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Microplastic accumulation in terrestrial insects on the example of social wasps (Hymenoptera: Vespidae)

Аккумуляция микропластика наземными насекомыми на примере складчатокрылых ос (Hymenoptera: Vespidae)

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Key words: Microplastics, man-made fibers, bioaccumulation, *Vespa*, *Vespula*, *Polistes*, Eurasia, North Africa.

Ключевые слова: микропластик, антропогенные волокна, биоаккумуляция, *Vespa, Vespula, Polistes*, Евразия, Северная Африка.

Abstract. The study of microplastic (MP) accumulation in terrestrial insects was conducted from 2012–2015 and continued through 2024 at 26 study areas located in 16 administrative regions of Eurasia and North Africa. A total of 466 wasp individuals from natural populations were analyzed. The study focused on three genera (*Vespa*, *Vespula*, and *Polistes*) from the family Vespidae as model objects, including a total of 9 species. The analysis revealed the presence of fibers of various lengths and colors, including black, blue, and transparent fibers, as well as orange, red, and blue fragments.

MP accumulation in wasps exhibited regional variations, with the highest MP contamination occurring in regions located in proximity to the World Ocean. The highest MP content, with an average of 4.00±2.00 item/ind, was recorded in Leningradskaya Oblast. Microplastics and fibers were abundant in wasps from Primorskii Krai and Sakhalinskaya Oblast, accounting for 2.83±0.89 item/ind and 3.00±1.00 item/ind on average, respectively.

The lowest content of microplastics and man-made fibers in wasps was recorded in the Republic of Crimea (0.30 ± 0.24 item/ind), South Kazakhstan Region (0.27 ± 0.40 item/ind), and Matruh Province, Egypt (0.28 ± 0.40 item/ind).

Black and transparent fibers that are likely to shed from synthetic textiles were most abundant. Plastic fragments were much less prevalent and were not detected in wasps from most of the study areas. Thus, terrestrial insects have the capacity to accumulate microplastics and man-made fibers, thereby contributing to their distribution within terrestrial ecosystems.

Резюме. Исследование по изучению аккумуляции микропластика (МП) наземными насекомыми проведено в период с 2012–2015 по 2024 год на 26 исследуемых участках, расположенных на территории 16 административных регионов Евразии и Северной Африки. Всего исследовано 466 особей ос из природных популяций. В качестве модельных объектов исследованы представители семейства Vespidae трёх родов (*Vespa, Vespula, Polistes*), среди которых изучено 9 видов. В осах зарегистрированы волокна разной длины чёрного, синего цвета и бесцветные волокна, а также оранжевые, красные и синие фрагменты.

В разных регионах накопление МП осами не одинаковое, наибольшее количество частиц выявлено в регионах, связанных с Мировым океаном. Регионом с наибольшими показателями содержания МП в осах является Ленинградская область, где среднее количество МП на осу составило 4.00±2.00 единиц на особь. Наиболее высокое содержание частиц зарегистрировано в осах, собранных в Приморском крае, где среднее количество МП и волокон на осу составило 2.83±0.89 ед./особь, а также в Сахалинской области — 3.00±1.00 ед./особь.

Регионами с наименьшими показателями содержания МП и антропогенных волокон в осах оказались Крымский

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полуостров (0.30±0.24 частиц на особь), Южно-Казахстанская Область (0.27±0.40 частиц на особь), и провинция Матрух, Египет (0.28±0.40 частиц на особь).

Наиболее распространённым типом частиц оказались чёрные и прозрачные волокна, источником которых с наибольшей вероятностью являются предметы текстильной промышленности. Пластиковые фрагменты встречались значительно реже и не регистрировались в осах, собранных в большинстве исследованных регионов.

Таким образом, наземные насекомые могут аккумулировать МП и антропогенные волокна и участвовать в их распространении в наземных экосистемах.

Introduction

Plastic use is inextricably intertwined with modern life. Plastic products have become ubiquitous in industrial processes, instrumentation, medicine, and art, as packaging and textile materials, and in many other spheres of human activity [Jones et al., 2022]. Plastic is one of the most pervasive components, yet the detrimental environmental consequences of its unlimited use remain widely unaddressed [Smith et al., 2021]. Over time, plastic items deteriorate and disintegrate into tiny plastic particles called microplastics (MPs) [Brown et al., 2023]. These particles penetrate terrestrial, freshwater and marine habitats, accumulating in ecosystems and affecting their biodiversity [Williams, Rangel-Buitrago, 2022].

The production and utilization of artificial polymers have shown rapid growth since the latter half of the previous century [Barnes et al., 2009]. Since that time, 8.3 billion metric tons of plastic have been produced, with most of it (about 60 %) being landfilled or released into the environment [UNEP, 2021]. The annual global production of plastic materials and products exceeds 400 megatons, only 9 % of which is recycled [Geyer et al., 2017; Plastics Europe, 2024].

The ubiquity of MPs in modern society is a result of anthropogenic activity. Microparticles derived from artificial polymers can be detected in various environments, including marine and freshwater ecosystems, the atmosphere, agroecosystems, natural soils, food, and drinking water [Nizzetto et al., 2016; Kumar et al., 2020]. The uptake and subsequent accumulation of MPs in an organism can result in nutrition deficiency due to reduced food intake. It is associated with alterations in enzyme activity, disruptions in ontogenesis, and behavioral changes, among other toxicological effects [He et al., 2020; Weber et al., 2020; Bartkova et al., 2021; Cappello et al., 2021; Balzani et al., 2022; Frank et al., 2023; Simakova et al., 2024]. Furthermore, MPs can act as a substrate for various microorganisms, including pathogenic, opportunistic, and antibiotic-resistant species [Bartkova et al., 2021; Xu et al., 2023]. The data accumulated on this subject are deeply concerning, as they indicate the potential for MP negative impact on biodiversity and ecosystem functioning in general [Reid et al., 2019; Rillig, Lehmann, 2020].

In contrast to other well-studied ecosystems (e.g., marine and freshwater), the impact of MPs on terrestrial systems is not yet fully understood. The volume of MP circulation in terrestrial ecosystems can be 4–23 times greater in mass than that in the ocean [Horton et al., 2017]. MPs can persist in soil for tens of years and directly or indirectly affect living organisms through interactions with the abiotic environment. Additionally, MPs can form associations with other pollutants, thereby facilitating their further transport [Teuten et al., 2009; Kumar et al., 2020; Baho et al., 2021;].

Insects are of great ecological significance to most aquatic and terrestrial ecosystems, and can be therefore used to study the distribution of plastic pollution within a specific area. These organisms are well-known for their high biomass productivity and species diversity, which makes them optimal subjects for the study of toxic substance accumulation [Oliveira et al., 2019; Liaqat et al., 2023].

Scant studies have evaluated and compared the accumulation of MPs in insects from different geographical regions. The research in this domain typically focuses on studies within a single country. Advancements have been made in understanding the MP bioaccumulation in studies of longhorn beetles (Coleoptera: Cerambycidae) within China. In 2023, the first study analyzed the differences in the MP content in different geographic regions within a solitary terrestrial insect family. This study revealed substantial variations in the number and type of MPs, depending on the insect's habitat [Zhu et al., 2023].

In the present study, the family Vespidae (social wasps) was chosen as a model object for monitoring the MP content in insects. This family is widespread and plays an important role in forests and agroecosystems. The distribution of species of this family across almost all continents is largely attributable to human activity. These insects are distinguished by their rapid reproduction, high biomass productivity, and extremely diverse diet, which makes them a suitable object for our study [Matsuura, Yamane, 1990; Richter, 2000; Lee et al., 2024]. The genera *Polistes* Latreille, 1802; *Vespula* Thomson, 1869; and *Vespa* Linnaeus, 1758 are remarkably similar in their ecological characteristics, dietary preferences, and interaction with the environment [Matsuura, Yamane, 1990; Richter, 2000; Bragina, Starikova, 2014]. This observation provides a foundation for integrating the data collected within a specific area.

The aim of the present study was to quantify the content of MPs and man-made fibers in social wasps (Hymenoptera: Vespidae) across different regions of Eurasia and North Africa.

Materials and methods

Material

The present study focused on representatives of the family Vespidae, comprising three genera (*Vespa*, *Vespula*, and *Polistes*). Nine species were chosen as model objects: *Vespula vulgaris* (Linnaeus, 1758), *Vespula germanica* (Fabricius, 1793); *Vespula koreensis* (Radoszkowski, 1887); *Vespa mandarinia* Smith, 1852;

Vespa dybowskii Andrй, 1884; *Vespa crabro* Linnaeus, 1758; *Polistes nimpha* (Christ, 1791); *Polistes mandarinus* Saussure, 1853; *Polistes dominula* (Christ, 1791).

Wasp individuals were collected between 2012–2015 and 2024 at 26 study areas distributed across 16 administrative regions of Eurasia and North Africa; in the Far East, earlier data (1993–2003) were used (Fig. 1). The total sample volume amounted to 466 wasp individuals.

The study used material collected from various regions of the Palaearctic: Crimea Peninsula, Leningradskaya Oblast, Yamalo-Nenets Autonomous District, Altai Territory, Tomskaya Oblast, Krasnoyarskii Krai, Republic of Khakassia, Republic of Tyva, Amurskaya Oblast, Primorskii Krai, Sakhalinskaya Oblast, Matruh Province in Egypt, South Kazakhstan, Issyk-Kul Region of Kyrgyzstan, Aimag Khovd of Mongolia, and Fukui Prefecture of Japan. (Table 1).

Material collection

The entomological method employed to collect wasps involved the use of net mowing (on dry grass in sunny weather along a 100-meter-long survey trail; the trail was laid out to include all biotopes or ecotones available in the area; the net was emptied of insects every 10 sweeps into a separate extermination chamber for each catch for easy counting). All the chambers were promptly labeled. A portion of the insects were captured on the wing using a hand net. A significant proportion of wasps were captured using a Mericke trap, which consists of yellow-colored plastic rectangular cuvettes 25 cm long, 19 cm wide, and not less than 3 cm deep. The cuvettes were set on soil in series, with a distance of 10 cuvettes installed every meter in a line across the chosen biotope. The cuvettes were filled with soapy water. The traps were inspected daily [Bagirov et al., 2011]. The captured wasps were then stored in 96 % ethanol for subsequent analysis.

Prior to examination, the specimens were pre-soaked in water to facilitate the removal of the intestine from the insect's abdomen.

Laboratory methods

Prior to homogenization, each insect was thoroughly washed in distilled water to ensure the removal of any MPs from its surface. The contents of the abdomen were separated from the exoskeleton, and then it was homogenized. For microscopic analysis and quantification of MPs and man-made fibers, wasps were homogenized in pools of 1–25 individuals. As a catalyst, 35 % H_2O_2 and 0.05 M $FeSO_4$ were added in a 3:1 (v/v) ratio to attain complete dissolution of organic tissues [Claessens et al., 2013; Karami et al., 2017; Lusher et al., 2020; Simakova et al., 2022]. The resulting homogenate was then filtered through a glass fiber membrane filter with a pore size of 1 μm (Membrane Solutions, China). The filters were inspected for the presence of microplastic under Stemi 2000-c binocular microscope. The microscopic analysis was conducted using the hot needle test to identify plastic fragments. This method employs the plastic/non-plastic principle to identify particles [Lusher et al., 2017, 2020; Beckingham et al., 2023]. For small fibers, the hot needle test is difficult to perform in most cases, therefore non-plastic materials, i.e. man-made cellulosic fibers, such as viscose or lyocell, can be included in the study. However, all the identified fibers were classified as man-made based on a number of morphological characteristics, such as the presence of pigments (color) and, for transparent fibers, a uniform diameter along the fiber length [Hidalgo-Ruz et al., 2012].

Microphotographs were obtained using an Axiocam ERc5s camera (Zeiss, Germany). Filters were stored in glass Petri dishes to prevent sampling contamination.

Table 1. Sampling sites with administrative regions, year of collection, and sample size
Таблица 1. Места сбора материала с указанием административных регионов, года сбора и объёма выборок

No. in map	Region	Location	Year	Samples, *n*	Coordinates
1	Crimea Peninsula	Feodosia	2015	9	45°02′56" N, 35°22′45" E
1	Crimea Peninsula	Feodosia	2024	29	45°1′36″ N, 35°23′2" E
2	Matruh Province, Egypt	El-Dabaa	2024	18	31°1′39" N, 28°26′20" E
3	Leningradskaya Oblast, Russia	Saint Petersburg	2024	20	59°55'54" N, 30°14'44" E
4	Yamalo Nenetskii Autonomnyi Okrug, Russia	Yamal	2019	5	66°72'02" N, 73°20'47" E
5	South Kazakhstan	Shymkent	2024	22	42°19'57" N, 69°36'33" E
6	Issik-Kul Region, Kyrgizstan	Cholpon-Ata	2024	8	42°38'59" N, 77°5'9" E
7	Altai Republic, Russia	Biysk	2017	2	52°30'42" N, 85°08'45" E
8	Tomskaya Oblast, Russia	Kyreevsk	2012–2024	283	56°22'1" N, 84°5'23" E
9	Khakasia Republic, Russia	Itkul Lake	2013	10	54°29'13.52" N 90°5'39.76" E
9	Khakasia Republic, Russia	Itkul Lake	2017	10	54°29'13.52" N 90°5'39.76" E
10	Krasnoyarskii Krai, Russia	Krasnoyarsk	2019	10	56°00'58" N, 92°53'40" E
10	Krasnoyarskii Krai, Russia	Krasnoyarsk	2024	4	56°2'30" N, 92°48'31" E
11	Krasnoyarskii Krai, Russia	Taymyr	2019	10	76°11'13" N, 95°56'05" E
12	Aimag Khovd, Mongolia	Har-Nuur Lake	2015	7	48°14'11" N, 93°15'15" E
13	Tyva Republic, Russia	Kyzyl	2019	10	51°43'07" N, 94°27'16" E
14	Primorskii Krai, Russia	Usuri Reserve	1993	5	44°56'44" N, 136°0'4" E
15	Sakhalinskaya Oblast, Russia	Boshnyakovo	2003	2	49°38'56" N, 142°10'31" E
16	Fukui Prefecture, Japan	Ono	1993	2	35°45'44" N, 137°02'23" E

Contamination from ambient air and from reagents was assessed using blank samples that were filtered and viewed simultaneously. During counting, the morphological characteristics of MPs were analyzed in parallel to attribute the detected polymer particle to one or another group. The collected fibers were then divided into six distinct groups based on their color and length criteria (i.e., fibers with a length more than 1 mm or less than 1 mm). Plastic fragments were classified in a separate group (less than 0.1 mm along the longest axis).

Statistical analysis

Data were analyzed using the R V 9.0.190275 statistical software [R Core team, 2022]. the Kruskal-Wallis test was used to compare the accumulation of mps and man-made fibers in wasps.

The present work is registered in ZooBank (www.zoobank.org) under urn:lsid:zoobank.org:pub:D20DDB52-89DA-44A0-A9CB-0D2B24F4F5B5

Results

We have conducted a study on MP accumulation in social wasps from different regions of Eurasia and North Africa.

A total of 566 particles (467 fibers and 99 fragments) were identified in the examined individuals (n = 466). The particles observed included fibers ranging from 0.1 to 2 mm in length and fragments of irregular shape, with sizes ranging from 0.05 to 0.1 mm along the longest axis. The colors of fibers included black, transparent, blue, and red, while the fragments exhibited a variety of colors, including red, blue, orange, and others (Fig. 3). Most abundant particles were black fibers < 1 mm in length. The total number of black fibers amounted to 173 particles, constituting 30.6 % of the total particle load. Black fibers > 1 mm in length were less abundant, with a total of 93 particles, accounting for 16.4 % of the total particle load. The prevalence of transparent fibers > 1 mm was observed to be 87 (15.4 % of the total particle load) (Fig. 2).

A comparison of the average values for the content of all types of MPs and fibers per wasp from 16 regions revealed significant regional variations (Kruskal-Wallis test, p-value = $2{,}2 \cdot 10^{-16}$) (Fig. 3).

Leningradskaya Oblast exhibited the highest MP content in wasps that amounted to 4.00 ± 2.00 item/ind on average. High MP content was recorded in wasps collected in Primorskii Krai and Sakhalinskay Oblast with an average of 2.83 ± 0.89 and 3.00 ± 1.00 item/ind, respectively.

The lowest MP and fiber content per wasp was found in the Crimea peninsula (0.30 ± 0.42 item/ind), South Kazakhstan (0.27 ± 0.40 item/ind), and Matruh Province, Egypt (0.287 ± 0.40 item/ind). The range of values in Tomskaya Oblast varied significantly (Fig. 4).

Thus, the regions with the highest MP and man-made fiber content in wasps are located in the European and eastern parts of Russia (Leningradskaya Oblast, Primorskii Krai, and Sakhalinskaya Oblast). It should be noted that data for the Far East were obtained between 1993 and 2003, and the situation has probably worsened by now.

Fig. 1. Map indicating sample collection points. Designaions (see Table 1): 1 — Feodosia, 2 — El-Dabaa, 3 — Saint Petersburg, 4 — Yamal Peninsula, 5 — Shymkent, 6 — Cholpon-Ata, 7 — Biysk, 8 — Kyreevsk, 9 — Lake Itkul, 10 — Krasnoyarsk, 11 — Taymyr Peninsula, 12 — Har-Nuur lake, 13 — Kyzyl, 14 — Usuri Reserve, 15 — Boshnyakovo, 16 — Ono.

Рис.1. Карта-схема с точками сбора материала. Обозначения (см. табл. 1): 1 — Феодосия, 2 — Эль-Дабаа, 3 — Санкт-Петербург, 4 — полуостов Ямал, 5 — Шымкент, 6 — Чолпон-Ата, 7 — Бийск, 8 — Киреевск, 9 — озеро Иткуль, 10 — Красноярск, 11 — полуостров Таймыр, 12 — озеро Хар-нуур, 13 — Кызыл, 14 — Уссурийский заповедник, 15 — Бошняково, 16 — Оно.

As previously stated, the most prevalent type was black fibers < 1 mm (Fig. 2). A statistical analysis revealed substantial variations in the distribution of these particles across geographical regions (p-value = $8.4 \cdot 10^{-10}$).

The analysis revealed large quantities of black fibers < 1 mm in length in wasps from Sakhalinskaya Oblast (3.00 ± 1.00 item/ind) and Primorskii Krai (1.83 ± 1.487 item/ind). The lowest number of these fibers were detected in individuals from the Crimea peninsula (0.14 ± 0.23 item/ind) and Matruh Province, Egypt (0.11 ± 0.20 item/ind). Black fibers < 1 mm in length were not found in wasps from South Kazakhstan and the Altai Republic (Fig. 4).

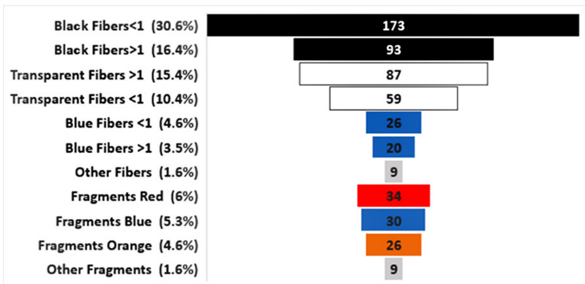

Fig. 2. Distribution of MPs and man-made fibers found in Palearctic wasps by size and color.

Рис. 2. Распределение МП и антропогенных волокон, найденных в осах Палеарктики, по размерам и цвету.

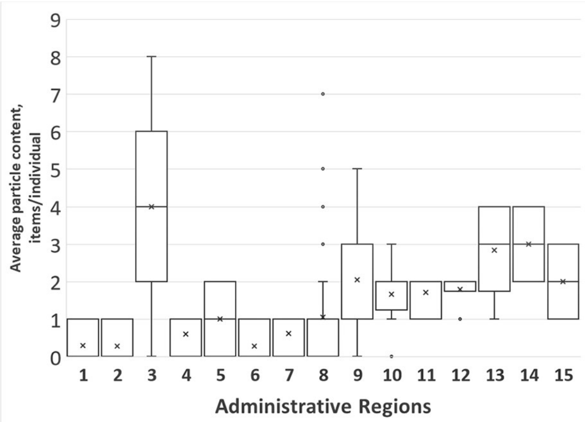

Fig. 3. Comparison of the average particle content per wasp across the study areas. Designations: ✕ — average values, lines — medians, ○ — outliers, numbering of sites see Fig. 1 and Table 1.

Рис. 3. Сравнение среднего количества частиц на одну осу в изученных регионах. Обозначения: ✕ — средние значения, линии — медианы, ○ — выбросы, нумерацию мест сбора см. рис. 1 и табл. 1.

A significant variation was observed among the regions in the prevalence of black fibers measuring 1–2 mm in length (p-value = $3.53 \cdot 10^{-9}$). The highest content of these particles was recorded in wasps from Leningradskaya Oblast (1.86 ± 1.20 item/ind), Primorskii Krai (0.67 ± 0.44 item/ind), and Fukui Prefecture, Japan (0.50 ± 0.50 item/ind). The lowest content of black fibers > 1 mm was recorded in wasps from Tomskaya Oblast (0.08 ± 0.15 item/ind) and Matruh Province, Egypt (0.06 ± 0.10 item/ind). These plastic particles were not found in the Yamalo-Nenets Autonomous Okrug, the Altai Republic, Issyk-Kul Region, Kyrgyzstan, the Tyva Republic, and Sakhalinskaya Oblast (Fig. 4).

Transparent fibers measuring 1–2 mm in length were abundant in wasps collected in all the study areas. These fibers constituted the third most prevalent category (Fig. 2), with the highest content being recorded in the Altai Republic (0.50 ± 0.50 item/ind), the Yamalo-Nenets Autonomous Okrug (0.48 ± 0.40 item/ind), and the Republic of Khakassia (0.48 ± 0.39 item/ind). The lowest content of these particles was detected in wasps from the Crimea peninsula (0.03 ± 0.05 item/ind), Matruh Province, Egypt (0.06 ± 0.10 item/ind), and South Kazakhstan (0.05 ± 0.09 item/ind). Transparent fibers > 1 mm in length were not detected in wasps from Issyk-Kul Region, Kyrgyzstan, Sakhalinskaya Oblast, Russia, and Fukui Prefecture, Japan.

Transparent fibers < 1 mm were frequently encountered, with the highest number found in the Altai Republic (0.500±0.500 item/ind), the Republic of Khakassia (0.50±0.50 item/ind), Aimag Khovd, Mongolia (0.285 ± 0.408 item/ind), and Tomskaya Oblast (0.253±0.390 item/ind). A small number of blue fibers were detected in Krasnoyarskaya Oblast (0.083±0.152 item/ind). In other regions, these plastic particles were not detected.

The highest content of blue fibers measuring 1–2 mm in length was detected in Aimag Khovd, Mongolia (0.57 ± 0.49 item/ind) and Fukui Prefecture, Japan (0.500 ± 0.500 item/ind). A small number of blue fibers were found in Tomskaya Oblast (0.020 ± 0.040 item/ind). In other regions, these plastic particles were not detected (Fig. 4).

The distribution of blue fibers < 1 mm was consistent across the regions. The average number of fibers varied from 0.50 ± 0.50 item/ind in Fukui Prefecture, Japan, to 0.03 ± 0.05 item/ind in the Crimea peninsula. In other regions, these particles were not found (Fig. 4).

Thus, transparent fibers < 1 mm and blue fibers of different sizes were recorded much less frequently than other fibers.

In contrast to fibers, plastic fragments were much less prevalent (Fig. 2). No significant variations in the content of fragments of different colors were identified in wasps; therefore, fragments of different colors (0.05–0.1 mm) were combined into one sample to analyze regional variations. The analysis showed significant variations in the total content of fragments in wasps from different regions (p-value = $2.2 \cdot 10^{-11}$). The highest content was recorded in wasps from Leningradskaya Oblast (0.90 ± 1.08 item/ind), Tomskaya Oblast (0.18 ± 0.31 item/ind), and the Republic of Khakassia (0.39 ± 0.48 item/ind). The highest average content of plastic fragments per wasp was found in South Kazakhstan (0.05 ± 0.09) and in the Republic of Tuva, where a single fragment was detected in one individual. These fragments were not detected in wasps collected in the Crimea peninsula, the Yamal peninsula, Altai Republic, Primorskii Krai, Sakhalinskaya Oblast, Aimag Khovd, Mongolia, Matruh Province, Egypt, and Fukui Prefecture, Japan (Fig. 4).

Thus, the European part of Russia (Leningradskaya Oblast) and the Far East exhibit the highest content of MPs and man-made fibers in wasps from all the study areas. Conversely, the lowest average content can be observed in southern regions, including the Crimea peninsula, South Kazakhstan, and Matruh Province, Egypt.

Discussion

In our previous study, no significant quantitative or qualitative differences in MP content were found in wasps of *Polistes* and *Vespula* genera [Lee et al., 2024]. In the present study, data on the three genera studied (*Vespa*, *Vespula*, and *Polistes*) were also compared. No significant differences were found in the average content of MPs and man-made fibers per wasp (p-value=0.7028).

The studied wasps exhibit similar biology and ecology [Matsuura, Yamane, 1990; Richter, 2000; Bragina, Starikova, 2014]. Thus, the lack of differences in MP accumulation allowed us to combine samples of different genera from the same region.

Fragments detected in wasps were of irregular shape with sizes of 0.05–0.1 mm along the longest axis and fibers measured 0.1–2 mm in length; however, fibers < 1 mm were the most prevalent. MPs with sizes ranging from 1 μm to 1 mm are classified as small [ISO 24187: 2023]. It is evident that insects and other invertebrates with a relatively small body size can easily ingest such particles. The internal organ systems are located in the

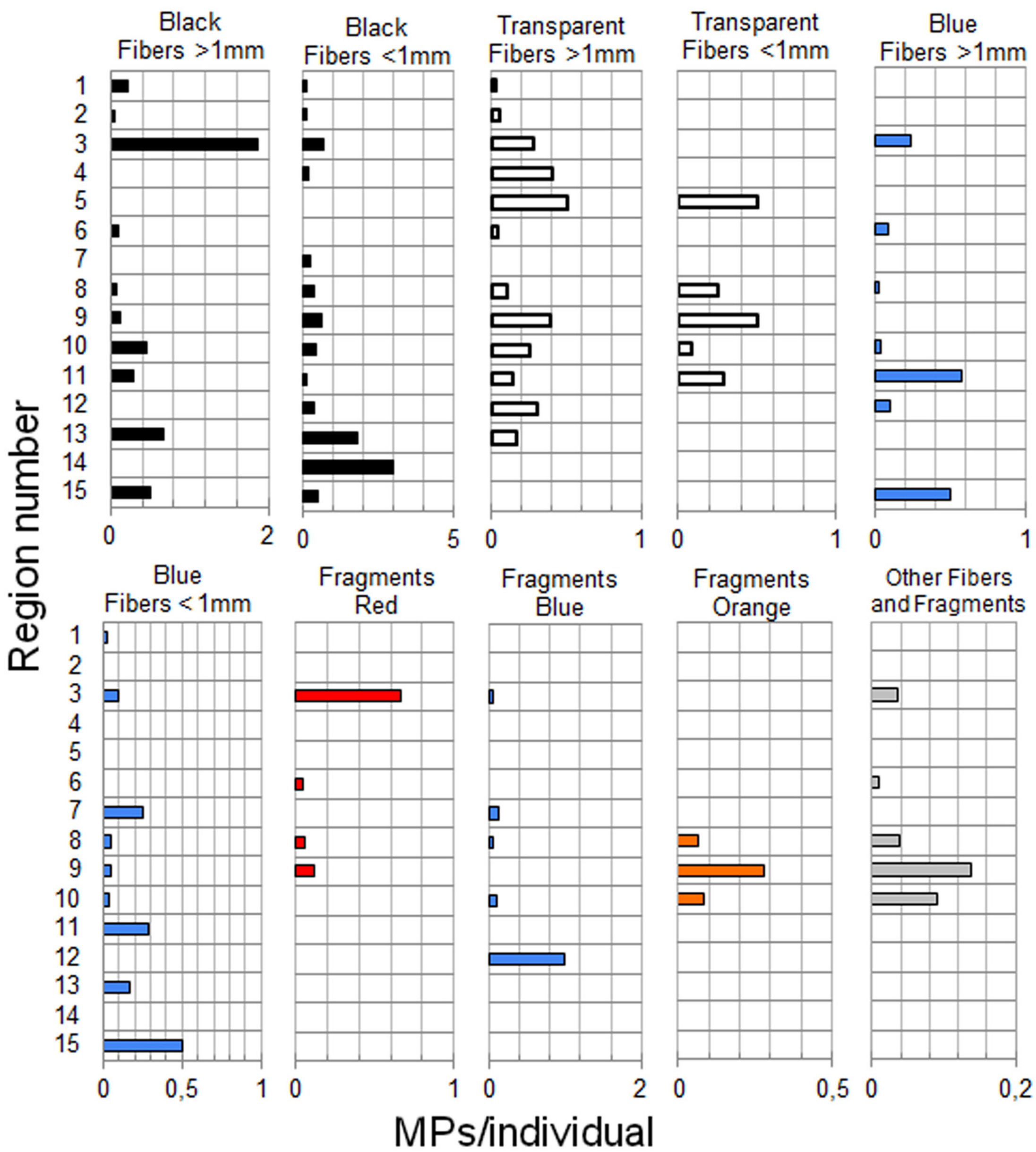

Fig. 4. Average number of different types of MPs per wasp in the study areas. Designations: numbering of sites see Fig. 1 and Table 1.
Рис. 4. Среднее количество разных типов МП на осу на исследованных территориях. Обозначения: нумерацию мест сбора см. рис. 1 и табл. 1.

abdomen, but MPs could only be found in the wasp's intestine. Ingested particles (0.02–2 mm) are not able to pass through the peritrophic membrane of the insect's intestine and invade adjacent organs and systems. The size of plastic particles affects the rate of consumption and excretion, as evidenced in recent studies on planktonic crustaceans [Frank et al., 2024]. The maximum diameter of particles that can be ingested by invertebrates (y, μm) depends on body length (x, mm) and is expressed as $y = 22x + 4.87$ [Burns, 1968]. In this study, the size of fine plastic particles and man-made fibers found in Eurasian and North African wasps is consistent with the size of the wasp's body.

The analysis of the quantitative content of particles in natural wasp populations showed that MPs can be primarily found in the west and east of Eurasia. The findings suggest evidence of significant pollution in the eastern region of Russia, despite the lack of large synthetic polymer manufacturing plants in this area [Industrial Map of Russia, 2024] (Fig. 5).

MPs are likely to spread through water and aerosols from other countries. It is recognized that MPs are pervasive across ecosystems and can easily accumulate within the organisms of animals and plants [Li et al., 2020; Chang et al., 2022; Manshoven et al., 2022; Dong et al., 2023;]; plastic particles can travel far distances through the atmosphere [Rednikin et al., 2024]. Consequently, the potential for MPs to be transported by sea currents, atmospheric aerosols, animal migration, or through dispersal of seeds, plant fruits, etc., cannot be neglected.

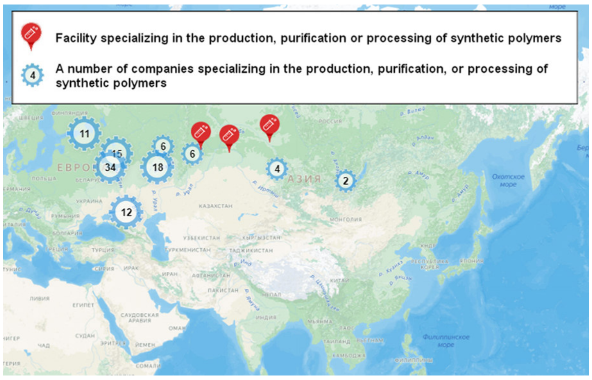

Fig. 5. Industrial map indicating chemical enterprises specializing in synthetic polymers [by Industrial map of Russia, 2024].

Рис. 5. Карта-схема, с обозначенными химическими предприятиями, специализирующимися на синтетических полимерах [по Industrial map of Russia, 2024].

This may explain higher MP content detected in wasps from areas located in proximity to the World Ocean.

Economically developed countries in East Asia, including China, Japan and South Korea, are among the primary contributors to global plastic waste [Cho et al., 2019; Mary et al., 2019]. China is the largest producer and consumer of synthetic polymers, with a production volume of 105.4 million tons in 2020 [Chen et al., 2023]. Japan produced more than 5.5 million tons, and South Korea produced more than 13 million tons of plastics in 2022 [The Japan Plastics Industry, 2022]. According to 2015 estimates, countries in East Asia contribute the most to marine plastic pollution [Jambeck et al., 2015].

The garment and textile industry is a significant source of environmental pollution with fibers, including MPs and semi-synthetic fibers (e.g. viscose, lyocell), which annually releases a considerable amount of man-made fibers of different colors to the environment [Kounina et al., 2024]. The annual release of MPs into the ocean ranges from 0.2 to 0.5 million tons, as reported in [Ellen MacArthur Foundation, 2017]. A study conducted on sea urchins in the Sea of Japan revealed that the predominant MP type in these organisms is plastic fibers measuring 0.3–1 mm in length [Simonova, Frank, 2024]. It should be noted that MPs can be transferred from aquatic to terrestrial ecosystems not only abiotically, but also by living organisms, particularly amphibious insects [Simakova et al., 2024]. Consequently, abundant MPs and fibers found in wasps from the Far East may be due to microplastic transport from marine ecosystems to terrestrial areas and their subsequent dispersal to surrounding areas.

A significant number of fibers and fragments were detected in the European part of Russia (Leningradskaya Oblast), which is apparently due to concentration of industrial complexes involved in production, processing and disposal of plastic materials and products (Fig. 5), and cross-border transfer of plastic waste from European countries, which are home to numerous industrial enterprises. Data on global production indicate that most industrial enterprises in the study areas are located in European countries and in China [Chang et al., 2022]. According to 2023 data, the production of plastics in European countries (primarily in Germany) exceeded 50 million tons, accounting for 12.3% of the global plastic production [Plastics Europe, 2024]. China took the lead in global production, with a share of 33.3% [Plastics Europe, 2024]. The wasps from Leningradskaya Oblast were collected in the area located in close proximity to the Gulf of Finland of the Baltic Sea, which suggests that the comparative abundance of MPs and man-made fibers in insects may be associated with significant pollution of the Baltic Sea. This hypothesis is supported by data on the abundance of MPs both in the Gulf of Finland and in other regions of the Baltic Sea [Dereszewska et al., 2023; Dimante-Deimantovica et al., 2023; Golubeva, Ershova, 2023].

The prevailing type of man-made particles is fibers, suggesting textiles as a primary source. Microfibers are released from textiles during the entire life cycle of fiber production, utilization, and waste disposal. Additionally, microfibers can be released into air, for instance, during drying and wearing clothes [Rednikin et al., 2024]. Synthetic and semi-synthetic textiles are considered an important source of plastic and viscose fibers, with synthetic textiles releasing an estimated 0.2 to 0.5 million tons of MPs into the oceans each year [Ellen MacArthur Foundation, 2017]. The present study confirmed the prevalence of man-made fibers, which were most frequently isolated in large quantities from wasps collected in all the study areas.

In this study, plastic fragments were less frequent than fibers. The highest content of fragments was found in wasps collected in Leningradskaya Oblast, Siberian Federal District (Tomskaya Oblast, Khakassia, Krasnoyarskii Krai), and Central Asia (Kazakhstan and Kyrgyzstan). Plastic products, including packaging materials, items, household goods, and car tires, deteriorate into fragments easily through wear and tear. It should be noted that MPs released into aquatic environment can be classified into primary or secondary MPs. Primary MPs are released into the environment directly in the form of small particles (< 5 mm along the longest axis), whereas secondary MPs are products of degradation of larger plastic items and components [Andrady, 2011]. Numerous MPs and cellulose microfibers are released into aquatic environment during washing of textiles made of synthetic and semi-synthetic fabrics. Under mechanical stress caused by wind, water, and sunlight (ultraviolet degradation), plastic waste degrades into smaller fragments, forming secondary MPs or nanoplastic particles < 1 μm in diameter. Annually, inadequate management of plastic waste yields 4–12 million tons of secondary MPs [d'Ambrières, 2019].

Conclusion

An analysis of the content of MPs and man-made fibers in terrestrial insects, on the example of social wasps from Eurasia and North Africa, showed that microparticles are ubiquitous in all 16 administrative regions that were studied. The study revealed a wide distribution of fibers and fragments of different colors and sizes (mostly small particles < 1 mm) in wasps. Most abundant particles were black and transparent fibers, which are most likely the product of the textile industry. Fragments were much less common and were not detected in most administrative regions.

The MP content in wasps varied significantly across different regions ($p < 0.001$, Kruskal-Wallis test). The regions with the lowest MP content per wasp were the Crimea peninsula, South Kazakhstan, and Matruh Province, Egypt. In contrast, the highest MP content was found in wasps from areas located in proximity to the World Ocean. Abundant MPs in wasps from the European part of Russia can be due to the presence of large enterprises and the proximity of the Baltic Sea, where a significant release of plastic waste has been documented.

Abundant MPs in wasps from the Russian Far East are due to proximity to the largest manufacturers and exporters of synthetic textiles — the countries of East Asia located along the Sea of Japan.

Terrestrial insects, such as social wasps, have been found to accumulate MPs and contribute to MP distribution within terrestrial ecosystems.

The large-scale studies on the content of MPs and man-made fibers in social wasps from Eurasia and North Africa conducted for the first time showed the evidence of plastic particle accumulation in terrestrial insects and their potential transport in terrestrial environment. MP pollution is a global environmental concern, yet studies of spatial distribution of MPs within terrestrial biocenoses require greater attention to this issue. Focus should be made on the analysis of MP content in insects from other areas. The analysis should include a wider range of terrestrial invertebrate fauna species as model objects.

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