	0.267
Size	−0.02	0.15	−0.30	0.26	0.31	0.880
Rotifers						
Temperature	8.08	9.07	−8.63	25.81	0.99	0.407
Exposure	10.34	2.02	2.67	14.34	0.99	0.000***
Size	0.26	0.25	−0.21	0.81	0.99	0.305
Tropical						
Temperature	−0.25	0.91	−1.75	1.26	0.88	0.797
Exposure	0.15	0.22	−0.21	0.52	0.88	0.530
Size	0.07	0.02	0.02	0.11	0.88	0.006***

Microplastics did not affect annelid feeding, growth, and survival. These finding are consistent with the results obtained by other researchers. For instance, Green et al. (2016) used annelids as model organisms (*Arenicola marina*) and demonstrated that microplastics (polyethylene and polylactic acid) had no effect on survivorship, biomass and behavior, although respiration rate was affected to an extent. It was expected that microplastics would have a significant effect on annelids considering the amount of microplastics consumed by annelids is higher than most herbivores, as suggested by other researchers (e.g., Parker et al., 2022). However, as has been demonstrated by many authors, it would seem that microplastics have no immediate effects on annelids because annelids process microplastics in similar ways as inorganic particles (e.g., sand grains). The digestive tract of most annelids can process inorganic material ingested along with organic particles (Jumars et al., 2015). For example, in some species of annelids (e.g., *Saccocirrus* and *Arenicola marina*) their straight digestive tracts (with cilia;

TABLE 4 Effect sizes of microplastic responses for each species included in the meta-analysis. Hedges'g values and associated p-values are also reported. Asterisks significant effects for each species *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. FFG denotes the functional feeding group. Hedges'g values of less than 0.2 represent small effects, values between 0.2 and 0.5 represent moderate effects, with values greater than 0.5 suggesting large effects.

Species	Grouping	FFG	Hedges'g	SE	p-value
Arenicola marina	Annelida	Deposit feeder	−0.06	0.09	0.532
Lumbriculus variegatus	Annelida	Deposit feeder	0.00	0.53	1.000
Tubifex spp.	Annelida	Deposit feeder	−1.02	0.53	0.055
Crassostrea gigas	Bivalve	Filter feeder	−0.40	0.13	0.003**
Mytilus edulis	Bivalve	Filter feeder	−3.02	0.60	<.0001***
Mytilus galloprovincialis	Bivalve	Filter feeder	−0.25	0.41	0.542
Ostrea edulis	Bivalve	Filter feeder	0.14	0.21	0.482
Perna viridis	Bivalve	Filter feeder	−1.42	0.22	<.0001***
Sphaerium corneum	Bivalve	Filter feeder	−0.18	0.50	0.725
Acartia clausi	Crustacean	Omnivore	−0.23	0.13	0.075
Asellus aquaticus	Crustacean	Shredder	−0.08	0.50	0.870
Balanus glandula	Crustacean	Filter feeder	0.00	0.16	0.995
Calanus helgolandicus	Crustacean	Omnivore	−0.10	0.46	0.827
Carcinus maenas	Crustacean	Predator/Omnivore	0.14	0.58	0.804
Centopages typicus	Crustacean	Omnivore	−1.79	0.35	<.0001***
Daphnia magna	Crustacean	Filter feeder	−0.34	0.06	<.0001***
Gammarus fossarum	Crustacean	Shredder	−0.27	0.19	0.161
Gammarus pulex	Crustacean	Shredder	−1.12	0.60	0.061
Hyalella azteca	Crustacean	Shredder	−0.67	0.21	0.001**
Idotea emarginata	Crustacean	Grazer	−0.06	0.09	0.512
Nephrops norvegicus	Crustacean	Omnivore	−1.31	0.46	0.005**
Platorchestia smithi	Crustacean	Deposit feeder	−0.42	0.25	0.073
Lytechinus variegatus	Echinoderm	Grazer	−1.67	0.65	0.010**
Paracentrotus lividus	Echinoderm	Grazer	−2.41	0.57	<.0001***
Tripneustes gratilla	Echinoderm	Grazer	0.62	0.32	0.058
Clarias gariepinus	Fish	Omnivore	−0.35	0.28	0.213
Cyprinus carpion	Fish	Predator	−2.93	0.21	<.0001***
Danio rerio	Fish	Omnivore	−1.47	0.09	<.0001***
Dicentrarchus labrax	Fish	Predator	0.38	0.29	0.189
Lates calcarifer	Fish	Predator	1.19	0.63	0.058
Oncorhynchus mykiss	Fish	Predator	0.53	0.83	0.522
Oryzias latipes	Fish	Omnivore	−0.21	0.18	0.234
Oryzias melastigma	Fish	Omnivore	−0.43	0.19	0.027*
Pimephales promelas	Fish	Omnivore	0.17	0.11	0.122
Pomatoschistus microps	Fish	Omnivore	−0.23	0.08	0.003**
Sebastes schlegelii	Fish	Predator	1.80	0.75	0.016*
Symphysodon aequifasciatus	Fish	Omnivore	−0.37	0.30	0.222
Crepidula onyx	Gastropod	Grazer	−0.58	0.13	<.0001***
Lymnaea stagnalis	Gastropod	Grazer	0.98	0.31	0.002**
Potamopyrgus antipodarum	Gastropod	Grazer	−0.23	0.14	0.091
Chironomus riparius	Hexapoda	Shredder	0.40	0.12	0.001**
Chironomus tepperi	Hexapoda	Shredder	−2.88	0.65	<.0001***
Culex pipiens	Hexapoda	Shredder	0.43	0.10	<.0001***
Caenorhabditis elegans	Nematoda	Bacterivore	−2.71	0.10	<.0001***
Brachionus koreanus	Rotifer	Omnivore	−1.25	0.24	<.0001***
Brachionus plicatilis	Rotifer	Omnivore	−0.81	0.07	<.0001***
Brachionus rotundiformis	Rotifer	Omnivore	−11.99	0.81	<.0001***

Pechenik, 2014) prevent hindrances or blockages by microplastics and other indigestible particles. Additionally, the ability to quickly regenerate damaged tissues (Kostyuchenko and Kozin, 2021), may increase their resilience to physical injuries caused by the ingestion of these particles (Besseling et al., 2013). However, it must be noted, there may be a long-term trade-off of ingesting microplastics, which may affect the individual fitness of annelids. For instance, ingesting plastic may cause annelids to expend energy capturing, ingesting and expelling a particle that offers no nutritional value.

Exposure of microplastics did not affect reproduction and survival of aquatic insects as documented by many authors (Ziajahromi et al., 2018; Khosrovyan et al., 2020). Researchers have hypothesized that aquatic larvae may have an effective feeding strategy to avoid non-food material (Khosrovyan and Kahru, 2020). This hypothesis is tenable considering that some aquatic insects have been shown to preferentially select for high quality food rich in long-chain polyunsaturated fatty acids (Guo et al., 2018).

In concordance with Hämer et al. (2014), microplastic exposure did not have deleterious effects on gastropod reproduction and survival. However, the decreased growth in gastropods exposed to microplastics could be compensatory effect due to food depletion by an increased abundance of microplastic particles in the food and a subsequent reduction of energy reserves. Such effects have already been demonstrated in sediment feeding annelids (Wright et al., 2013a).

Exposure to microplastics had negative effects on feeding, growth, and reproduction of bivalves. Bivalves as filter feeders, use their gill cilia to drive water through their mantle cavity to obtain food (McElwain and Bullard, 2014). Ingestion of microplastics probably affects feeding by substantially decreasing water flow through blocking bivalve openings. These blockages potentially limit the uptake of food as well as gas exchange in bivalves. To date several works have demonstrated that mussels adjust the opening width of their valves to the amount of food particles in the water column and to the quality of the suspended particulate matter. An increase in the abundance of microplastics, which can potentially harm the animals by injuring epithelia or by causing blockages, leads to a rapid reduction of valve openings (Wright et al., 2013b; Rist et al., 2016). A reduction in feeding and of oxygen uptake by suspended inorganic particles ultimately results in reductions in energy availability and metabolism, which ultimately reduces growth. Because microplastics microplastic are absorbed into gill filaments and the gill septum of bivalves this may cause problems in the reproduction of bivalves (McElwain and Bullard, 2014). For instance, many bivalves (freshwater unionids) incubate their larvae during part of their development in "marsupials" formed by the septa within the gill's filaments, therefore microplastic particles could impair reproduction by damaging gill filaments and gill septa (Pechenik, 2014).

Crustaceans (mostly zooplankton) and bivalves (many of which are filter feeders) were susceptible to microplastic exposure and their feeding, growth and reproduction were negatively affected (Figure 1). The effects of microplastic on feeding in filtering organism are reasonable considering that filter feeders do not choose their food and obtain food by filtering large volumes of water and usually display the highest quantities of microplastics in their digestive tracts (Sfriso et al., 2020). Considering crustaceans and bivalves are key to many aquatic food webs effects on the feeding and growth may affect consumers at higher trophic levels. Considering bivalves and crustaceans make up the bulk of seafood consumed by humans (Guillen et al., 2019; Hu and Chan, 2020) there is potential that these microplastics may be passed to humans (Smith et al., 2018), however this is beyond the scope of this work.

Fish, the only vertebrate included in this study, were negatively affected by microplastics (Figure 1). As vertebrates the effect of microplastics on fish may occur due to the buildup of ingested microplastics in their digestive tract, which ultimately leads to low caloric intake and malnutrition (Yin et al., 2018). Decreases in caloric intake are ultimately associated with decreases in growth and reproduction in fishes (Watts et al., 2016). Additionally, microplastics may block gills that may affect oxygen consumption and the movement of ions in and out of fishes. These blockages may affect the osmoregulation and respiration rates in fishes, which in turn may affect behavior and fitness as a whole (Li et al., 2018). For instance, fish exposed to microplastics have been shown to swim slower and catch fewer prey items than their conspecifics not exposed to plastics (Huang et al., 2022). In addition, fish that are exposed to microplastics have elevated levels of Gamma-Aminobutyric Acid (GABA), an inhibitory neurotransmitter that reduces excitability, in their brains. These high levels of GABA caused slower reaction times, and reduced ability to swim and catch prey (Huang et al., 2022).

Congruent to finding by Parolini et al. (2020), grazers and deposit-feeders were not significantly affected by microplastics. With regards to grazers many of them use their 'teeth' to scrap, grasp and tear the food from the benthos (Contreras and Castilla, 1987). Subsequently, many grazers will form boluses (Bonasoro and Carnevali, 1994) that may prevent fragmented and irregular plastics from damaging tissues of the digestive tracts. With regards to deposit feeders, that obtain their food on the surface and subsurface layers of sediment may not be affected by microplastics because many of deposit feeders have mucus-lined proboscis and tentacles that only sticks to small particles while not attaching to larger particles may reduce the effects of microplastics of deposit feeders (Lopez and Levinton, 1987; Wright et al., 2013b). Similarly, many deposit-feeders are able to rapidly egest materials that are not nutritionally beneficial (Lopez and Levinton, 1987; Pechenik, 2014).

Broadly, I found that microplastics had no effect on survival for most aquatic organisms. This may suggest that some

TABLE 5 Select studies documenting the effect of microplastics in freshwater systems. Only species that occur in the tropics are documented here.

Species	plastic type	Summary of effects	References
Daphnia magna	Polyethylene	Elevated mortality	Ogonowski et al., (2016)
Gammarus pulex	Polyethylene terephthalate	No effect on growth, metabolism, behaviour	Weber et al., (2018)
Clarias gariepinus	low density polyethylene	No effect on mortality opercular respiratory rate increase reduced swimming speed, travel distance and movement patterns of the fish	Tongo and Erhunmwunse, (2022)
Clarias gariepinus	low density polyethylene	increased the degree of tissue change in gills and liver	Karami et al., (2016)
Potamopyrgus antipodarum	Mixture of plastics	No effect on morphology, reproduction, and development	Imhof and Laforsch, (2016)
Chironomus riparius	Mixture of plastics	widening of wings, elongation of the mentums and shape of the mandibles prolonged development time	Stanković et al., (2020)

organisms are able to withstand exposure to microplastics. A potential explanation for the none effects of microplastics observed may be related to gut morphology of some animals considered. For instance, detritivorous shredders, amphipods are evolutionary adapted to process non-digestible food components. The chitinous peritrophic membrane in crustaceans is secreted in the midgut where it encloses the food to protect the digestive system against particle-induced injuries (Pechenik, 2014). While there is no way from the studies analysed here to determine whether organisms selectively avoid microplastics, there is evidence in the literature that organism may potentially avoid microplastics when food is plenteous. For instance, sea urchins (*Tripneustes gratilla*) selected algae (their preferred food) over polyethylene microplastics when food was abundant (Kaposi et al., 2014). Elsewhere, marine copepods (*Temora longicornis*) selectively avoided 80% of microplastics after 'tasting' them with their mouth parts, almost indicative of taste discrimination between plastic and algae in zooplankton (Xu et al., 2022).

I found significant differences in effect sizes between freshwater and marine systems, with freshwater systems showing more negative effects (Figure 2B). The data reveal the ubiquity of microplastic in both systems and that the microplastic effects vary by habitat and may be more pronounced in freshwater systems than marine systems (*sensu* Scherer et al., 2018). These findings also support the assertion that aquatic organisms may be affected by microplastics globally, as evidenced by the number of studies that document microplastic occurrence globally. Currently, there are few studies that have documented the transfer of microplastics to higher trophic levels (but see (Nelms et al., 2018; Costa et al., 2020). The effects of microplastic transfer to higher trophic levels remains an opportunity for future research.

Tropical freshwater revealed that microplastic have no effect on feeding, growth and survival of organisms. These findings are mostly congruent with studies on microplastics in freshwater biota that occur in the tropics (summarized in Table 5). Studies on the potential adverse effects caused by microplastic exposure are scarce for freshwater compared to marine ecosystems. Some of our conclusions on freshwater systems and also the freshwater in the tropics may be limited by the few available studies. The few studies in freshwater organisms focus on water fleas (*Daphnia magna;* Ogonowski et al., 2016), amphipods (*Hyalella Azteca* and *Gammarus pulex;* Au et al., 2015; Weber et al., 2018), New Zealand mud snail (*Potamopyrgus antipodarum;* Imhof and Laforsch, 2016) as well as the African Catfish (Tongo and Erhunmwunse, 2022). Null effects in tropical freshwater systems may be related to crustacean gut morphology (as discussed above) and studies conducted over noticeably short microplastic exposures (1–28 days with most studies carried over 2 days). More studies assessing the acute and chronic effect of microplastic on freshwater organism are therefore warranted. This is particularly tenable considering that a study by Gallitelli et al. (2021) showed that microplastic over time can cause subtle changes in behavior in freshwater insects. Particularly, case building caddisflies (*Odontocerum albicorne*) constructed cases using microplastic polymers instead of natural items when presented with microplastics. Moreover, when presented with natural substrates and microplastics, mayflies (*Ephemera Danica*) were observed to burrow into microplastic substrates rather than natural ones. These preferences for microplastics versus natural substrates may not harm individual animals but may affect the animals that feed on some of these organisms. Indeed, insect larvae appear to not necessarily perceive microplastics as a direct stressor especially considering that freshwater insect feeding and growth was positively affected by microplastic exposure, but microplastic exposure had no effects on reproduction and survival (Figure 1). Further studies ought to be conducted to understand the chronic effects of microplastics on insects. Such, investigations should also focus on behavior (e.g., drift behavior) in invertebrates exposed to microplastics as these are the chronic effects that are common in some organisms exposed to microplastics (Issac and Kandasubramanian, 2021).

Microplastic size, duration of exposure to microplastic, and temperature had no effects on the effect of microplastic exposure on fish and invertebrates. I would have expected the aforementioned factors to have significant effects on organism response to microplastics. Considering, climate change is already causing increased temperatures, extreme weather events, including tropical storms, which can redistribute microplastics between terrestrial, freshwater and marine environments (Chen et al., 2021), the effects of temperature of organisms may become more evident in the future. For instance, microplastic are known to increase in seawater and sediments after a severe storm (Wang et al., 2019). As such, stronger winds, rainfall, and sea level rises are likely to release plastics trapped in sediments. Researchers have demonstrated that flooding in rivers worsens riverine plastic pollution, with flood risk areas often becoming sites with high plastic accumulation during flooding events (Roebroek et al., 2021). Elsewhere, temperature rises (from 20 to 25°C), increased the microplastic induced mortality (from 8 to 33%). Authors should consider conducting controlled experiments across varying temperature regimes. Concerning the effect of microplastic sizes, it may be expedient for authors to not just report microplastic size but to report the weight (or volume) of microplastic particles used, because size alone does not actually consider the density of microplastics. Concerning duration, where most studies only occurred for 2 days it is very plausible that the exposure time was short in most studies. As such, it may be useful for authors to focus on more chronic effects (long term studies) as opposed to the acute (short-term) effects of microplastic exposure.

Here I focused on four main responses assessed out of the copious number of response recorded in many studies in the literature that include gene expression (Mazurais et al., 2015) and physical malformations (Pedà et al., 2016). The exposure to microplastics may have more indirect or subtle effects. For instance, microplastic ingestions may alter the community structure of microbiota in fishes (Zhang et al., 2021), and even humans (Tamargo et al., 2022). Since gut microbiota are shaped by diet: they have coevolved with its host to create a symbiotic relationship, whereby the gut community receives favorable conditions, whilst the host benefits from access to essential nutrients. As such, if the host's diet is impaired by microplastics, the host will suffer from malnutrition, but its gut symbionts will also be afflicted by a lack of nutrients and substrate necessary to feed the community, potentially leading to shifts in gut community structure. Consequently, symbiotic bacteria may not be able to provide the same functions, especially considering that microbial gene expression is also linked to host diet (*sensu* Friberg et al., 2019). In addition, microplastics may have effects other than the four I considered. Specifically, microplastics may act as endocrine disruptors by releasing chemicals that mimic or antagonize sex hormones such estrogen (Yang et al., 2011). These chemicals may subsequently negatively impact reproduction (e.g., change in functions of reproductive organs, change in sex specific behaviors) and respiratory functions (Hu et al., 2020). Examining the aforementioned data in a way similar to the current study may be challenging, as quantification of these responses are sometimes qualitative (presence or absence of fluorescence) or not always reported in forms that can be easily extracted.

Additional considerations and conclusions

Here the meta-analysis considered studies from 1900 to 2021, and as such the results presented here may change with future perturbations and microplastic production. Considering the world experienced a global pandemic (Covid 19; Liu et al., 2020) that affected millions of people globally (Simonsen and Viboud, 2021). The use of plastic-based personal protection equipment has risen dramatically since the COVID-19 pandemic (De-la-Torre and Aragaw, 2021). Surgical masks are made from various polymer materials (e.g., polyethylene, polyester, etc.). The use of plastic-based personal protection devices (such as N95 masks) during pandemic increases plastic waste, which may end up in aquatic systems. The constant use of plastic made protection devices will continue to increase and may potentially change the interpretation of my results in the future owing to potential deposition of microplastic into aquatic systems (De-la-Torre and Aragaw, 2021). A pandemic (Liu et al., 2020), anthropogenic climate change (Fawzy et al., 2020) and an increasing human population (Sadigov, 2022) will all change the potential effects of microplastics on aquatic biota.

Comparing the distribution of studies in the literature -where tropics and the African continent underrepresented- there is a need for more controlled studies examining the effects of microplastics on fauna in the tropics and the African continent. Some of the immediate needs for tropical aquatic systems include and are not limited to long-term multiple species studies that examine effects of microplastic, the potential of microplastic transfer to higher trophic levels and how microplastics can alter the ethology of organisms. Similarly, standardization of concentrations and exposure conditions are needed from several aquatic systems to allow for more comparable data. Specifically, methods for reporting microplastic concentrations varied considerable among studies, impeding the analysis of microplastic concentration as moderator variable. Given that many authors report the concentration microplastics as number of microplastic pieces per unit volume (e.g., de Sá et al., 2015; Blarer and Burkhardt-Holm, 2016), while others report weight of microplastic per unit volume (e.g., Fonte et al., 2016), and many others report percent plastic by weight of sediment and/or food (e.g., Hämer et al., 2014). While standardization of how concentrations are reported may be difficult across many academic fields in microplastic research, researchers should think about reporting both the size and weight of microplastics as density per unit volume (detailed in Phuong et al., 2016). Additionally, authors should consider studies from various freshwater systems with varying limnological characteristics (e.g., stormwater wetlands, natural lakes, streams and rivers with varying flowing regimes).

Overall, the findings here demonstrate that the effects of microplastics vary by species and feeding mode. The differences may be mediated depend on the taxa as well as the anatomy and physiology of the organism in question. Additionally, microplastics coupled with contaminates that adhere to them may pose an additional threat to freshwater and terrestrial biota (Colabuono et al., 2010; Tanaka et al., 2013; Carbery et al., 2018). Further, research is required on how different species are affected in the field, where they encounter different microplastic types of varied sizes and shapes throughout their lifetime. There is a need to consider other physiological effects such as those presented here especially when considering the nexus between plastics ecosystem structure and function. Addressing questions on the potential threat of microplastics for freshwater environments is crucial for policy makers to develop appropriate and informed measures to address microplastics contamination in freshwater systems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Funding

This study was funded from start-up funds provided to SM by Rhodes College. The APC was funded by the Rhodes College Department of Biology.

Acknowledgments

I am grateful for all the authors whose hard work made these data available for this study. I am also grateful for the assistance of Gabriele M. Dagan who helped with data extraction.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.999349/full#supplementary-material

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