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Interaction of microplastics and terrestrial and aquatic insects (bioaccumulation, degradation, ecotoxicological effects)

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Abstract

World production of convenient and durable materials made of synthetic plastics during the last 70 years caused the dispersal of microplastic particles in the environment. Microplastic pollution is the focus of interest worldwide due to its global distribution and adverse effects on living organisms. The largest number of studies addressing this issue explored the aquatic environment, yet terrestrial ecosystems also suffer from microplastic pollution. Insects are crucial for most terrestrial ecosystems. Few can compete with them in biomass productivity and species diversity, which makes them targets for studying the toxic bioaccumulation. This review article presents a systematic analysis of data on bioaccumulation, degradation of microplastics by aquatic and terrestrial entomofauna, and its ecotoxicological effects.

Keywords

Bioaccumulation, degradation, ecotoxicological effects, microplastics, terrestrial and aquatic insects

Introduction

Intensive production and widespread use of synthetic plastics began in the 1950s (Barnes et al. 2009). However, global practices extensively used for disposal of plastic products are not perfect. According to 2015 data, 6,300 million tons of plastics have been produced since the middle of the twentieth century, of which only 9% have been recycled (Geyer et al. 2017).

The largest market share includes low-cost thermoplastic polymers, which contain high/low density polyethylene terephthalate and polyethylene, and linear low-density polyethylene (High density and low pressure polyethylene, high density polyethylene (low density) and linear low density polyethylene), polyvinyl chloride, polypropylene and polystyrene (Chamas et al. 2020). Microplastics are synthetic polymer particles less than 5 mm in size along the longest axis (Bergmann et al. 2015). At present, microplastic pollution poses a serious global environmental threat. Microparticles of artificial polymers have been encountered in a wide variety of environments such as marine and freshwater ecosystems, the atmosphere, agroecosystems, natural soils, food, and drinking water (Kumar et al. 2020; Nizzetto et al. 2016).

Plastic is ubiquitous, and it makes an impact on the biosphere. Unlike other well-studied ecosystems, such as marine and freshwater bodies, microplastics in terrestrial systems have been studied insufficiently. Yet, the amount of microplastics in terrestrial ecosystems can 4–23 fold exceed that in the ocean (Horton et al. 2017; Nizzetto et al. 2016).

Microplastics are pollutants that persist in the environment for centuries and can interact with the abiotic environment in a complex manner, directly or indirectly affect living organisms, and interact with other pollutants, facilitating their transport (Baho et al. 2021; Teuten et al. 2009).

Microplastics are a heterogeneous type of pollutant that exhibits a wide range of properties, such as the polymer type and, hence, its density, particle size, shape, and color. Plastic microparticles alter physical and chemical properties of soil and affect the soil fauna (Baho et al. 2021; Boots et al. 2019). They can easily enter the body of living organisms (Slootmaekers et al. 2019; Kumar et al. 2020; Rillig et al. 2017). The absorption of microplastics by organisms may be not fatal, but it can cause chronical effects, for example, reduced food intake that causes starvation, developmental disorders and behavioral changes, and long-term toxicological effects (He et al. 2020; Bartkova et al. 2021; Cappello et al. 2021; Weber et al. 2020). In addition, microplastics can be a substrate for unwanted microorganisms, like antibiotic-resistant bacteria (Bartkova et al. 2021). This causes concern as it can have an adverse effect on ecosystem biodiversity and its functioning (Rilig and Lehmann 2020; Reid et al. 2019).

Insects are a good object to study the dispersal of plastic pollution. Insects are crucial for most aquatic and terrestrial ecosystems. Few can compete with them in biomass productivity and species diversity, which makes them targets for studying the bioaccumulation of toxic substances (Miguel Oliveira et al. 2019).

The aim of this review was to perform a systematic analysis of data reported on bioaccumulation and degradation of microplastics by insects in aquatic and terrestrial ecosystems and their ecotoxicological effects. We analyzed modern literary and information sources addressing the study of pollution of terrestrial ecosystems and bioaccumulation of microplastics by insects, which can cause environmental and physiological effects.

Result

Overview of bioaccumulation and ecotoxicology of microplastics

Microplastics differ from other pollutants. Many of the adverse physiological effects caused by microplastics apparently depend on their physical parameters such as particle shape and size. In model experiments, plastic pollution often shows a sublethal or even small positive effect (Simakova et al. 2022; Al-Jaibachi et al. 2018). The indirect impact of microplastics on soil fauna entails primarily changes in soil properties. Plastic inclusions affect the soil structure, granulometric composition, gas and liquid content, and the activity of microbial communities (Rilig and Lehmann 2020).

Apart from changes in soil properties, after ingestion, microplastics can have a variety of effects on organisms exposed to them. The adverse effects can be classified as physical effects (caused by the particle shape, size or concentration) and chemical effects (caused by chemical additives coming from the plastic or absorbed along with microplastics from the environment). Chemical additives, such as phthalates and bisphenol A, are added to plastic products during manufacturing to impart color and transparency to the plastic material, and to raise its resistance to abiotic and biotic factors (Hahladakis et al. 2018). Phthalate molecules are not bound chemically to plastics, but interact physically via van der Waals forces; therefore, they can easily diffuse into the environment through air, water, or soil (Henkel et al. 2019). Plastic microparticles exhibit hydrophobic properties, and their surface can also adsorb and accumulate hydrophobic organic pollutants, such as organochlorine pesticides or polycyclic aromatic hydrocarbons (Fudlosid et al. 2022; Sun et al. 2021). Some studies report the adsorption of heavy metals (cadmium, zinc, nickel, lead) on the microplastic surface, which is facilitated by the formation of biofilms (Kirstein et al. 2016; Teuten et al. 2009). There are also data indicating the impact of microplastics on hormonal and reproductive functions of arthropods. In particular, microplastics release chemicals that exhibit hormone-like properties, for example, act like estrogen, thus causing endocrine disrupting effects (Yang et al. 2011).

Interaction of terrestrial insects and microplastics

Currently, researchers lack knowledge of whether and to what extent microplastics affect terrestrial animals. Recent studies have shown various adverse effects of microplastics on patterns of feeding, growth, reproduction and behavior of insects (Miguel Oliveira et al. 2019; Boots et al. 2019; Kumar et al. 2020; He et al. 2020; Cappello et al. 2021).

Microplastics can be easily dispersed in soil layers by invertebrates, such as termites, ants, and earthworms (Rillig et al. 2017; Miguel Oliveira et al. 2019). Invertebrates promote the transport of organic and inorganic materials within and between soil systems. In the plastic-contaminated environment, insects and worms moving in the thickness of soil horizons enhance the dispersal of microplastic particles and synthetic fibers through active transfer of soil and litter between habitats (Anderson 1998).

The effect of microplastics on vital processes has been best studied in model experiments on several species of terrestrial insects: flies *Drosophila melanogaster* Meigen, 1830, *Hermetia illucens* (Linnaeus, 1758); bees *Apis mellifera* Linnaeus, 1758; crickets *Gryllodes sigillatus* (Walker, 1869) (Table 1).

Table 1. Effects of microplastics on terrestrial and aquatic insects of different species

Species	Effect on weight	Effect on mortality	Effects on growth and development	Microplastic digestion	Transport from one environment to another	Bioaccumulation	Effect on behavior	Microplastic avoidance	Authors
Drosophila melanogaster	NO	+	–	ND	ND	YES	ND	YES	Kholy and Naggar 2022; Dinan et al. 2001
Apis mellifera	ND	NO	ND	ND	ND	YES	ND	NO	Buteler et al. 2022; Liebezeit and Liebezeit 2013, 2015
Hermetia illucens	+/–	+	+/–	ND	ND	ND	ND	ND	Cho et al. 2020
Gryllodes sigillatus	–	+	–	ND	ND	ND	ND	ND	Fudlosid et al. 2022
Tenebrio molitor	NO	NO	NO	YES	ND	NO	ND	NO	Yang et al. 2015b; Peng et al. 2019
Plodia interpunctella	NO	NO	NO	YES	ND	NO	ND	NO	Yang et al. 2014, 2015a
Culex pipiens	NO	NO	NO	ND	YES	YES	YES	NO	Al-Jaibachi et al. 2018, 2019
Aedes aegypti	+	NO	+	ND	YES	YES	YES	NO	Simakova et al. 2022

Species	Effect on weight	Effect on mortality	Effects on growth and development	Microplastic digestion	Transport from one environment to another	Bioaccumulation	Effect on behavior	Microplastic avoidance	Authors
Pantala sp.	ND	ND	ND	ND	ND	YES	ND	ND	Maneechan and Prommi 2022
Simulium equinum	ND	ND	ND	ND	ND	YES	ND	ND	Corami et al. 2022
S. ornatum	ND	ND	ND	ND	ND	YES	ND	ND	Corami et al. 2022
Chironomus riparius	+	NO	+	ND	ND	YES	ND	ND	Silva et al. 2021

Note: «+» – positive effects, «–» – adverse effects, +/- – can be positive or negative depending on the microplastic type, «NO» – no effect, «ND» – no data, «YES» – the effect is observed.

Effect of microplastics on the viability of terrestrial insects

The study conducted on *Drosophila melanogaster* revealed a significant effect of microplastics on adult survival. The diet was supplemented with 2-μm polystyrene particles at different concentrations (0.005, 0.05, 0.5 μg/ml). Drosophila males showed a great sensitivity to polystyrene intake through food. At microplastics concentration of 0.5 μg per 1 ml of food, all males in the group died within 14 days, while some females survived up to 20 days. In addition to a longer lifespan, individuals grown on 'clean' food were found to be more resistant to starvation. Histological analysis of the middle intestine sections of flies showed a negative microplastics effect at the cellular level. High concentrations of microplastics caused necrosis and apoptosis of intestinal epithelial cells (Kholy and Naggar 2022).

A number of experiments were performed on honey bees *Apis mellifera* to analyze the effects of microfibers added to the diet. Polyester fibers, a polyethylene terephthalate-based textile, with an average size of 0.42 mm were added to the sucrose solution at a concentration of 100 mg per liter of food. All individuals remained viable 24 and 48 hours after feeding. Subsequently, the intestinal tract of 80 worker bees was examined for the presence of microplastics. The average fiber content was 1.27 ± 1.5 fibers per individual. No negative effects on bees were found, but the authors assume that the effects of long-term exposure can be more distinct (Buteler et al. 2022).

The effect of microplastics on the survival of insects was also studied on larvae of the black soldier fly *Hermetia illucens* (Cho et al. 2020). Fly larvae were grown in a substrate with different supplements, including 400–500 μm polystyrene microspheres, 400–500 μm polyethylene microspheres, and NaCl salt. Microplastics were added in the amount of 5, 10, and 20% of the total weight of the food substrate. The survival rate of individuals grown on polystyrene was 5% lower compared to the control on day 20 and on day 24 of the experiment. The presence of polyethylene microparticles in the substrate did not significantly affect the larvae mortality (Cho et al. 2020). Thus, the effects of different polymers on insect survival are different.

Food selectivity

Some insects, including *Drosophila melanogaster*, show the ability to detect plastics in food. Polystyrene microspheres 2 μm in size were added to the diet at different concentrations (0.005, 0.05, 0.5 μg/mL). The flies were given plastic-contaminated food and 'clean' food (without microplastics). Regardless of particle concentration, flies more often chose microplastic-free food. Only 7% of males chose food with the highest microplastic concentration, while females avoided plastic-contaminated food (Kholy and Naggar 2022).

In (Buteler et al. 2022), bee sensitivity to microplastic contamination of the food substrate was experimentally studied. Apis mellifera bees were given two sucrose solution feeders, one of which was supplemented with polyester microfibers (polyethylene terephthalate-based textiles). However, the bees did not show distinct avoidance or preference (Buteler et al. 2022).

Effect of microplastics on the growth, development and physiology of terrestrial insects

Few works focus on the impact of microplastics on the growth, development and physiological processes of terrestrial insects despite their high significance, as compared to that studied on other living organisms.

Gryllodes sigillatus crickets grown on food supplemented with certain microplastics exhibited significantly lower adult body weight compared to control individuals fed 'clean' food. The study used two types of microplastics. The first type was fluorescent polyethylene microspheres, polymers commonly used in the production of plastic materials. The polyethylene microsphere diameter was 90–106 μm. Fluorescence facilitated tracking of ingestion of the microspheres during the experiment. The second type used was polyethylene terephthalate-based synthetic textiles. The fabric was scissored into small pieces and mixed to mimic microfiber waste from tumble dryers and washing machines. The polyethylene terephthalate-based fibers were 12.7 ± 0.01 μm thick and 743.9 ± 59.3 μm long. The amount of microplastics in food varied in different groups. The crickets were divided into 4 groups of 24 individuals each. The amount of microplastics in food attained 2.5%, 5% and 10% of the dry weight of food. The control group was given microplastic-free food. Changes in the body weight and volume were recorded weekly. By the end of the experiment, 40 males and 39 females survived (out of 96 individuals with the sex ratio of 1:1). Ingestion of polyethylene microspheres did not significantly affect the growth of both males and females. Thus, polyethylene microspheres did not have an impact on the growth parameters of crickets compared to polyethylene terephthalate fibers. Females grown on food with more than 1% of polyethylene terephthalate exhibited visual differences from the control group. Individuals from the control group were superior to the experimental group in all parameters (chest length, abdomen length, head width and chest width). It was assumed that the shape and the type of microplastic polymer are important in laboratory experiments on physiological effects. The experimental results also suggested that insects can consume more food to compensate for the reduced nutrient content (Fudlosid et al. 2022).

The effect of microplastics on the weight of adults was studied on larvae of the black soldier fly *Hermetia illucens*. The total weight of the fly larvae grown on food waste containing polystyrene powder microparticles 400–500 μm in diameter (shape not specified) exceeded that of the fly larvae in the control group on day 20 and on day 24. The weight of flies grown on food waste containing polyethylene (400–500 μm) was lower than that of flies in the control on day 6. The pupation rate increased and the substrate consumption decreased with increasing polyethylene concentration. Regardless of the plastic type, addition of NaCl decreased the larval weight and the pupation rate (Cho et al. 2020). Thus, the microplastic type has an effect on the growth and development of terrestrial insects.

The 2009 study by Jörg Elmann et al. (Oehlmann et al. 2009) showed that phthalates and bisphenol A affect the reproductive function of all the animal groups studied, including amphibians, fish, molluscs, and insects. The above substances disrupt the development of crustaceans and amphibians and cause genetic aberrations. Biological effects were observed when the microplastics content in the medium varied from a nanogram to microgram per liter (Oehlmann et al. 2009). The experiment on the tumor cell line BII (l[2]mbn) in *Drosophila melanogaster* (bred to study ecdysteroid-specific reactions) (Clement et al. 1993) showed that bisphenol A and diethyl phthalates act as antagonists of ecdysteroid receptor at medium concentration (EC50) of 1.0×10^{-4} m and (EC50) of 2.0×10^{-3} m, respectively (Dinan et al. 2001).

Microplastics in products produced by insects

Plastic is actively used in all branches of human activity, and its particles are now ubiquitous across the planet. Bioaccumulation is manifested not only in the accumulation of microplastics in the bodies of animals, but also in the products of their vital activity (Liebezeit and Liebezeit 2013, 2015). Since 2013, plastic particles and fibers have been detected in the honey we eat. A total of 19 honey samples from Germany, France, Mexico and Spain were analyzed. As a result, a large number of microfibers (from 40 to 660 fibers per kg of honey) and plastic microfragments (up to 38 fragments per kg) were detected (Liebezeit and Liebezeit 2013).

In 2015, the analysis of 47 honey samples from different countries in Europe and Latin America showed similar results. The microplastic content in the samples ranged from 10 to 336 fibers and from 2 to 82 fragments. The fiber length varied from 40 μm to several mm, and the fragment size attained several tenths of μm (Figure 1) (Liebezeit and Liebezeit 2015).

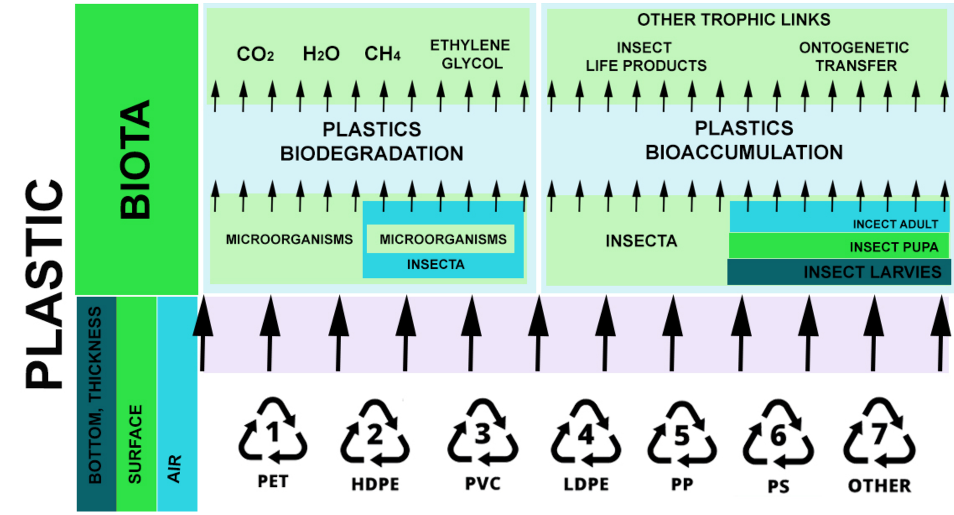

Figure 1. Scheme illustrating the interaction of microplastics and terrestrial and aquatic insects.

Terrestrial insects as plastic-degrading agents

Interestingly, some insects feature the ability to recycle plastic. There is evidence that beetles *Tenebrio molitor* Linnaeus, 1758 are able to chew and swallow fragments of plastic packaging, including polyvinyl chloride, polyethylene, and polypropylene films (Yang et al. 2015b; Peng et al. 2019). The authors showed that foamed polystyrene is effectively decomposed in the intestines of darkling beetle larvae within a short time period (less than a day). The larvae that were grown on EPS were able to survive for one month, and their development was similar to those whose diet consisted of bran. The methods of gel permeation chromatography, nuclear magnetic resonance spectroscopy, and thermogravimetric infrared Fourier transformed spectroscopy revealed that long-chain polystyrene molecules are cleaved, and depolymerized metabolites are formed in the intestine of larvae. Within 16 days, 47.7% of the ingested polystyrene carbon was converted to CO2, and the remainder was excreted as faeces. Labeled carbon atoms in the polystyrene composition were detected in larval biomolecules, namely, in lipids. Rapid biodegradation of polystyrene in the intestines of *T. molitor* larvae can be promising for development of new biotechnologies for plastic waste utilization (Figure 1) (Yang et al. 2015b).

In addition to beetles, butterflies exhibit the ability to digest plastic. Larvae of the barn moth *Plodia interpunctella* Hübner, 1813 were found to digest polyethylene. The intestinal microflora of the larvae was analyzed, and two strains of bacteria (*Enterobacter asburiae* YT1 and *Bacillus* sp.YP1), which enzymes were involved in digestion, were isolated (Yang et al. 2014, 2015b). After 28 days of the strain incubation, viable biofilms were formed on the polyethylene surface, and hydrophobicity of the polyethylene material decreased. Scanning electron microscopy and atomic force microscopy showed damages 0.3–0.4 μm deep on the film surface. The formation of carbonyl groups was confirmed by X-ray photoelectron spectroscopy and microscopy combined with infrared Fourier (FTIR) spectroscopy. Suspension cultures of strains YT1 and YP1 (108 cells/ml) are able to degrade approximately 6.1 ± 0.3% and 10.7 ± 0.2% (by weight) of polyethylene films during 60 days of incubation. A total of 12 water-soluble polyethylene biodegradation products were isolated. The results showed the presence of plastic-degrading bacteria in the intestines of *Lepidoptera* larvae and provided evidence for plastic biodegradation in the environment (Figure 1) (Yang et al. 2014). Further studies included a genomic analysis of bacterial strains to confirm that polyethylene is the only source of carbon for YP1 strain (Yang et al. 2015a).

Interaction of microplastics and aquatic insects

The effect of microplastics on aquatic insects was studied on cultures of the genera *Aedes* Meigen, 1818, *Culex* Meigen, 1818, and *Chironomus* Meigen, 1803, and on natural populations of larvae of dragonfly *Pantala* Hagen, 1861, and midge *Simulium* Latreille, 1802 (Table 1).

Bioaccumulation of microplastics in aquatic insects

Ontogenetic transfer of microplastics by aquatic insects

Experimental studies have shown that fluorescent polystyrene microspheres found in the aquatic habitat of larvae of mosquitoes *Culex pipiens* Linnaeus, 1758, do not significantly affect their weight and mortality. The larvae exhibited normal development in the medium at microplastic concentrations of 0, 50, 100, and 200 particles per 1 ml. The particle diameter was 2 and 15 μm. The intensity of microplastic absorption directly depended on the particle concentration and size. Microplastics were transferred from larva to pupae and adult mosquitoes. A significant transfer was recorded for 2-μm microspheres. Microspheres of 15 μm were found sporadically in adults. The amount of accumulated microplastics decreased with each transition from one stage to the next one (larvae > pupae > adults). The concentration of polystyrene microspheres in larvae was 3,000–4,000 particles per larva; in pupae, this value almost halved and attained 1,000–1,600 particles. In adults, however, no more than 50 particles were found. Thus, the greatest microplastic losses were recorded during the pupa-to-imago transition (Figure 1) (Al-Jaibachi et al. 2018, 2019).

In addition to mosquitoes of the genus *Culex*, a similar study was carried out for blood-sucking mosquitoes *Aedes aegypti* (Linnaeus, 1762) (Simakova et al. 2022). The study confirmed the transfer of microplastics from the aquatic larval stage to the ground-air adult stage. The experiment employed 2-μm fluorescent polystyrene microspheres. Mosquito larvae were kept in the aqueous medium at a concentration of 8.0 × 106 microplastic particles per ml. The concentration of microplastic particles in the medium was measured before and after the experiment. The results showed a 2.4-fold decrease in the content of microplastic particles in the medium, which indicated their active absorption by larvae. On average, 7.30 × 106 particles were detected in one larva after 3-day cultivation, which is much higher than the microplastic content in individuals at subsequent stages (on average, 15.8 particles per pupa and 10.9 particles per adult). This critically differs from the microplastic content in mosquitoes of the genus *Culex*, where the greatest losses occurred during the pupa-to-adult transition. The medium supplemented with a high microplastic content did not have a significant effect on the survival of *Ae. aegypti*. Mosquitoes that consume plastic in aquatic ecosystems are likely to transport particles to terrestrial food chains (Figure 1) (Simakova et al. 2022).

Study of microplastic bioaccumulation in natural populations of aquatic insects

A total of 95 microplastic particles 400–500 μm in size were found in the intestines of 180 dragonfly larvae of the genus *Pantala* (species not indicated) from the central regions of Thailand. Chemical analysis performed using FT-IR spectroscopy revealed three different polymers, including polymethyl methacrylate, polyethylene terephthalate, and polypropylene (Figure 1) (Maneechan and Prommi 2022).

A similar study was carried out for larvae of *Simulium equinum* (Linnaeus, 1758) and *Simulium ornatum* (Meigen, 1818) from central Italy. The specimens were examined for small microplastic particles (<100 μm along the maximum axis) and synthetic fibers. Representatives of *S. ornatum* contained more diverse microplastics, which may be associated with many factors, including species habitat and biology. Nylon-6 (kapron) was most numerous and its number attained 327 ± 14 particles per larva. The largest number of microplastic particles per individual was found in *S. ornatum* larvae from the Minyon River, and it equaled 1,565±56 particles per larva, which is 4 fold more than that in *S. equinum* inhabiting this river (442±30 particles per larva). In larvae from the Treya River, the number of microplastic particles was significantly lower (358±27 in *S. ornatum* and 423±29 in *S. equinum*). Different number of microplastic particles in different habitats may be associated with the activities of industrial enterprises located nearby (Corami et al. 2022).

Effect of microplastics on the growth and development of aquatic insects

Microplastic ingestion by insects can trigger special physiological mechanisms. Thus, ingestion of polyethylene particles by larvae of the mosquito *Chironomus riparius* (Meigen, 1804) activates the phenol oxidase system (Silva et al. 2021). This enzymatic system is responsible for the innate immune response to a parasite or pathogen. The phenol oxidase and total system (phenol oxidase in combination with prophenol oxidase) was studied. Polyethylene particles 32–63 μm in size were used in the experiment. A total of 5 and 20 g of polyethylene were added per kg of food for *Chironomus riparius* larvae increased the activity of the main phenol oxidase system by 26 and 29%, respectively, and the activity of the total system increased by 48% in both cases. The authors suggest that this is caused by the damage to the epithelial cells of the intestinal lumen (Silva et al. 2021).

The sublethal effect of dioctyl phthalate was also recorded. The presence of this plasticizer in water at a concentration of 0.3 μg/l increased the body volume of *C. riparius* females at the larval stage. In addition, its concentration of 0.5 μg l–1 increased the expression of heat shock protein and hemoglobin genes in larvae of the mosquito *C. tentans* Meigen, 1803 (Lee et al. 2006).

Unlike chironomids, microplastics do not have a significant effect on the development of mosquitoes *Cx. pipiens*. When polystyrene microspheres 2 and 15 μm in size contained in the medium at concentrations of 0, 50, 100, and 200 particles per 1 ml were absorbed by the larvae, the weight of the developed adults did not significantly differ from that in the control group (Al-Jaibachi et al. 2018, 2019).

Physiological effects of mosquitoes *Ae. aegypti* exposed to polystyrene microspheres were different. Mosquito larvae that developed in an aquatic medium with polystyrene particles at a concentration of 8.0 × 106 per ml were bigger than those from the control group. They also exhibited a more active feeding behavior (Simakova et al. 2022). The average weight of larvae that developed in the artificially polluted medium significantly exceeded ($p<0.01$) that of those from the control group at all stages of the life cycle. The most apparent differences were recorded at the pupal stage (1.60 mg in the control group and 2.30 mg in the experimental group). The authors suggest that larvae readily consume microplastics, but it does not provide nutrition. As a result, the larvae feeds more actively in order to prepare for metamorphosis (Simakova et al. 2022). Thus, microplastics affect the feeding behavior of insects.

Conclusion

In recent years, distribution and ecotoxicology of microplastics have been studied intensively; however, the data obtained are insufficient to understand the effect of this pollutant and the terrestrial environment with its inhabitants. Most of the recent studies investigate the marine environment and less often fresh water, terrestrial biotopes being poorly studied. The study of fresh water and its inhabitants is of relevance since plastic pollutants are ubiquitous in rivers and lakes (Frank et al. 2022). The focus of our interest is on the terrestrial and aquatic-terrestrial ecosystems. According to some estimates, only agricultural soils can accumulate more microplastics than ocean basins (Baho et al. 2021), including natural biocenoses. Due to their ubiquitous distribution in most ecosystems, insects are highly exposed to microplastic pollution.

A number of papers have been published recently on the effect of microplastics on various animal species, including insects. However, further studies on the mechanisms and cause-effect relationship are needed, since the available data show that different species respond differently to microplastic pollution. Among all the incredible taxonomic diversity of insects, only several species have been investigated. A great number of studies is devoted to aquatic insects. Mosquitoes are of interest due to their ability to transport microplastics from the aquatic to terrestrial environment, contributing to pollution spread. Another topic of interest is the study of potential plastic-degrading agents. These include some representatives of beetles and Lepidoptera. The darkling beetle larvae are able to survive on plastic alone, and it does not affect their development. However, microplastics found in the environment or in food have an adverse effect on all animals. Bisphenol A and diethyl phthalates exhibit ecdysteroid antagonist activity in Drosophila cells. Polystyrene in food of fruit flies significantly shortens their lifespan. In the plastic-contaminated environment, the survival rate of *Hermetia illucens* larvae was found to reduce. The effect of polyethylene terephthalate on crickets was also studied. Individuals that fed on contaminated food during development were much smaller compared to those from the control group. Similar results were observed for *Hermetia illucens* fed on the food substrate supplemented with polyethylene. The ingestion of polyethylene by *Chironomus* larvae activates the phenol oxidase system. The addition of dioctyl phthalate caused the expression of heat shock genes in *C. tentans*.

A number of insects were able to distinguish contaminated food from 'clean' food. For example, most fruit flies chose plastic-free food. Some insects were not significantly affected by microplastics during the experiments. Polyester fibers added to food for bees did not have a considerable effect on their vital activity. *Aedes* and *Culex* mosquitoes were completely resistant to microplastics (polystyrene) exposure. Aedes larvae exhibited a large body weight in the environment with plenty of polystyrene microspheres. Similar results were observed for *Chironomus* females in dioctyl phthalate-containing water.

In addition to assessment of the microplastic effect on insects, quantification of plastic pollution in natural environment is of relevance. Studies into this issue included larvae of dragonfly *Pantala* and midge *Simulium*. A significant amount of microplastics was detected in both species. It should be noted that microplastics were found in honeybee products.

It has now been established that some insect species are able to digest microplastic (Yang et al. 2014, 2015b, 2015b), while others exhibit developmental abnormalities (Fudlosid et al. 2022; Kholy and Naggar 2022; Silva et al. 2021). Some representatives of Insecta were resistant to the microplastic pollution and were able to transfer microplastics between different habitats (Al-Jaibachi et al. 2018, 2019; Simakova et al. 2022). The effect of microplastic pollution on the life processes of most large taxa of insects is poorly understood. Yet, the obtained data show that this effect largely depends on the particle shape and size, and the polymer type (Fudlosid et al. 2022).

Plastic pollution is a global problem and requires further study. More data are needed for different regions with different climatic conditions. In addition, the effect of microplastics or plastic accumulation is still studied poorly for a huge number of large taxa of insects. In addition, the search for promising candidates as plastic-degrading agents is topical.

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References

Al-Jaibachi R, Cuthbert R N, Callaghan A (2018) Up and away: ontogenic transference as a pathway for aerial dispersal of microplastics. Biology letters 14(9): 20180479. https://doi.org/10.1098/rsbl.2018.0479

Al-Jaibachi R, Cuthbert RN, Callaghan A (2019) Examining effects of ontogenic microplastic transference on *Culex* mosquito mortality and adult weight. Science of The Total Environment 651: 871–876. https://doi.org/10.1016/j.scitotenv.2018.09.236

Anderson JM (1998) Invertebrate-mediated transport processes in soils Agriculture. Ecosystems & Environment 24: 5–19. https://doi.org/10.1016/0167-8809(88)90052-7

Baho DL, Bundschuh M, Futter MN (2021) Microplastics in terrestrial ecosystems: Moving beyond the state of the art to minimize the risk of ecological surprise. Global Change Biology 27: 3969–3986. https://doi.org/10.1111/gcb.15724

Barnes DK, Galgani F, Thompson RC, Barlaz M (2009) Accumulation and fragmentation of plastic debris in global environments. Philosophical transactions of the Royal Society of London. Series B 364(1526): 1985–1998. https://doi.org/10.1098/rstb.2008.0205

Bartkova S, Kahru A, Heinlaan M, Scheler O (2021) Techniques used for analyzing microplastics, antimicrobial resistance and microbial community composition: A mini-review. Frontiers in Microbiology 12: 413. https://doi.org/10.3389/fmicb.2021.603967

Bergmann M, Gutow L, Klages M (2015) Springer Marine anthropogenic litter. Berlin, Germany, 447 pp. https://doi: 10.1007/978-3-319-16510-3

Boots B, Russell CW, Green DS (2019) Effects of microplastics in soil ecosystems: Above and below ground. Environmental Science & Technology 53(19): 11496–11506. https://doi.org/10.1021/acs.est.9b03304

Buteler M, Alma AM, Stadler T, Gingold AC, Manattini MC, Lozada M (2022) Acute toxicity of microplastic fibers to honeybees and effects on foraging behavior. The Science of the total environment 822: 153320. https://doi.org/10.1016/j.scitotenv.2022.153320

Cappello T, De Marco G, Oliveri Conti G, Giannetto A, Ferrante M, Mauceri A, Maisano M (2021) Time-dependent metabolic disorders induced by short-term exposure to polystyrene microplastics in the Mediterranean mussel *Mytilus galloprovincialis*. Ecotoxicology and environmental safety 209: 111780. https://doi.org/10.1016/j.ecoenv.2020.111780

Chamas A, Moon H, Zheng J, Qiu Y, Tabassum T, Jang J-H, Abu-Omar M, Scott SL, Suh S (2020) Degradation rates of plastics in the environment. ACS Sustainable Chemistry & Engineering 8: 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635

Cho S, Kim CH, Kim MJ, Chung H (2020) Effects of microplastics and salinity on food waste processing by black soldier fly (*Hermetia illucens*) larvae. Journal of Ecology and Environment 44(1): 7. https://doi.org/10.1186/s41610-020-0148-x

Clement CY, Bradbrook DA, Lafont R, Dinan L (1993) Assessment of a microplate-based bioassay for thedetection of ecdysteroid-like or antiecdysteroid activities. Insect Biochemistry and Molecular Biology 23: 187–193.

Corami F, Rosso B, Iannilli, V, Ciadamidaro S, Bravo B, Barbante C (2022) Occurrence and Characterization of Small Microplastics (<100 μm), Additives, and Plasticizers in Larvae of Simuliidae. Toxics 10: 383. https://doi.org/10.3390/toxics10070383

Dinan L, Bourne P, Whiting P, Dhadialla TS, Hutchinson TH (2001) Screening of environmental contaminants for ecdysteroid agonist and antagonist activity using the *Drosophila melanogaster* B-II cell in vitro assay. Environmental toxicology and chemistry 20(9): 2038–2046. https://doi.org/10.1897/1551-5028(2001)020<2038:soecfe>2.0.co;2

Frank Y, Ershova A, Batasheva S, Vorobiev E, Rakhmatullina S, Vorobiev D, Fakhrullin R (2022) Microplastics in Freshwater: A Focus on the Russian Inland Waters. Water 14(23): 3909. https://doi.org/10.3390/w14233909

Fudlosid S, Ritchie MW, Muzzatti MJ, Allison JE, Provencher J, MacMillan HA (2022) Ingestion of Microplastic Fibres, But Not Microplastic Beads, Impacts Growth Rates in the Tropical House Cricket Gryllodes Sigillatus. Frontiers in physiology 13: 871149. https://doi.org/10.3389/fphys.2022.871149

Geyer R, Jambeck J R, Law KL (2017) Production, Use, and Fate of All Plastics Ever Made. Science Advances 3: 25–29. https://www.science.org/doi/10.1126/sciadv.1700782

Hahladakis J N, Velis CA, Weber R, Iacovidou E, Purnell P (2018) An Overview of Chemical Additives Present in Plastics: Migration, Release, Fate and Environmental Impact during Their Use, Disposal and Recycling. Journal of Hazardous Materials 344: 179–199. https://doi.org/10.1016/j.jhazmat.2017.10.014

He D, Bristow K, Filipović V, Lv J, He H (2020) Microplastics in Terrestrial Ecosystems: A Scientometric Analysis. Sustainability 12(20): 8739. https://doi.org/10.3390/su12208739

Henkel C, Hüffer T, Hofmann T (2019) The Leaching of Phthalates from PVC Can Be Determined with an Infinite Sink Approach. MethodsX 6: 2729–2734. https://doi.org/10.1016/j.mex.2019.10.026

Horton AA, Walton A, Spurgeon DJ, Lahive E, Svendsen C (2017) Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. The Science of the total environment 586: 127–141. https://doi.org/10.1016/j.scitotenv.2017.01.190

Kholy SE, Naggar YA (2022) Polystyrene Microplastic Beads Caused Cellular Alterations in midgut cells and Sex-Specifc Toxic Effects on Survival, Starvation Resistance, and

Excretion of the Model Insect Drosophila melanogaster. Scientific reports 13(1): 204. https://doi.org/10.1038/s41598-022-27284-7

Kirstein IV, Kirmizi S, Wichels A, Garin-Fernandez A, Erler R, Löder M, Gerdts G (2016) Dangerous hitchhikers? Evidence for potentially pathogenic *Vibrio* spp. on microplastic particles. Marine environmental research 120: 1–8. https://doi.org/10.1016/j.marenvres.2016.07.004

Kumar M, Xiong X, He M, Tsang DCW, Gupta J, Khan E, Harrad S, Hou D, Sik Ok Y, Bolan N (2020) Microplastics as pollutants in agricultural soils. Environmental Pollution 265: 114980. https://doi.org/10.1016/j.envpol.2020.114980

Lee SM, Lee SB, Park CH, Choi J (2006) Expression of heat shock protein and hemoglobin genes in *Chironomus tentans* (Diptera, chironomidae) larvae exposed to various environmental pollutants: a potential biomarker of freshwater monitoring. Chemosphere 65(6): 1074–1081. https://doi.org/10.1016/j.chemosphere.2006.02.042

Liebezeit G, Liebezeit E (2013) Non-pollen particulates in honey and sugar. Food additives & contaminants. Part A, Chemistry, analysis, control, exposure & risk assessment 30(12): 2136–2140. https://doi.org/10.1080/19440049.2013.843025

Liebezeit G, Liebezeit E (2015) Origin of Synthetic Particles in Honeys. Polish Journal of Food and Nutrition Sciences 65(2): 143–147. https://doi.org/10.1016/j.trac.2019.02.018

Maneechan W, Prommi TO (2022) Occurrence of microplastics in edible aquatic insect *Pantala* sp. (Odonata: Libellulidae) from rice fields. PeerJ 10: 12902. https://doi.org/10.7717/peerj.12902

Miguel Oliveira, Olga MCC Ameixa, Amadeu MVM Soares (2019) Are ecosystem services provided by insects "bugged" by micro (nano)plastics? TrAC Trends in Analytical Chemistry 113: 317–320.

Nizzetto L, Langaas S, Futter M (2016) Do microplastics spill on to farm soils? Nature 537(7621): 488. https://doi.org/10.1038/537488b

Oehlmann J, Schulte-Oehlmann U, Kloas W, Jagnytsch O, Lutz I, Kusk KO, Wollenberger L, Santos E M, Paull GC, Van Look KJ, Tyler CRA (2009) Critical analysis of the biological impacts of plasticizers on wildlife. Philosophical transactions of the Royal Society of London. Series B 364(1526): 2047–2062. https://doi.org/10.1098/rstb.2008.0242

Peng BY, Su Y, Chen Z, Chen J, Zhou X, Benbow ME, Criddle CS, Wu WM, Zhang Y (2019) Biodegradation of Polystyrene by Dark (*Tenebrio obscurus*) and Yellow (*Tenebrio molitor*) Mealworms (Coleoptera: Tenebrionidae). Environmental science & technology 53(9): 5256–5265. https://doi.org/10.1021/acs.est.8b06963

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden J D, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews 94(3): 849–873. https://doi.org/10.1111/brv.12480

Rillig M, Ziersch L, Hempel S (2017). Microplastic transport in soil by earthworms. Scientific Reports 7: 1362. https://doi.org/10.1038/s41598-017-01594-7

Rillig MC, Lehmann A (2020) Microplastic in terrestrial ecosystems. Science 368(6498): 1430–1431. https://doi.org/10.1126/ science.abb5979

Silva CJM, Beleza S, Campos D, Soares AMVM, Patrício Silva AL, Pestana JLT, Gravato C (2021) Immune response triggered by the ingestion of polyethylene microplastics in the dipteran larvae *Chironomus riparius*. Journal of hazardous materials 414: 125401. https://doi.org/10.1016/j.jhazmat.2021.125401

Simakova A, Varenitsina A, Babkina I, Andreeva Y, Bagirov R, Yartsev V, Frank Y (2022) Ontogenetic Transfer of Microplastics in Bloodsucking Mosquitoes *Aedes aegypti* L. (Diptera: Culicidae) Is a Potential Pathway for Particle Distribution in the Environment. Water 14: 1852. https://doi.org/10.3390/w14121852

Slootmaekers B, Catarci Carteny C, Belpaire C, Saverwyns S, Fremout W, Blust R, Bervoets L (2019) Microplastic contamination in gudgeons (*Gobio gobio*) from Flemish rivers (Belgium). Environmental Pollution 244: 675–684. https://doi.org/10.1016/j.envpol.2018.09.136

Sun S, Shi W, Tang Y, Han Y, Du X, Zhou W, Zhang W, Sun C, Liu G (2021) The Toxic Impacts of Microplastics (MPs) and Polycyclic Aromatic Hydrocarbons (PAHs) on Haematic Parameters in a marine Bivalve Species and Their Potential Mechanisms of Action. Science of The Total Environment 783: 147003. https://doi.org/10.1016/j.scitotenv.2021.147003

Teuten EL, Saquing JM, Knappe DR, Barlaz MA, Jonsson S, Björn A, Rowland SJ, Thompson RC, Galloway TS, Yamashita R, Ochi D, Watanuki Y, Moore C, Viet P H, Tana TS, Prudente M, Boonyatumanond R, Zakaria microplastic, Akkhavong K, Ogata Y, Hirai H, Iwasa S, Mizukawa K, Hagino Y, Imamura A, Saha M, Takada H (2009) Transport and release of chemicals from plastics to the environment and to wildlife. Philosophical transactions of the Royal Society of London. Series B 364(1526): 2027–2045. https://doi.org/10.1098/rstb.2008.0284

Weber A, von Randow M, Voigt AL, Au, Mvd, Fischer E, Meermann B, Wagner M (2020) Ingestion and toxicity of microplastics in the freshwater gastropod *Lymnaea stagnalis*: No microplastic-induced effects alone or in combination with copper. Chemosphere 263: 128040. https://doi.org/10.1016/j.chemosphere.2020.128040

Yang CZ, Yaniger SI, Jordan VC, Klein DJ, Bittner GD (2011) Most plastic products release estrogenic chemicals: A potential health problem that can Be solved. Environmental health perspectives 119(7): 989–996. https://doi.org/10.1289/ehp.1003220

Yang J, Yang Y, Wu WM, Zhao J, Jiang L (2014) Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environmental science & technology 48(23): 13776–13784. https://doi.org/10.1021/es504038a

Yang Y, Chen J, Wu WM, Zhao J, Yang J (2015a) Complete genome sequence of *Bacillus* sp. YP1, a polyethylene-degrading bacterium from waxworm's gut. Journal of biotechnology 200: 77–78. https://doi.org/10.1016/j.jbiotec.2015.02.034

Yang Y, Yang J, Wu WM, Zhao J, Song Y, Gao L, Yang R, Jiang L (2015b) Biodegradation and Mineralization of Polystyrene by Plastic-Eating Mealworms: Part 1. Chemical and Physical Characterization and Isotopic Tests. Environmental science & technology 49: 20. https://doi.org/10.1021/acs.est.5b02661