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ECOTOXICOLOGICAL ASPECTS OF MICROPLASTIC CONTAMINATION OF BEEKEEPING PRODUCTS

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Summary. The article summarizes recent scientific findings on the presence of microplastics in bee products and highlights the key trends reflecting the impact of human activities on the environment. It examines the factors that cause the accumulation of synthetic polymer particles in honey, pollen, bee bread, propolis, and wax, and analyzes the biological response of bees to the impact of microplastics from the perspectives of physiology, toxicology, and ecology. Particular attention is given to the methodological aspects of identifying microplastic particles in bee products, as well as the challenges of standardizing this process. The presented data aim to integrate existing research results in the context of assessing risks to human health and ecosystem stability and developing veterinary and sanitary control methods. This material is intended for specialists in veterinary medicine, food safety, apitherapy, and ecology

Keywords: honey bee, synthetic polymers, human health, veterinary and sanitary control

Introduction. The accumulation of microplastic particles in the natural environment has become one of the key environmental challenges of the 21st century. The scale and speed of the spread of polymer particles of various origins are forming new patterns of pollution that affect all components of the biosphere — the atmosphere, soil, surface and groundwater, and plant and animal organisms. In recent years, the attention of scientists (Gómez-Méndez et al., 2024; Al Naggar et al., 2024; Pasquini et al., 2023; Kadarsah et al., 2025) has increasingly focused on assessing such contamination in food products, especially in bee products, which are traditionally considered natural, organic, and biologically valuable. Bee products, especially honey, have historically been highly trusted by consumers and are widely used in nutrition, medicine, pharmacology, veterinary medicine, and cosmetology. This, along with the unique ecological properties of bees as super bioindicators, makes the study of microplastics in honey and other bee products particularly relevant.

The honey bee (*Apis mellifera* L.) is a highly sensitive bioindicator for monitoring the ecological state of the environment. In the process of collecting nectar and pollen, bees interact with a full range of environmental factors. Since worker bees have a flight radius of up to 5 km, they gather information about the state of the environment over large areas. This allows their products to serve as indicators of environmental pollution levels.

In this regard, honey, pollen, bee bread, and wax are increasingly being considered not only as food products but also as matrices that accumulate microplastics. Studies show that contamination with synthetic particles is not a random phenomenon, but a systemic characteristic of modern apiaries (Basaran et al., 2024; Rani-Borges et al., 2024; Gómez-Méndez et al., 2024). These data raise new scientific questions about the mechanisms of interaction between microplastics and bees, the physicochemical properties of particles, and the processes of their migration and accumulation in bee products.

The problem's relevance is exacerbated by the fact that microplastics can carry a wide range of toxic substances, including phthalates, bisphenol A, pesticides, heavy metals, and organic toxicants. Combined with the active metabolism and high physiological vulnerability of bees, these factors can cause behavioral disorders, reduced immune defense, impaired larval development, and general weakening of colonies. For humans, the main risk is the possible entry of synthetic particles into the digestive system during honey consumption, but the indirect toxic effect through adsorbed impurities may be more significant. Microplastics are considered a promising marker of food chain contamination in the One Health system, so a systematic study of them in bee products is important for human food safety.

Due to the absence of standardized methods for detecting microplastics in bee products, the presence of various identification techniques, and the limited systematic research conducted both regionally and globally, there is a pressing need for a comprehensive review of existing scientific data. This review should also establish directions for future research in this area.

The work **aims** to systematize current information on the characteristics of microplastic contamination of bee products, to identify the mechanisms of their entry into the 'environment-bee-product' system, analyzing data on the possible toxicological effects on bees and humans, and evaluating existing analytical control methods and prospects for further research in the field of veterinary and food safety.

Materials and methods. Theoretical research methods were used, namely analysis and synthesis of scientific sources, systematization of data, and generalization of results to form directions for further empirical research. To form the review material, 38 scientific sources from the last 15 years were analyzed, including publications in peer-reviewed journals of international databases, FAO reports, and data from experimental studies in ecology, toxicology, and beekeeping.

The reliability of the obtained data was ensured through structural, comparative, and contextual analyses. Information on the mechanisms by which microplastics enter the bodies of bees and bee products was integrated. A critical assessment of the advantages and limitations of modern analytical methods was also carried out.

Results and discussion. Bertosh (2025) considers the problem of microplastics in drinking water and food products as a potential threat to human health. The author emphasizes the ability of synthetic particles to adsorb toxic chemical compounds (phthalates, bisphenol A, pesticides, heavy metals) and their possible interaction with the gut microbiota. Particular attention is paid to nanoplastics, which, due to their ability to penetrate biological barriers, may have increased toxicological potential. Other authors also emphasize the global nature of the microplastics problem and its impact on the environment. For example, Kirsanova (2024) highlights the persistence of polymer particles and their ability to remain in the biosphere for long periods of time, posing a threat to ecological balance and human health. For their part, Kotovenko et al. (2024) analyze the current state of microplastic pollution, identify the main sources of its release into the environment, and consider methods of drinking water purification, emphasizing the need to improve control technologies.

The presence of microplastics in bee products is a topic of active research around the world. The number of scientific publications on this subject is constantly growing (Cortés-Corrales et al., 2024; Rodrigues et al., 2025). The available literature discusses not only the detection of microplastic particles, but also the mechanisms of their migration, the biological reactivity of bees to the effects of microplastics, and the potential toxicological consequences for consumers of bee products (Rani-Borges et al., 2024; Al Naggar et al., 2024).

The first systematic evidence of honey contamination by synthetic fibers came from studies conducted by G. Liebezeit and E. Liebezeit (2015). The researchers found polymer particles in honey from various European countries. The authors noted that the number of microparticles found ranged from several dozen to several hundred per kilogram of product, and most of the particles were fibers of textile origin. These results became the starting point for subsequent studies, in which the presence of microplastics in honey was not only confirmed but also studied, taking into account environmental, technological, and regional factors.

A study by Basaran et al. (2024) analyzed honey from different regions of Turkey, where microplastic particle concentrations ranged from 0 to 1,280 particles/kg. The authors describe significant regional contrasts, which they attribute to varying levels of urbanization, traffic intensity, local industrial facilities, and the nature of agricultural activities. Urbanized areas are characterized by higher concentrations of polyester fibers, which is likely due to textile waste and significant atmospheric pollution.

Similar trends have been described in studies in Latin America. Rani-Borges et al. (2024), analyzing *Melipona quadrifasciata* honey, recorded the presence of microplastics in 100% of samples. Here, too, synthetic fibers predominated, and their size and color allowed the authors to suggest various sources of contamination, ranging from synthetic fabrics to elements of car tires and fragments of packaging materials. These data are consistent with the results of studies from South Korea, where Choi et al. (2024) found 10–1,020 particles/kg in honey from different regions of the country.

A common pattern noted by authors from different countries is the stable dominance of fibers over other forms of microplastics. This indicates that the main source of contamination is atmospheric air containing particles of synthetic textiles that enter bee products during the collection of nectar and pollen. At the same time, the presence of polyethylene and polypropylene fragments indicates an additional contribution of plastic, which may originate from river basins, technological elements of beehives, or surface waters used by bees.

The study by Buteler et al. (2025) investigated the presence of synthetic and natural microfibers in honey and bees in Argentina. The authors showed that fibers constitute the vast majority of particles found, which is consistent with previous international studies. They emphasized that the main source of contamination is atmospheric air saturated with textile fibers, which enter bee products during the collection of nectar and pollen. In addition, the paper draws attention to the potential environmental consequences of such pollution for bee health and honey quality, as well as the need to develop methods for monitoring and reducing the impact of microplastics in agroecosystems.

According to Gómez-Méndez et al. (2024), plant pollen is significantly more contaminated with microplastics than honey. In their study, all samples of bee pollen contained various types of microplastics, ranging from microfibers to whole fragments. This is due to the special structure of the exine of pollen grains, which has microscopic grooves, spikes, and ridges that can trap foreign particles. In addition, pollen from wind-pollinated plants is carried over long distances by the wind and can also stick to the exoskeleton of bees and be added to pollen by bees, which increases the likelihood of further contamination of the hive environment and the products obtained.

Most studies emphasize the link between pollen contamination and the state of the atmospheric environment. Pollen from urban areas has a higher number of microplastic fibers, while samples from rural areas more often contain polyethylene fragments. This is probably due to agricultural films and the use of synthetic packaging. These data are important for interpreting bee products as bioindicators of environmental health because they allow us to conclude local sources of pollution.

Bee bread is a natural fermented product made from bee pollen, honey, and enzymes from the digestive glands of worker bees. This process results in lactic acid fermentation, alcoholic fermentation, and the synthesis of biologically active substances. While the origin of bee bread determines its high nutritional value, it also contributes to the accumulation of microplastics. Studies analyzing bee bread alongside bee pollen and honey reveal higher microplastic concentrations in bee bread than in bee pollen. Scientists suggest that this may be due to fermentation processes increasing the ability of bee bread to retain hydrophobic particles.

Bee bread is a long-term food reserve for bees, making it important for assessing the continuous influx of microplastics into bee colonies' food chains. The accumulation of microplastics in bee bread can harm the development of larvae, since it serves as their main source of protein and minerals.

Wax occupies a special position among bee products because it can accumulate not only microplastics but also a wide range of chemical pollutants, including pesticides, heavy metals, polycyclic aromatic hydrocarbons, and veterinary drug residues (Mullin et al., 2010). Its lipid nature is the reason for its high affinity with hydrophobic molecules and particles. A number of studies suggest that old honeycombs can accumulate and contain significantly more microplastics than new ones, indicating cumulative pollution processes.

Data from simultaneous analysis of wax and honey are particularly revealing. Microplastic levels in wax often exceeded those in honey by 3–10 times. This highlights the importance of wax as the 'long-term memory' of the apiary, reflecting the historical state of pollution (Cortés-Corrales et al., 2024; Buteler et al., 2025). Laboratory studies by Al Naggar et al. (2023) have shown that chronic exposure to polystyrene fragments leads to a decrease in feed consumption and the weight of worker bees. Despite no change in mortality rates, the researchers note that the decrease in body weight may be associated with metabolic imbalance or compensatory responses of the body to the presence of foreign particles in the intestine.

A number of studies have reported a decrease in the speed of bees returning to the hive, which may indicate a disturbance in their spatial orientation. The authors suggest that microplastics may affect the nervous system of insects by modifying ion channels or interfering with receptor systems, which is consistent with data on its effect on the cognitive functions and behavior of bees (Pasquini et al., 2023; Buteler et al., 2025; Al Naggar et al., 2024).

The presence of microplastics in human tissues is associated with a number of potential risks. Studies show that they can cause local inflammatory reactions, oxidative stress, and disruption of cellular processes. Animal experiments confirm a possible impact on the cardiovascular system, in particular, accelerating the development of atherosclerosis. Microplastics have already been found in human arteries, highlighting their possible contribution to vascular pathology (Pittalwala, 2025).

Its impact on reproductive health is of particular concern. The detection of microplastics in the placenta and reproductive organs indicates a risk to fetal development and reproductive system function. In addition, the surface of microplastics can serve as a substrate for pathogenic and antibiotic-resistant bacteria, posing an additional threat to human health (Savchuk, 2025; Abbas, Ahmed and Ahmad, 2025).

An analysis of current scientific research shows that the problem of microplastic contamination of bee products is multifactorial and lies at the intersection of food safety, ecotoxicology, bee physiology, and global environmental change. Most authors emphasize that microplastics should be considered a new class of pollutants capable of migrating through various environments and entering food chains (Garrido Gamarro and Costanzo, 2024). The variety of approaches to its detection in honey, pollen, and bee bread often complicates the comparison of results, but the available data allow us to form an integrated picture of the scale and mechanisms of contamination.

Most studies indicate that microplastics are present in bee products, regardless of the geographical location of the study. This has been observed in urbanized areas of Europe and in subtropical regions of Latin America (Basaran et al., 2024; Rani-Borges et al., 2024). Such consistency in results indicates the wide migratory capacity of polymer particles and their persistence in the environment. Particularly indicative is the dominance of synthetic microfibers, which, due to their low mass and high aerodynamic stability, are easily transported by air currents and settle on plant surfaces, flowers, and water sources. This explains the detection of microfibers in honey even from remote apiaries located in relatively clean regions (Zhang et al., 2023).

The mechanisms by which microplastics enter honey, bee bread, and pollen are complex and involve some complementary pathways. The main one is considered to be atmospheric transport: bees come into contact with particles in the air during flight, and these particles are adsorbed onto the covering structures of their bodies. Particles also enter the hive through plant surfaces, where they accumulate as a result of atmospheric dust deposition (Gómez-Méndez et al., 2024). Bees use surface water for thermoregulation and food preparation, and even low concentrations of microplastics in water bodies cause them to re-enter the bee colony.

Another vector may be the abrasive destruction of plastic components of equipment or containers, although this mechanism is usually considered secondary. The formation of bee bread creates additional conditions for the retention of fine particles, as pollen is compacted and mixed with honey and bee enzymes to form a matrix capable of accumulating microplastics.

In general, the entry of particles into hive products is a multifactorial process that is sensitive to seasonality, landscape structure, and the intensity of anthropogenic pressure.

Physiological effects of microplastics on bees. The presence of microplastics in hive products indicates contact with bees, which has been confirmed by some experimental studies. According to Al Naggar et al. (2023), prolonged exposure to polystyrene particles in feed leads to a decrease in body weight and changes in feed consumption intensity. This is probably due to mechanical irritation of the intestinal walls or impaired intestinal motility.

Larvae may be vulnerable to the effects of microplastics, as bee bread is the main source of protein and biologically active substances in their diet. However, there are currently virtually no systematic studies in this area. Bee products are increasingly being recognized as valuable indicators of environmental health. As bees collect food within a radius of 3–5 km, analyzing honey, pollen, or bee bread provides an integrated assessment of atmospheric, soil, and technogenic pollution levels in the area (Garrido Gamarro and Costanzo, 2024). The presence of synthetic fibers in honey is correlated with traffic intensity, population density, and the type of industrial facilities in the region. Some researchers propose using bee products to monitor polymer aerosols, which is particularly relevant in urban and industrial areas.

Although honey's contribution to the overall dietary intake of microplastics is insignificant compared to seafood or mineral salt, the issue of chronic exposure remains important. Potential risks include the interaction of particles with the intestinal microbiota, the possible penetration of particles smaller than 20–50 μm into colon crypts, and the transfer of chemical contaminants on their surface (Zhang et al., 2023). Of particular concern is nano plastics, which, due to their nanoscale size, are capable of overcoming cellular barriers, but remain difficult to detect using current methods.

Methods for studying microplastics. The study of microplastics in food products usually involves several consecutive steps. First, samples are prepared, which involves chemical or enzymatic destruction of the organic matrix and subsequent filtration to isolate particles (Huang, Hu, and Wang, 2022).

The next step is morphological analysis using optical (Maes et al., 2017; Kalaronis et al., 2022) or electron microscopy, which allows the origin, shape, and size of microplastics to be determined (Misumi et al., 2018; Lou et al., 2023). To confirm the polymeric nature, spectroscopic methods are used, in particular FTIR (Primpke et al., 2017; Araujo et al., 2018; Cunsolo et al., 2021) and Raman spectroscopy (Gago et al., 2016; Huang, Hu, and Wang, 2022), as well as pyrolysis gas chromatography with mass spectrometry (Py GC/MS) (Seeley and Lynch, 2023; Zhang et al., 2023), which allows the types of polymers to be identified.

The final step involves quantitative assessment, integrating imaging results and chemical identification to provide a comprehensive overview of the level and nature of microplastic contamination in food products.

Recent studies demonstrate the significant potential of machine learning for identifying microplastics using SEM, fluorescence, FTIR, and Raman spectroscopy (Kedzierski et al., 2019; Shi et al., 2022; Meyers et al., 2022; Hufnagl et al., 2022). In particular, the PlasticNet model (Zhu, Parker, and Wong, 2023), trained on spectra of 11 types of virgin polymers, achieved over 95% classification accuracy, confirming the promise of deep learning in this direction.

At the same time, its effectiveness for environmental samples remains unexplored. Another approach (Weber, Zinnen, and Kerpen, 2023), combining algorithms and expert assessment, used over 64,000 Raman spectra from the environment and wastewater, achieving high accuracy (recall ≥ 99.4%, precision ≥ 97.1%) and reducing annotation time from several hours to less than one hour per sample.

Hu et al. (2024) proposed the use of artificial intelligence for the rapid identification of microplastics and the prediction of their environmental behavior. The authors developed a model capable of automatically recognizing microplastics in complex environmental matrices and simulating their migration and transformation. This approach not only significantly reduces sample analysis time but also opens up prospects for the creation of real-time microplastic monitoring systems, which could become an important tool for environmental policy and risk management.

At the same time, the lack of internationally agreed standards makes it difficult to compare the results of different studies. Significant differences exist in sample preparation methods, filter pore sizes, organic matrix cleaning procedures, and polymer composition verification methods (FTIR, Raman, and Py-GC/MS). A lack of control over laboratory contamination can also lead to false positive results. Therefore, developing a unified protocol for determining microplastics in bee products is one of the key tasks of modern food analytics.

Prospects for further research. Further development in this area should cover several key aspects. First, it is necessary to create an international standard for the detection of microplastics in food products, including honey. Second, the development of highly sensitive methods for analyzing nanoplastics, which have a significantly higher toxicological potential, is promising. Third, there is an urgent need to study the impact of microplastics on the intestinal microbiota of bees, which plays a decisive role in feed digestion, immune response, and behavioral reactions. Another important area of research is the migration of microplastics within bee colonies through food chains and the assessment of risks to vulnerable populations, such as children, people with chronic gastrointestinal diseases, or those with altered immune reactivity.

Conclusions. Microplastics are a stable, multi-component contaminant in bee products, reflecting levels of anthropogenic pressure and urbanization. Honey, bee pollen, bee bread, and wax can potentially contain synthetic particles regardless of geography or landscape, confirming the scale and persistence of polymeric micro-pollutants in the biosphere.

The main type of microplastic is textile fibers, which spread through the air and enter hive products due to their mobility and stability. Meanwhile, the presence of polyethylene and polypropylene indicates local sources of pollution, such as agriculture, transport, and households. The presence of microplastics in bee products can be used as an indicator of environmental health and as a tool for environmental monitoring.

Microplastics cause subclinical changes in bee physiology, including a decrease in body weight, changes in food consumption, and disorientation. Even minimal toxic effects can have consequences for the ecosystem, particularly with prolonged exposure, and the accumulation of synthetic particles in bee bread poses a risk to brood development.

While the risk to humans of consuming honey containing microplastics is low, it is significant in the context of chronic exposure. Of particular concern are the adsorption of chemical contaminants and interaction with the microbiota. Meanwhile, nanoplastics, which can penetrate biological barriers, are the least studied and potentially the most toxic.

A key challenge remains the standardization of methods for determining microplastics in bee products. Current differences in sample preparation, filtration parameters, identification methods, and contamination control make it difficult to compare results between studies. Improving these procedures is a necessary prerequisite for the development of internationally agreed standards and monitoring systems. Microplastic research is important for risk assessment, the development of new analytical technologies, and ensuring food safety.

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