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# Interactions between microplastics and microbiota in a One Health perspective

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ABSTRACT

Microplastics are recognised as ubiquitous pollutants as they are now found in all terrestrial and marine ecosystems. The interactions between microbiota and microplastics are an issue of fundamental importance in studying and maintaining global health. Microplastics alter the structures and functions of microbial communities, resulting in adverse health effects. A comprehensive understanding of these effects through interdisciplinary research is essential to mitigate pollution and protect the health of ecosystems. The review aims to explore these interactions within a One Health framework. Indeed, a deeper understanding of the processes involved in the interaction between microbiota and microplastics could pave the way for new and promising strategies to mitigate the harmful effects of microplastics on ecosystems and human health.

## 1. Introduction

The term plastic was coined by Leo Baekeland in 1907, the term being derived from the Greek word ‘plastikos’, meaning flexible and easy to mould [1]. Plastic is a material with unique characteristics such as lightness, flexibility and strength. Despite its unique properties, ineffective disposal combined with irresponsible behaviour has made plastic one of the most worrying pollutants for global health. Annual plastic production has more than doubled in 20 years, and it is estimated that nearly 70 million tonnes of plastic will be released into the environment by 2050 [2]. The degradation of plastics is an extremely complex process that can take hundreds of years and involves phenomena such as photodegradation, hydrolytic degradation and the action of physical and biological agents [3]. The plastic particles produced by degradation can be classified as macroplastics (size >25 mm), mesoplastics (size between 5 and 25 mm) microplastics (MP) (size of less than 5 mm) and nanoplastics (NP) (size between 1 nm and 1 μm). Moreover, the MP can be classified into two main categories: primary MP and secondary MP. Primary MP are specifically manufactured to be less than 5 mm in size, such as the plastic microspheres used in personal care products. Secondary MP is formed from large pieces of plastic that degrade over time through the action of sunlight, water, and wind [4–6]. MP are currently environmental contaminants found in terrestrial and marine ecosystems. Polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC) are the main plastic polymers found in the environment. MP accumulate in marine sediments and coastal areas, with higher concentrations near urbanised and industrial areas. In addition, MP have also been found in remote areas such as glaciers, polar regions, and the deep sea [7–9]. The routes of exposure to MP include ingestion, inhalation and contact with the skin [10–12]. Different studies have shown that MP can release toxic chemicals and additives used during manufacturing, which can penetrate tissues and cause damage at the cellular and molecular levels. Fig. 1 highlights some of the mechanisms by which MP can affect the microbiota. In addition, the potential effect of MP in inducing systemic inflammatory responses, increasing the risk of chronic diseases such as obesity, diabetes, and heart disease, has been studied [13–16]. Several studies have shown that marine organisms can ingest large quantities of MP with intestinal

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obstructions and damage to cell membranes. In addition, MP can act as carriers of pollutants, such as polychlorinated biphenyls (PCBs) and dioxins, which are absorbed by the tissues of marine organisms. This phenomenon can severely affect marine species' health and marine ecosystems' biodiversity [17,18]. MP significantly affect terrestrial species, especially animals that accidentally ingest them. In fact, it has been demonstrated that MP causes increased inflammation and disruption of reproductive systems, affecting the survival of many terrestrial species, such as birds, reptiles, and mammals. In addition, releasing toxic chemicals from MP can adversely affect the growth and development of terrestrial organisms, generating concerns for biodiversity and the balance of ecosystems [19]. MP can have severe implications for the food chain as they are ingested by marine and terrestrial organisms, thus entering the food chain. This can cause direct harm to the organisms that ingest them but can also have cascading effects on all subsequent trophic levels. The microbiota is the microbial community colonised in a certain type of district or ecological niche. It performs crucial functions such as digestion, immune system regulation, and protection against pathogens [20,21]. Variations within the microbiota provide valuable information on functional and structural changes induced by external factors such as MP [22,23]. A thorough understanding of this complex relationship is essential to take targeted and informed action to preserve universal health. Interactions between microbiota and MP influence the bioaccumulation of MP in organisms, the transfer of harmful chemicals, and the degradation of MP in the environment [24–26]. It is crucial to study the composition of the microbiota and its specific functions to understand how the microbiota is modified or influenced by MP. This review highlights how exposure to MP alters the microbiota in humans, animals, insects, marine sediments and soil, underlining the importance of the One Health approach. The review summarises the evidence available in the literature on the effects of MP on the microbiota, with the aim of identifying under-researched areas of study and little-known implications from a One Health perspective (study inclusion criteria are reported in the supplementary material).

### 1.1. MP and human gut microbiota

The human microbiota provides an immense amount of genetic information. In fact, this genetic information is estimated to be 150 times greater than the genetic information of the entire human genome. The term microbiota refers to a microbial community colonising a particular type of environment or ecological niche. The human body is characterised by cutaneous, oral, vaginal, pulmonary, oesophageal, gastric and nasal microbiota, in addition to the gut microbiota, which is the best studied human microbiota. The gut microbiota is now recognised as a genuinely essential organ in maintaining health [27–29]. Through the provision of unique enzymes and biochemical pathways, the microbiota has a crucial role in the extraction of nutrients from food. MP can interact with the human gut microbiota, affecting the composition and function of microbial communities. Experimental studies have shown that ingestion of MP can alter gut microbes' diversity and relative abundance, with potential health consequences such as gut inflammation, dysbiosis, and altered metabolic functions [30,31]. A study by Tamargo et al. investigated the effects of MP on the colonic microbiota [32]. The simgi® system reproduced the human digestive tract as a dynamic simulator during the study. The phylogenetic analysis showed that after PE terephthalate treatment, important differences in taxa were found depending on the three compartments of the simgi® system considered: ascending colon, transverse colon and descending colon. In particular, exposure to PE terephthalate in the ascending colon resulted in an increase in the *Firmicutes* and *Desulfobacterota* phyla and a decrease in *Bacteroidetes*. At the level of the transverse colon, however, there was a noticeable increase in *Proteobacteria* and *Desulfobacterota*, alongside a sharp decline in the relative abundance of *Bacteroidetes*, which dropped to 10 %. Finally, at the level of the descending colon, a decrease in the relative abundance of *Bacteroidetes*of more than 15 % was noted. The results of the study showed that for the phyla *Bacteroides* and *Parabacteroides*, there was a decrease in abundance in all compartments of the colon. Meanwhile, an increase was observed for *Escherichia/Shigella*and *Bilophila* in the transverse and descending colon. Huang et al. investigated the effects of PE MP and tetrabromobisphenol A on the gut microbiota [33]. The study analysed faecal samples from ten healthy

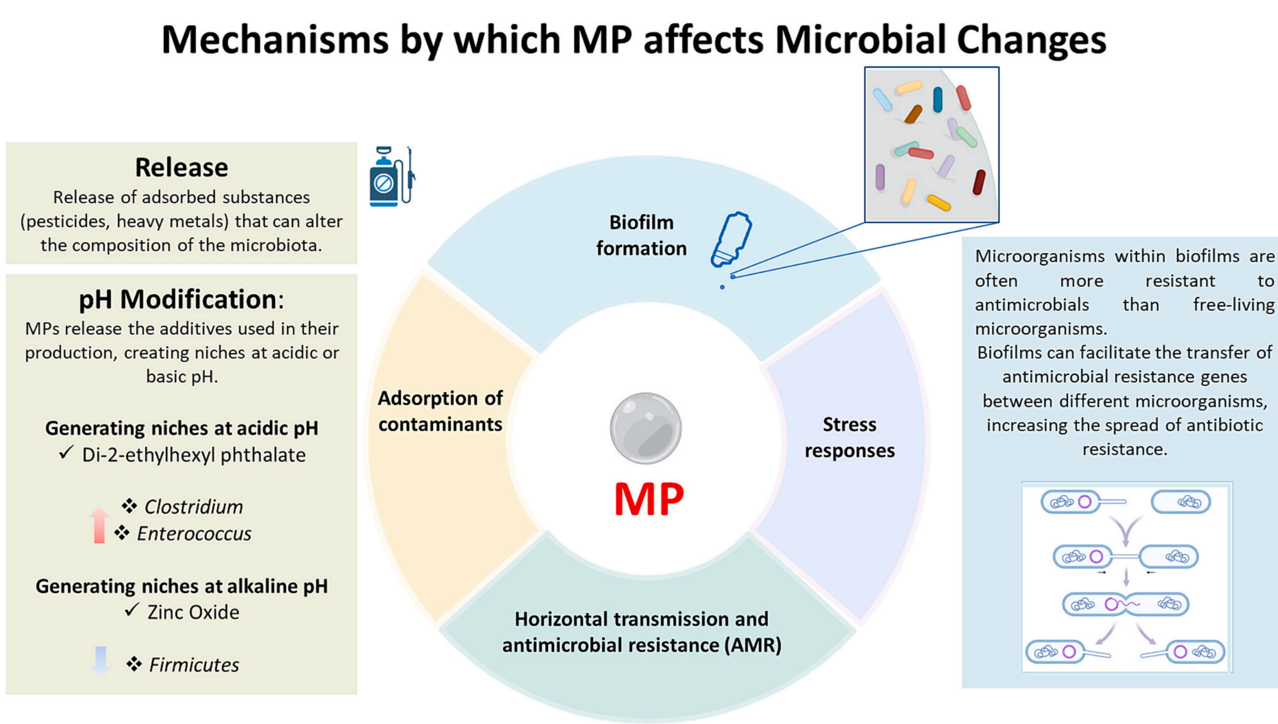


**Fig. 1.** MP and microbiota interaction mechanisms.

volunteers who had not been treated with antibiotics for at least 3 months. Exposure to MP involved treatment with tetrabromobisphenol alone (5 and 25 mg/L) or in combination with PE. The study results showed that *Firmicutes* was the dominant phylum in the control group, representing 78.89 % of the bacterial community. However, the percentage of *Firmicutes* was drastically reduced, reaching values of 35.2 % and 0.9 % after exposure to 5 mg/L and 25 mg/L tetrabromobisphenol A, respectively. The effects of consuming takeaway food stored in single-use plastic containers on oral and gut microbiota were investigated by Zha et al. [34]. The enrolled patients were divided into occasional, frequent and non-consumers based on the frequency of takeaway food consumption. The results highlighted that *Firmicutes*, *Proteobacteria* and *Actinobacteriota* represented the most abundant phyla present in the oral microbial community of the three groups. In particular, the oral microbiota of the frequent users group (consumption $\geq$ three times a week) showed an increase in *Thiobacillus*and *Oribacterium* bacteria. On the contrary, the analysis of the intestinal microbial community of the enrolled subjects revealed that *Faecalibacterium*, *Collinsella* and *Dorea* were the three genera most associated with the group of occasional consumers (once a week). While *Agathobacter*, *Collinsella* and *Dorea* were the genera most associated with the frequent consumers group. In a study conducted by Zhang et al., the effects of MP contamination on the nasal and intestinal microbiota of subjects living near a plastics factory (high exposure group) were assessed by comparing them to the microbiota of subjects living in Huanhuaxi Park in Chengdu, China (low exposure group) [35]. The analysis of relative abundance demonstrated that the phyla *Proteobacteria* and *Campylobacterota* were significantly reduced in the high exposure group compared to the low exposure group ($P < 0.05$). The genera *Bacteroides*, *Actinomyces*, *Porphyromonas*, *Haemophilus*, *Gardnerella* and *Gemella* were significantly lower in the high exposure group than in the low exposure group. Moreover, a study by Yan et al., analysed the impact of MP in subjects suffering from inflammatory bowel disease (IBD) [36]. The study underscored a pronounced elevation in the faecal concentration of MP in patients with IBD, registering at 41.8 elements/g dm, compared to 28.0 elements/g dm observed in healthy controls. This substantial disparity in MP levels suggests a potential involvement of these particles in the pathogenesis of IBD.

### 1.2. MP and animal gut microbiota

MP also pose a high risk to animal health. Exposure to MP in farm animals poses a risk to the animals' health and humans, who are at the top of the food chain and consume contaminated dairy products and animal meat [37]. The interaction between MP and animal microbiota provides a new key to understanding the remarkable impact of these contaminants on a global scale. It has been shown that MP and plasticisers such as bisphenol A and phthalates can alter the gastrointestinal microbial community of teleost fish. In particular, MP contamination has been shown to increase opportunistic pathogenic bacteria such as *Mycoplasma,Actinobacillus* and *Stenotrophomona* [38]. A study in Muscovy ducks found that exposure to MP increased the abundance of *Streptococcus* and *Helicobacter* with damage to the gut [39]. Li et al. highlighted how exposure to MP in chickens resulted in profound dysbiosis [40]. The study showed the disappearance of 11 gut bacterial genera after exposure to MP (*Caproiciproducens*, *Fusobacterium, Angelakisella*, *Ignatzschineria*, *Colidextribacter*, *Pseudoflavonifractor*, *Papillibacter*, *Tuzzerella*, *Rikenella*, *eubacterium_ventriosum* group and *V9D2013*_group). A study by Zou et al. showed how MP contamination reduced growth in chickens and highlighted an alteration in the gut microbial community [41]. In this regard, the study highlighted a drastic decrease in *Proteobacteria* and an increase in *Cyanobacteria*. The *Proteobacteria* phylum is involved in the breakdown of complex nutrients, contributing to intestinal metabolism and digestion. In this regard, the *Enterobacteriaceae* family, which belongs to the *Proteobacteria* phylum, is crucial in the fermentation of carbohydrates that are not digestible by the host.

In contrast, although cyanobacteria are bacteria commonly found in the gut microbiota of chickens, their presence profoundly impacts animal health. They produce cyanotoxins, such as microcystins, nodularins and anatoxins, which are highly toxic. A study of faecal samples from 45 *Caretta caretta* turtles found the presence of plastic debris in all samples analysed [42]. The study also showed how plastic debris altered the turtle's gut microbial community, increasing *Cetobacterium somerae*. At present, data on the effects of MP on the microbiota of animals is limited. However, the data presented show how these contaminants alter the normal composition of the microbiota, leading to health risks. Currently, there is limited data on changes in the gut microbiota of companion animals due to MP. MP contamination is one of the major global public health challenges. The analysis of microbiota interactions with MP represents an innovative vision for maintaining the health of livestock, companion animals and wildlife. Fig. 2 shows how exposure to MP alters the gut microbiota in different animal species [39–41,43–47].

### 1.3. MP and microbiota of insects

Various studies have highlighted how the presence of plastic in the environment determines the creation of favourable habitats for vectors of arboviruses such as *Aedes aegypti* and *Aedes albopictus* responsible for the spread of viruses such as Dengue, Chikungunya, Zika and Yellow Fever [48–50]. It has been observed that tyres and plastic containers, which are used for various purposes, become collection sites for stagnant water, which help to increase survival rates and reduce the predation of mosquito larvae. In addition to these activities, MP have been hypothesised to facilitate mosquito vector activity. In a study by Edwards et al., the effects of PS MP on *Aedes aegypti* and *Aedes albopictus* mosquito larvae were analysed [51]. The effects of MP on gut damage and the fungal and bacterial microbiota have been evaluated. The study's results indicated that MP exposure had a minimal impact on adult emergence rates. Furthermore, it was found that exposure to MP established a change in the intestinal bacterial microbiota with an increase in *Elizabethkingia* and *Aspergillus.Elizabethkingia anophelis* is an aerobic Gram-negative bacterium ubiquitously found in soil, aquatic environments, plants and digestive segments of animals [52]. The presence of *Elizabethkingia anophelis*in the gut of mosquitoes facilitates the lysis of red blood cells by bacterial haemolysins, contributing to the digestion of ingested blood. The study conducted by Chen et al., showed that *Elizabethkingia anophelis* can respond to the extreme conditions determined by iron availability due to meals [53]. In detail, the study conducted by Chen et al., showed that *Elizabethkingia anophelis* responds to such fluctuations using multiple iron absorption pathways such as TonB-dependent outer membrane transporters and chelating proteins. Furthermore, the study showed that the presence of *Elizabethkingia anophelis* and its ability to lyses red blood cells is linked to increased fertility in mosquitoes. In a study by Yan et al., it was shown that the uptake and accumulation of PS MP in *Aedes aegypti* mosquitoes is present in all stages of insect life, from larvae to pupae to adults [54]. The study reported that *Aedes aegypti* larvae feed by accumulating an average of $7.3 \times 106$ MP in 3 days. Furthermore, it was found that the amount of MP was significantly reduced in mosquitoes compared to pupae, with an average of 15.8 elements in pupae and 10.9 elements in adults. Finally, the study indicated that MP uptake did not significantly influence the survival rate in the various life stages of the insect. In a study by Li et al., the effects of MP on *Culex quinquefasciatus* mosquitoes, vectors of *Wuchereria bancrofti*, Zika virus and West Nile virus were evaluated [55]. The study showed that MP exposure was associated with a reduction in the lethal effect of pyrethroid insecticides from 97.77% to 48.88 % ($p <$ 0.05) with a 15.1 % removal of deltamethrin concentration. The study also reported that the most abundant microbes in the midgut of *Culex quinquefasciatus* were *Wolbachia* spp. (43.74 %) and *Elizabethella* spp. (21.05 %), Moreover, that a reduction in *Wolbachia* abundance was observed following MP exposure. *Wolbachia*, an endosymbiont

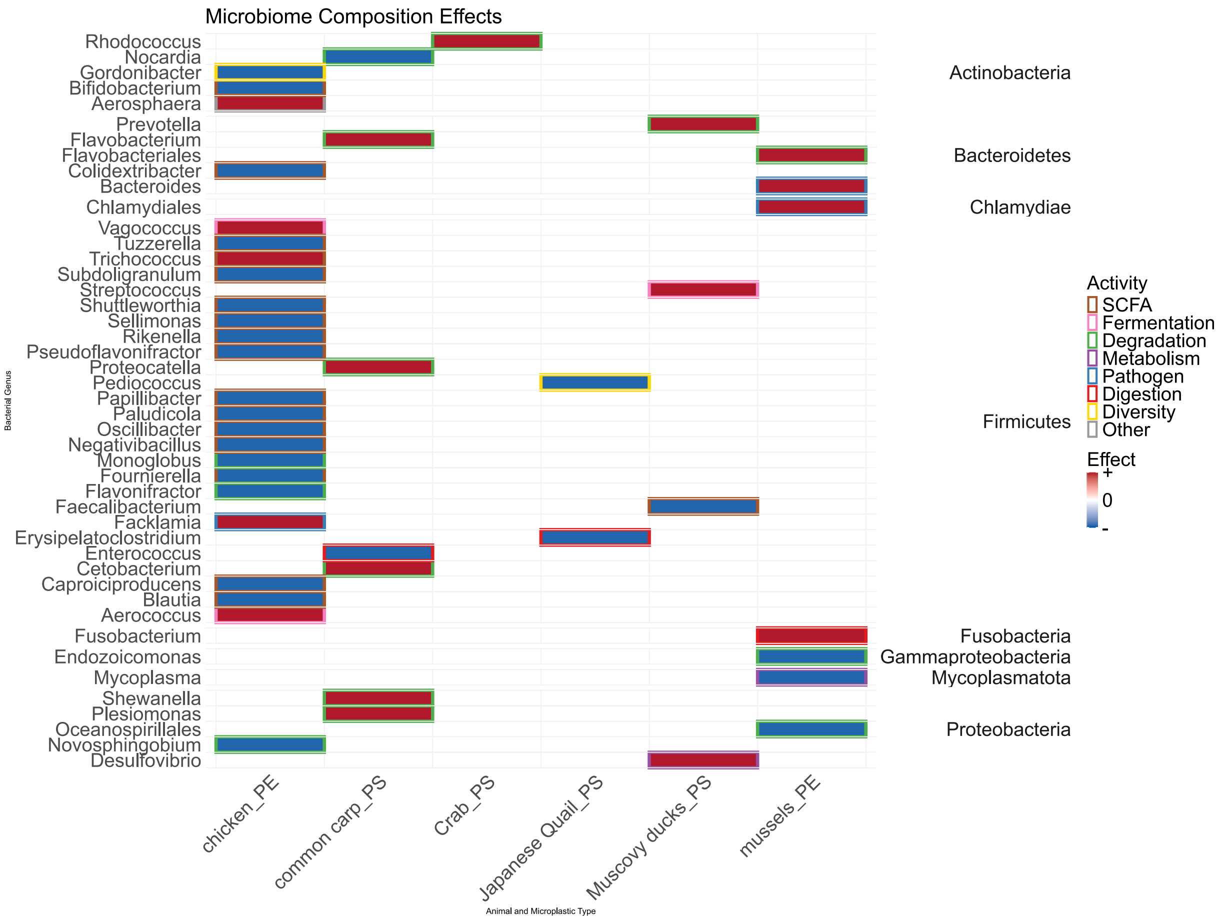


**Fig. 2.** Alteration of animal microbiota following exposure to MP.
**Caption** Fig. 2: SCFA: short chain fatty acids, PE, PS: polystyrene.

intracellular bacterium, colonises a wide range of insects, including mosquitoes. *Wolbachia* has recently been studied for its ability to cause sterility in *Aedes* mosquitoes [56]. This mechanism appears to be due to a process known as cytoplasmic incompatibility, a phenomenon that renders mating between *Wolbachia*-infected and non-infected mosquitoes infertile. In addition to this evidence, we must also highlight the presence of studies that show that exposure to MP can be harmful to mosquito survival. In this regard, a study by Malafaia et al., analysed the effect of PE MP on *Culex quinquefasciatus* larvae [57]. The results of the study indicated that exposure to MP results in significant suppression of total glutathione and radical scavenger levels. Furthermore, it was reported that superoxide dismutase activity did not differ between the treated and untreated groups, while acetylcholinesterase activity was significantly increased in larvae exposed to MP. Moreover, Wang et al., evaluated the effects of exposure to PS MP on the gut microbiota of honeybees [58]. The relative abundance analysis showed that the genera *Lactobacillus*and *Bifidobacterium* had an abundance of 72 % and 12.33 %, respectively, before exposure. However, after 10 days of exposure to 100 nm diameter PS MP, a reduction of *Lactobacillus* to 54.34 % was observed. Furthermore, after 15 days of exposure, a reduction in the abundance of *Bifidobacterium*to 6.35 % was highlighted. Fig. 3 shows how exposure to MP alters the gut microbiota in insects [51,58–60].

### 1.4. MP and marine sediment microbiota

MP are now found not only in all oceans but also in all the seas, with a distribution that extends from coastal regions to extreme depths. The enormous distribution of MP in the oceans is one of the main global concerns, as fish populations ingest these substances with harmful consequences. It has also been shown that plastics often form physical barriers that trap fish populations and that MP alters the marine ecosystem by affecting the microbiota of its sediments. The microbiota of marine sediments is essential for decomposing dead organic matter, which is the main source of nutrients for benthic organisms (worms, molluscs and crustaceans) and the marine food chain. The microbiota of marine sediments is essential for the degradation of carbohydrates, fats and proteins into simpler substances such as $H_2O$ and $CO_2$. The alteration of the microbiota of these sediments by MP has a major impact on the marine balance, with consequences for the whole ecosystem. In this regard, a study by Seeley et al. observed how different types of MP can modify the composition of microbial communities in coastal sediments [61]. The study highlighted how PVC treatment caused a significant reduction in *Ectothiorhodospiraceae*, *Magnetococcaceae*, *Sedimenticolaceae*, *Chromatiaceae*, *Lentimicrobiaceae*, *Pirellulaceae*, *Woeseiaceae* and *Thermoanaerobaculaceae*. It was also found that PVC treatment reduced the denitrification activity of the sediment microbial community. Denitrification is a catabolic process mediated by sediment microbes that is necessary to remove the reactive nitrogen typical of coastal systems [62]. Denitrification converts nitrates ($NO_3$-) and nitrites ($NO_2$) into nitrous oxide ($N_2O$) and nitrogen ($N_2$), thereby regulating the balance of the ecosystem. Li et al., showed how MP alters sediments' chemical-physical properties [63]. The study highlighted how MP are able to reduce pH from 7.10 to 6.75, reduce total nitrogen content by 13.96–23.97 %, reduce cation exchange index and total phosphorus content, and increase the amount of total organic carbon. Such changes in chemical-physical characteristics have been correlated with a decrease in the diversity of sediment bacterial communities. In

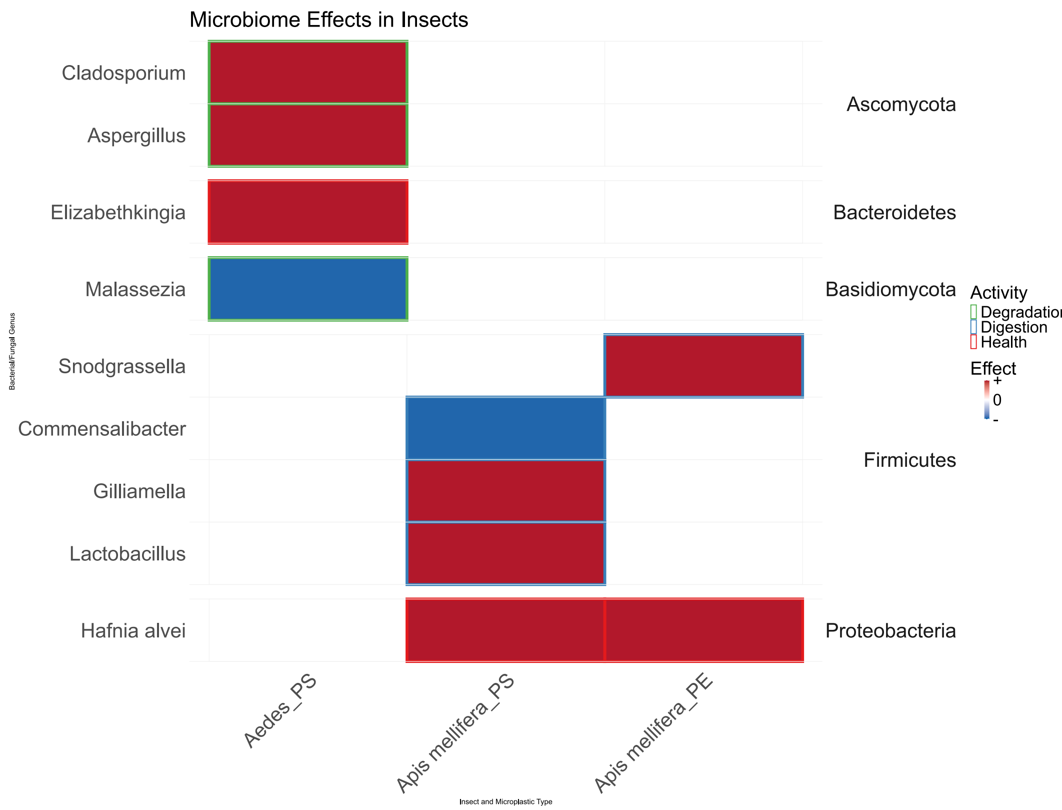


**Fig. 3.** alteration of insects microbiota following exposure to MP.
**Caption** Fig. 3**:** PS: polystyrene, PE: polyethylene.

this regard, it has been shown that MP, acting on the total organic carbon content, determine an increase in *Bacteroidotes* with a variation in the diversity of the microbial community. Several studies underline that coastal sediments, sediments at great depths, and sediments from freshwater basins can constitute a huge pool for the deposition of MP. In this context, it has now been shown that sediments represent "wells" for MP collection [64]. This phenomenon is related to the chemical-physical properties of the materials considered, which, when endowed with a density greater than that of seawater (>1.02 g/cm-$^3$), tend to sink and accumulate in the sediments. Despite the large amount of data showing the presence of MP in marine and coastal sediments, studies analysing the impact of MP on the microbiota of the same sediments are limited. It is therefore necessary to increase the available data on this topic to adequately address MP pollution by identifying innovative management strategies.

### *1.5. MP and soil microbiota*

Having colonised every natural ecosystem, MP is also found in soil with highly variable concentrations that can reach 67 g/kg$^{-1}$ [65]. Despite efforts to recover large plastic materials dispersed in the environment, soil contamination by MP is an ever-increasing problem. In this context, several efforts have been made in recent years to understand the impact of MP on the soil microbiota. The soil microbiota comprises a vast microbial community characterised by bacteria, protozoa, viruses, fungi and archaea, crucial for implementing soil biogeochemical processes. These processes are essential for maintaining fertility and the health of vegetation. In this regard, soil microbiota is crucial for the mineralisation process by converting organic matter into nutrients for plants, the nitrogen fixation process by making atmospheric nitrogen available, the denitrification process, the nitrification processes by oxidising the ammonium ion in nitrites and nitrates, and for cycling of nutrients such as nitrogen, phosphorus and sulphur. The impact of MP on the soil microbiota was analysed in a study by Feiet al., who highlighted how soil contamination with PE and PVC MP increased the relative abundance of *Burkholderiaceae*, suggesting how bacteria involved in nitrogen fixation can be stimulated by MP contamination [66].

Furthermore, PVC contamination was associated with increased relative abundance of *Frankiales*, *Propionibacteriales* and *Micrococcales*. In contrast, PE contamination was associated with a decrease, suggesting how different contaminants can determine specific changes in the soil microbiota. A study by Dong et al., showed that PS MP dramatically reduced the relative abundance of *Proteobacteria* and *Firmicutes*, while significantly increasing the abundance of *Bacteroidetes* (Fig. 4) [67]. Several studies have demonstrated how MPs can alter the fungal community of soil microbiota. It has been shown that MP, acting as important carbon reserves, can determine an increase in the genera *Fusarium*, *Aspergillus* and *Penicillium* [68]. It has also been shown how MP contamination can have toxic effects on plants by modulating the microbial composition of the soil. In this regard, a study by Qian *et al.* highlighted how MP can increase the amount of *Xanthomonas*, a bacterial pathogen for plants [69]. Analysis of the changes in soil microbiota caused by MP is an innovative key to ensuring the fertility and health of terrestrial ecosystems [70]. Although several studies have addressed this issue, we need to expand our knowledge of the effects of MP contamination on soil microbiota.

## 2. Conclusions

MP represent a serious threat to environmental ecosystems and to human and animal health. The present review analyses the effects of MP on the microbiota of humans, animals, insects, marine sediments and soil, highlighting the need for a multidisciplinary approach to find innovative solutions to a global problem. The proposed review highlights the under-researched implications of the effects of MP on the

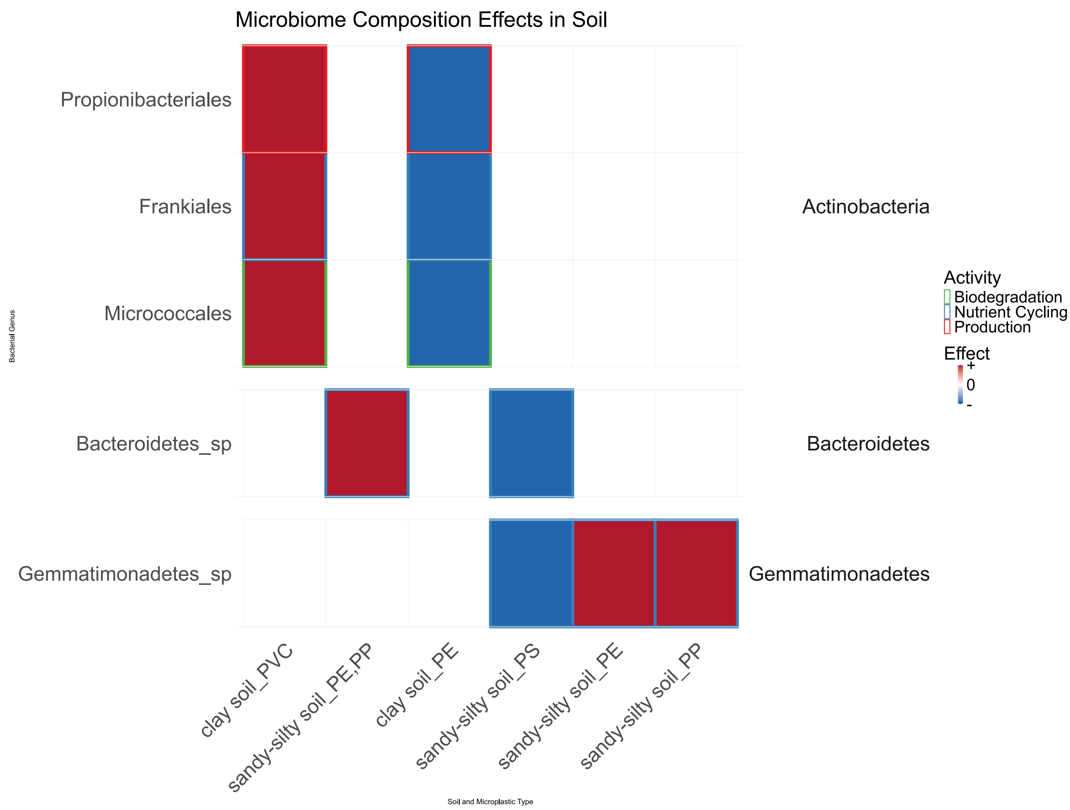


**Fig. 4.** alteration of soil microbiota following exposure to MP.
**Caption** Fig. 4**:** PS: polystyrene, PE: polyethylene, PP: polypropylene PVC: polyvinyl chloride.

microbiota. In this regard, the review highlights how MP may favour the re-emergence of diseases by increasing vector fecundity by acting at the microbiota level. In addition, the review identifies the study of the effects of MP on marine sediment microbiota and soil microbiota as an innovative and currently under-researched area. In addition, the proposed review highlights how the One Health approach, characterised by multidisciplinary collaborations, research integrated with monitoring and control methods, and efforts in the policy and awareness-raising fields, represents the crucial and indispensable approach for the management of MP pollution and for the analysis of its effects on the microbiota.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.onehlt.2025.101002.

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## CRediT authorship contribution statement

**Anna Caterina Procopio:** Writing – original draft, Visualization, Methodology, Data curation. **Alessio Soggiu:** Writing – review & editing, Visualization, Methodology, Data curation. **Andrea Urbani:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Paola Roncada:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

## Declaration of competing interest

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

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Figs. 1 and graphical abstract created with BioRender.com.

## Data availability

The proposed research presents already published data

## References

[1] J. Barros, S. Seena, Plastisphere in freshwaters: an emerging concern, Environ. Pollut. 290 (2021) 118123, https://doi.org/10.1016/j.envpol.2021.118123.
[2] A.E. Schwarz, S.M.C. Lensen, E. Langeveld, L.A. Parker, J.H. Urbanus, Plastics in the global environment assessed through material flow analysis, degradation and environmental transportation, Sci. Total Environ. 875 (2023) 162644, https://doi.org/10.1016/j.scitotenv.2023.162644.
[3] J.E. Weinstein, B.K. Crocker, A.D. Gray, From macroplastic to microplastic: degradation of high-density polyethylene, polypropylene, and polystyrene in a salt marsh habitat, Environ. Toxicol. Chem. 35 (2016) 1632–1640, https://doi.org/10.1002/etc.3432.
[4] M. Malankowska, C. Echaide-Gorriz, J. Coronas, Microplastics in marine environment: a review on sources, classification, and potential remediation by membrane technology, Environ. Sci.: Water Res. Technol. (2021), https://doi.org/10.1039/D0EW00802H.
[5] C.B. Alvim, M.A. Bes-Piá, J.A. Mendoza-Roca, Separation and identification of microplastics from primary and secondary effluents and activated sludge from wastewater treatment plants, Chem. Eng. J. 402 (2020) 126293, https://doi.org/10.1016/j.cej.2020.126293.
[6] A.L. Lusher, I.L.N. Bråte, K. Munno, R.R. Hurley, N.A. Welden, Is it or isn't it: the importance of visual classification in microplastic characterization, Appl. Spectrosc. 74 (2020) 1139–1153, https://doi.org/10.1177/0003702820930733.
[7] Y. Zhang, T. Gao, S. Kang, S. Allen, X. Luo, D. Allen, Microplastics in glaciers of the Tibetan plateau: evidence for the long-range transport of microplastics, Sci. Total Environ. 758 (2021) 143634, https://doi.org/10.1016/j.scitotenv.2020.143634.
[8] H. Dong, L. Wang, X. Wang, L. Xu, M. Chen, P. Gong, C. Wang, Microplastics in a remote Lake Basin of the Tibetan plateau: impacts of atmospheric transport and glacial melting, Environ. Sci. Technol. 55 (2021) 12951–12960, https://doi.org/10.1021/acs.est.1c03227.

[9] Z. Wang, Y. Zhang, S. Kang, L. Yang, X. Luo, P. Chen, J. Guo, Z. Hu, C. Yang, Z. Yang, T. Gao, Long-range transport of atmospheric microplastics deposited onto glacier in southeast Tibetan plateau, Environ. Pollut. 306 (2022) 119415, https://doi.org/10.1016/j.envpol.2022.119415.

[10] S. Gamage, Y. Mahagamage, Microplastics in personal care products and cosmetics in Sri Lanka, Heliyon 10 (2024) e29393, https://doi.org/10.1016/j.heliyon.2024.e29393.

[11] A. Dąbrowska, M. Mielańczuk, M. Syczewski, The Raman spectroscopy and SEM/EDS investigation of the primary sources of microplastics from cosmetics available in Poland, Chemosphere 308 (2022) 136407, https://doi.org/10.1016/j.chemosphere.2022.136407.

[12] R.Z. Habib, J.A.K. Aldhanhani, A.H. Ali, F. Ghebremedhin, M. Elkashlan, M. Mesfun, W. Kittaneh, R. Al Kindi, T. Thiemann, Trends of microplastic abundance in personal care products in the United Arab Emirates over the period of 3 years (2018-2020), Environ. Sci. Pollut. Res. Int. 29 (2022) 89614–89624, https://doi.org/10.1007/s11356-022-21773-y.

[13] A.G. Lee, S. Kang, H.J. Yoon, S. Im, S.J. Oh, Y.K. Pak, Polystyrene microplastics exacerbate systemic inflammation in high-fat diet-induced obesity, Int. J. Mol. Sci. 24 (2023) 12421, https://doi.org/10.3390/ijms241512421.

[14] T. Okamura, M. Hamaguchi, Y. Hasegawa, Y. Hashimoto, S. Majima, T. Senmaru, E. Ushigome, N. Nakanishi, M. Asano, M. Yamazaki, R. Sasano, Y. Nakanishi, H. Seno, H. Takano, M. Fukui, Oral exposure to polystyrene microplastics of mice on a Normal or high-fat diet and intestinal and metabolic outcomes, Environ. Health Perspect. 131 (2023) 27006, https://doi.org/10.1289/EHP11072.

[15] R. Marfella, F. Prattichizzo, C. Sardu, G. Fulgenzi, L. Graciotti, T. Spadoni, N. D'Onofrio, L. Scisciola, R. La Grotta, C. Frigé, V. Pellegrini, M. Municinò, M. Siniscalchi, F. Spinetti, G. Vigliotti, C. Vecchione, A. Carrizzo, G. Accarino, A. Squillante, G. Spaziano, D. Mirra, R. Esposito, S. Altieri, G. Falco, A. Fenti, S. Galoppo, S. Canzano, F.C. Sasso, G. Matacchione, F. Olivieri, F. Ferraraccio, I. Panarese, P. Paolisso, E. Barbato, C. Lubritto, M.L. Balestrieri, C. Mauro, A. E. Caballero, S. Rajagopalan, A. Ceriello, B. D'Agostino, P. Iovino, G. Paolisso, Microplastics and Nanoplastics in Atheromas and cardiovascular events, N. Engl. J. Med. 390 (2024) 900–910, https://doi.org/10.1056/NEJMoa2309822.

[16] Y. Wang, Z. Wei, K. Xu, X. Wang, X. Gao, Q. Han, S. Wang, M. Chen, The effect and a mechanistic evaluation of polystyrene nanoplastics on a mouse model of type 2 diabetes, Food Chem. Toxicol. 173 (2023) 113642, https://doi.org/10.1016/j.fct.2023.113642.

[17] M. Llorca, M. Ábalos, A. Vega-Herrera, M.A. Adrados, E. Abad, M. Farré, Adsorption and desorption behaviour of polychlorinated biphenyls onto Microplastics' surfaces in water/sediment systems, Toxics 8 (2020) 59, https://doi.org/10.3390/toxics8030059.

[18] M.A. Fraser, L. Chen, M. Ashar, W. Huang, J. Zeng, C. Zhang, D. Zhang, Occurrence and distribution of microplastics and polychlorinated biphenyls in sediments from the Qiantang River and Hangzhou Bay, China, Ecotoxicol. Environ. Saf. 196 (2020) 110536, https://doi.org/10.1016/j.ecoenv.2020.110536.

[19] H. Ma, S. Pu, S. Liu, Y. Bai, S. Mandal, B. Xing, Microplastics in aquatic environments: toxicity to trigger ecological consequences, Environ. Pollut. 261 (2020) 114089, https://doi.org/10.1016/j.envpol.2020.114089.

[20] E.Z. Gomaa, Human gut microbiota/microbiome in health and diseases: a review, Antonie Van Leeuwenhoek 113 (2020) 2019–2040, https://doi.org/10.1007/s10482-020-01474-7.

[21] J.Y. Yoo, M. Groer, S.V.O. Dutra, A. Sarkar, D.I. McSkimming, Gut microbiota and immune system interactions, Microorganisms 8 (2020) 1587, https://doi.org/10.3390/microorganisms8101587.

[22] S. Long, Y. Yang, C. Shen, Y. Wang, A. Deng, Q. Qin, L. Qiao, Metaproteomics characterizes human gut microbiome function in colorectal cancer, NPJ Biofilm. Microbiom. 6 (2020) 14, https://doi.org/10.1038/s41522-020-0123-4.

[23] Y. Wang, Y. Zhou, X. Xiao, J. Zheng, H. Zhou, Metaproteomics: a strategy to study the taxonomy and functionality of the gut microbiota, J. Proteome 219 (2020) 103737, https://doi.org/10.1016/j.jprot.2020.103737.

[24] X. Qiu, Z. Qi, Z. Ouyang, P. Liu, X. Guo, Interactions between microplastics and microorganisms in the environment: modes of action and influencing factors, Gondwana Res. 108 (2022) 102–119, https://doi.org/10.1016/j.gr.2021.07.029.

[25] H. Yang, G. Chen, J. Wang, Microplastics in the marine environment: sources, fates, impacts and microbial degradation, Toxics 9 (2021) 41, https://doi.org/10.3390/toxics9020041.

[26] A. Menéndez-Pedriza, J. Jaumot, Interaction of environmental pollutants with microplastics: a critical review of sorption factors, bioaccumulation and ecotoxicological effects, Toxics 8 (2020) 40, https://doi.org/10.3390/toxics8020040.

[27] R.M. Sherman, S.L. Salzberg, Pan-genomics in the human genome era, Nat. Rev. Genet. 21 (2020) 243–254, https://doi.org/10.1038/s41576-020-0210-7.

[28] Y. Fan, O. Pedersen, Gut microbiota in human metabolic health and disease, Nat. Rev. Microbiol. 19 (2021) 55–71, https://doi.org/10.1038/s41579-020-0433-9.

[29] A. Almeida, S. Nayfach, M. Boland, F. Strozzi, M. Beracochea, Z.J. Shi, K.S. Pollard, E. Sakharova, D.H. Parks, P. Hugenholtz, N. Segata, N.C. Kyrpides, R.D. Finn, A unified catalog of 204,938 reference genomes from the human gut microbiome, Nat. Biotechnol. 39 (2021) 105–114, https://doi.org/10.1038/s41587-020-0603-3.

[30] B. Li, Y. Ding, X. Cheng, D. Sheng, Z. Xu, Q. Rong, Y. Wu, H. Zhao, X. Ji, Y. Zhang, Polyethylene microplastics affect the distribution of gut microbiota and inflammation development in mice, Chemosphere 244 (2020) 125492, https://doi.org/10.1016/j.chemosphere.2019.125492.

[31] J.N. Huang, B. Wen, J.G. Zhu, Y.S. Zhang, J.Z. Gao, Z.Z. Chen, Exposure to microplastics impairs digestive performance, stimulates immune response and induces microbiota dysbiosis in the gut of juvenile guppy (Poecilia reticulata), Sci. Total Environ. 733 (2020) 138929, https://doi.org/10.1016/j.scitotenv.2020.138929.

[32] A. Tamargo, N. Molinero, J.J. Reinosa, V. Alcolea-Rodriguez, R. Portela, M. A. Bañares, J.F. Fernández, M.V. Moreno-Arribas, PET microplastics affect human gut microbiota communities during simulated gastrointestinal digestion, first evidence of plausible polymer biodegradation during human digestion, Sci. Rep. 12 (2022) 528, https://doi.org/10.1038/s41598-021-04489-w.

[33] W. Huang, H. Yin, Y. Yang, L. Jin, G. Lu, Z. Dang, Influence of the co-exposure of microplastics and tetrabromobisphenol a on human gut: simulation in vitro with human cell Caco-2 and gut microbiota, Sci. Total Environ. 778 (2021) 146264, https://doi.org/10.1016/j.scitotenv.2021.146264.

[34] H. Zha, J. Lv, Y. Lou, W. Wo, J. Xia, S. Li, A. Zhuge, R. Tang, N. Si, Z. Hu, H. Lu, K. Chang, C. Wang, G. Si, L. Li, Alterations of gut and oral microbiota in the individuals consuming take-away food in disposable plastic containers, J. Hazard. Mater. 441 (2023) 129903, https://doi.org/10.1016/j.jhazmat.2022.129903.

[35] X. Zhang, H. Wang, S. Peng, J. Kang, Z. Xie, R. Tang, Y. Xing, Y. He, H. Yuan, C. Xie, Y. Liu, Effect of microplastics on nasal and intestinal microbiota of the high-exposure population, Front. Public Health 10 (2022) 1005535, https://doi.org/10.3389/fpubh.2022.1005535.

[36] Z. Yan, Y. Liu, T. Zhang, F. Zhang, H. Ren, Y. Zhang, Analysis of microplastics in human feces reveals a correlation between fecal microplastics and inflammatory bowel disease status, Environ. Sci. Technol. 56 (2022) 414–421, https://doi.org/10.1021/acs.est.1c03924.

[37] F. Bahrani, A. Mohammadi, S. Dobaradaran, G.E. De-la-Torre, H. Arfaeinia, B. Ramavandi, R. Saeedi, A. Tekle-Röttering, Occurrence of microplastics in edible tissues of livestock (cow and sheep), Environ. Sci. Pollut. Res. Int. 31 (2024) 22145–22157, https://doi.org/10.1007/s11356-024-32424-9.

[38] O. Adamovsky, J.H. Jr Bisesi, C.J. Martyniuk, Plastics in our water: fish microbiomes at risk? Comp. Biochem. Physiol. Part D Genomics Proteomics 39 (2021) 100834 https://doi.org/10.1016/j.cbd.2021.100834.

[39] B. Liu, D. Yu, C. Ge, X. Luo, L. Du, X. Zhang, C. Hui, Combined effects of microplastics and chlortetracycline on the intestinal barrier, gut microbiota, and antibiotic resistome of Muscovy ducks (Cairina moschata), Sci. Total Environ. 887 (2023) 164050, https://doi.org/10.1016/j.scitotenv.2023.164050.

[40] A. Li, Y. Wang, M.F. Kulyar, M. Iqbal, R. Lai, H. Zhu, K. Li, Environmental microplastics exposure decreases antioxidant ability, perturbs gut microbial homeostasis and metabolism in chicken, Sci. Total Environ. 856 (2023) 159089, https://doi.org/10.1016/j.scitotenv.2022.159089.

[41] W. Zou, S. Lu, J. Wang, Y. Xu, M.A. Shahid, M.U. Saleem, K. Mehmood, K. Li, Environmental microplastic exposure changes gut microbiota in chickens, Animals (Basel). 13 (2023) 2503, https://doi.org/10.3390/ani13152503.

[42] E. Biagi, M. Musella, G. Palladino, V. Angelini, S. Pari, C. Roncari, D. Scicchitano, S. Rampelli, S. Franzellitti, M. Candela, Impact of plastic debris on the gut microbiota of Caretta caretta from northwestern Adriatic Sea, Front. Mar. Sci. 8 (2021), https://doi.org/10.3389/fmars.2021.637030.

[43] Z. Liu, P. Yu, M. Cai, D. Wu, M. Zhang, M. Chen, Y. Zhao, Effects of microplastics on the innate immunity and intestinal microflora of juvenile Eriocheir sinensis, Sci. Total Environ. 685 (2019) 836–846, https://doi.org/10.1016/j.scitotenv.2019.06.265.

[44] M.Y. Ouyang, X.S. Feng, X.X. Li, B. Wen, J.H. Liu, J.N. Huang, J.Z. Gao, Z.Z. Chen, Microplastics intake and excretion: resilience of the intestinal microbiota but residual growth inhibition in common carp, Chemosphere 276 (2021) 130144, https://doi.org/10.1016/j.chemosphere.2021.130144.

[45] L. Jing, Y. Zhang, Q. Zhang, H. Zhao, Polystyrene microplastics disrupted physical barriers, microbiota composition and immune responses in the cecum of developmental Japanese quails, J. Environ. Sci. (China) 144 (2024) 225–235, https://doi.org/10.1016/j.jes.2023.08.020.

[46] L.L. Li, R. Amara, S. Souissi, A. Dehaut, G. Duflos, S. Monchy, Impacts of microplastics exposure on mussel (Mytilus edulis) gut microbiota, Sci. Total Environ. 745 (2020) 141018, https://doi.org/10.1016/j.scitotenv.2020.141018.

[47] K. Park, W.S. Kim, J.W. Park, T.H. Kim, I.S. Kwak, Bioaccumulation, microbiome composition and immunity, and epigenetic signatures associated with exposure to spherical, fibrous, and fragmented microplastics in the mussel Mytilus galloprovincialis, J. Hazard. Mater. 462 (2024) 132691, https://doi.org/10.1016/j.jhazmat.2023.132691.

[48] A.C. Procopio, S. Colletta, E. Laratta, M. Mellace, B. Tilocca, C. Ceniti, A. Urbani, P. Roncada, Integrated one health strategies in dengue, One Health. 18 (2024) 100684, https://doi.org/10.1016/j.onehlt.2024.100684.

[49] M.G. Onyango, R. Lange, S. Bialosuknia, A. Payne, N. Mathias, L. Kuo, A. Vigneron, D. Nag, L.D. Kramer, A.T. Ciota, Zika virus and temperature modulate Elizabethkingia anophelis in Aedes albopictus, Parasit. Vectors 14 (2021) 573, https://doi.org/10.1186/s13071-021-05069-7.

[50] M. Mulatier, A. Boullis, C. Dollin, G. Cebrián-Torrejón, A. Vega-Rúa, Chikungunya virus infection and Gonotrophic cycle shape Aedes aegypti oviposition behavior and preferences, Viruses 15 (2023) 1043, https://doi.org/10.3390/v15051043.

[51] C.C. Edwards, G. McConnel, D. Ramos, Y. Gurrola-Mares, K. Dhondiram Arole, M. J. Green, J.E. Cañas-Carrell, C.L. Brelsfoard, Microplastic ingestion perturbs the microbiome of Aedes albopictus (Diptera: Culicidae) and Aedes aegypti, J. Med. Entomol. 60 (2023) 884–898, https://doi.org/10.1093/jme/tjad097.

[52] P. Kämpfer, H. Matthews, S.P. Glaeser, K. Martin, N. Lodders, I. Faye, Elizabethkingia anophelis sp. nov., isolated from the midgut of the mosquito Anopheles gambiae, Int. J. Syst. Evol. Microbiol. 61 (2011) 2670–2675, https://doi.org/10.1099/ijs.0.026393-0.

[53] S. Chen, B.K. Johnson, T. Yu, B.N. Nelson, E.D. Walker, Elizabethkingia anophelis: physiologic and transcriptomic responses to Iron stress, Front. Microbiol. 11 (2020) 804, https://doi.org/10.3389/fmicb.2020.00804.

[54] J. Yan, S. Yao, T. Zhang, Z. Ye, J. Weng, X. Hu, K. Zhang, Microplastics and their impacts on organisms and trophic chains, Water 14 (2022) 4069, https://doi.org/10.3390/w14244069.

[55] J.H. Li, X.H. Liu, G.R. Liang, H.T. Gao, S.H. Guo, X.Y. Zhou, D. Xing, T. Zhao, C. X. Li, Microplastics affect mosquito from aquatic to terrestrial lifestyles and are transferred to mammals through mosquito bites, Sci. Total Environ. 917 (2024) 170547, https://doi.org/10.1016/j.scitotenv.2024.170547.

[56] A.A. Hoffmann, B.L. Montgomery, J. Popovici, I. Iturbe-Ormaetxe, P.H. Johnson, F. Muzzi, M. Greenfield, M. Durkan, Y.S. Leong, Y. Dong, H. Cook, J. Axford, A. G. Callahan, N. Kenny, C. Omodei, E.A. McGraw, P.A. Ryan, S.A. Ritchie, M. Turelli, S.L. O'Neill, Successful establishment of Wolbachia in Aedes populations to suppress dengue transmission, Nature 476 (2011) 454–457, https://doi.org/10.1038/nature10356.

[57] G. Malafaia, T.M. da Luz, A.T.B. Guimarães, A.P. da Costa Araújo, Polyethylene microplastics are ingested and induce biochemical changes in Culex quinquefasciatus (Diptera: Culicidae) freshwater insect larvae, Ecotoxicol. Environ. Contam. 15 (2020) 79–89.

[58] K. Wang, J. Li, L. Zhao, X. Mu, C. Wang, M. Wang, X. Xue, S. Qi, L. Wu, Gut microbiota protects honey bees (Apis mellifera L.) against polystyrene microplastics exposure risks, J. Hazard. Mater. 402 (2021) 123828, https://doi.org/10.1016/j.jhazmat.2020.123828.

[59] L. Zhu, K. Wang, X. Wu, H. Zheng, X. Liao, Association of specific gut microbiota with polyethylene microplastics caused gut dysbiosis and increased susceptibility to opportunistic pathogens in honeybees, Sci. Total Environ. 918 (2024) 170642, https://doi.org/10.1016/j.scitotenv.2024.170642.

[60] K. Wang, L. Zhu, L. Rao, L. Zhao, Y. Wang, X. Wu, H. Zheng, X. Liao, Nano- and micro-polystyrene plastics disturb gut microbiota and intestinal immune system in honeybee, Sci. Total Environ. 842 (2022) 156819, https://doi.org/10.1016/j.scitotenv.2022.156819.

[61] M.E. Seeley, B. Song, R. Passie, R.C. Hale, Microplastics affect sedimentary microbial communities and nitrogen cycling, Nat. Commun. 11 (2020) 2372, https://doi.org/10.1038/s41467-020-16235-3.

[62] S. Bonaglia, F.J. Nascimento, M. Bartoli, I. Klawonn, V. Brüchert, Meiofauna increases bacterial denitrification in marine sediments, Nat. Commun. 5 (2014) 5133, https://doi.org/10.1038/ncomms6133.

[63] W. Li, Z. Wang, W. Li, Z. Li, Impacts of microplastics addition on sediment environmental properties, enzymatic activities and bacterial diversity, Chemosphere 307 (2022) 135836, https://doi.org/10.1016/j.chemosphere.2022.135836.

[64] L. Van Cauwenberghe, L. Devriese, F. Galgani, J. Robbens, C.R. Janssen, Microplastics in sediments: a review of techniques, occurrence and effects, Mar. Environ. Res. 111 (2015) 5–17, https://doi.org/10.1016/j.marenvres.2015.06.007.

[65] S. Fuller, A. Gautam, A procedure for measuring microplastics using pressurized fluid extraction, Environ. Sci. Technol. 50 (2016) 5774–5780, https://doi.org/10.1021/acs.est.6b00816.

[66] Y. Fei, S. Huang, H. Zhang, Y. Tong, D. Wen, X. Xia, H. Wang, Y. Luo, D. Barceló, Response of soil enzyme activities and bacterial communities to the accumulation of microplastics in an acid cropped soil, Sci. Total Environ. 707 (2020) 135634, https://doi.org/10.1016/j.scitotenv.2019.135634.

[67] Y. Dong, M. Gao, X. Liu, W. Qiu, Z. Song, The mechanism of polystyrene microplastics to affect arsenic volatilization in arsenic-contaminated paddy soils, J. Hazard. Mater. 398 (2020) 122896, https://doi.org/10.1016/j.jhazmat.2020.122896.

[68] C. Accinelli, H.K. Abbas, V. Bruno, L. Nissen, A. Vicari, N. Bellaloui, N.S. Little, W. Thomas Shier, Persistence in soil of microplastic films from ultra-thin compostable plastic bags and implications on soil aspergillus flavus population, Waste Manag. 113 (2020) 312–318, https://doi.org/10.1016/j.wasman.2020.06.011.

[69] H. Qian, M. Zhang, G. Liu, T. Lu, Q. Qu, B. Du, X. Pan, Effects of soil residual plastic film on soil microbial community structure and fertility, Water Air Soil Pollut. 229 (2018) 261, https://doi.org/10.1007/s11270-018-3916-9.

[70] Y. Sun, C. Duan, N. Cao, X. Li, X. Li, Y. Chen, Y. Huang, J. Wang, Effects of microplastics on soil microbiome: the impacts of polymer type, shape, and concentration, Sci. Total Environ. 806 (2022) 150516, https://doi.org/10.1016/j.scitotenv.2021.150516.