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SHORT COMMUNICATION

Highway to brood cell: bumblebees ingest and transfer tire wear particles more frequently than polystyrene microplastics

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Abstract
Pollinators like bumblebees are exposed to microplastics (MP) pollution during foraging. After returning to the colony foragers may subsequently spread MP in the nest or transfer ingested MP to larvae during cooperative brood care. Experimental studies have shown that MP can exert negative effects on hymenopteran pollinators, such as impaired cognition or increased mortality. However, as physical and chemical properties of MP depend on for instance polymer type, effects of MP and also their transfer within colonies may be polymer-specific. Currently research has predominantly focused on standard MP types like polystyrene (PS-MP). However, especially in urban environments tire wear particles (TWP) constitute a major MP source. We thus compared the uptake and transfer of PS-MP and the environmentally relevant TWP within colonies of the buff-tailed bumblebee *Bombus terrestris*. *B. terrestris* colonies were provided with sugar water spiked with 0.4% w/v PS-MP or TWP for four weeks, after which we examined the gut system of workers and larvae and the whole body of pupae, as well as honeypot contents and wax for the presence of MP using stereo microscopy. We show that TWP were significantly more frequently ingested by workers, transferred to larvae, and incorporated into nesting materials than PS-MP. We suggest that bumblebees fail to recognise TWP as pollutants, potentially due to their rough surface, which may facilitate 'masking' of the particles by a coating of sugar water. Given the widespread presence of TWP in human-altered landscapes and the higher frequency of uptake they may pose a much greater risk than PS-MP. Our findings highlight the need for comparative studies on health effects of different environmentally relevant MP types.

Keywords Particulate pollution · Particulate matter · Cooperative brood care · Social insects · Insect pollinators

Introduction

The substantial decline in terrestrial insect abundance and diversity (e.g. Wagner et al. 2021), as part of the global biodiversity loss, is a critical threat to ecosystem functioning. Among the factors contributing to the decline in terrestrial insect populations are anthropogenic pollutants, including pesticides, artificial light, and particulate contaminants (Feldhaar and Otti 2020; Wagner 2020; Wagner et al. 2021).

Negative consequences of anthropogenic pollutants can range from sublethal health effects, such as decreased body mass or antennal olfactory perception to increased mortality (Grenis and Murphy 2019; Thimmegowda et al. 2020; Wang et al. 2023; Zilnik et al. 2023). One type of particulate anthropogenic pollutants are microplastics (MP), defined as plastic particles measuring less than 1000 µm (International Standard ISO 24187 2023). These particles can be created by the breakdown of larger plastic debris in the environment (i.e., secondary MP; Manzoor et al. 2022) as a result of improper disposal of plastic waste (Thompson et al. 2024). MP have been shown to induce a multitude of adverse health effects in insects, such as impaired cognition and learning, disrupted gut microbiota and metabolism, or increased mortality (Balzani et al. 2022; Pasquini et al. 2024; Cappa et al. 2025; Li et al. 2025).

MP are steadily accumulating in the environment (Lau et al. 2020) and have received increasing attention in recent years (Xing et al. 2025). However, there is still a large

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discrepancy between the amount of attention a particular MP type receives and its actual environmental relevance and the health risk potential it poses. For example, tire wear particles (TWP) are among the largest MP sources (e.g. Thompson et al. 2024), but only subject in a fraction of the articles published in MP research (499 TWP publications from 2000 to 2021 vs. 18964 MP publications from 2020 to 2024; Wu et al. 2023; Xing et al. 2025). TWP are released from the tire material due to mechanical abrasion and physical friction between the tire and the road surface during driving (Kovochich et al. 2021). They are mainly composed of natural or synthetic rubber and carbon black (Suman et al. 2020; Patra et al. 2022; Mattsson et al. 2023). In addition, TWP contain a variety of toxic substances, including heavy metals such as zinc (~1% by mass, Councell et al. 2004) and organic compounds like phthalates (Hwang and Young 2004). Due to their unique composition, TWP differ significantly in their physico-chemical properties from other polymer types (e.g. Knight et al. 2020). The respective physico-chemical properties of different MP types can result in idiosynchratic health effects (e.g. Ferrante et al. 2024; Cappa et al. 2025) or uptake and transfer frequencies of MP in insects. In terms of physico-chemically mediated differences in health effects, bumblebees, for instance, are differentially affected by different MP polymers. While exposure to polystyrene MP reduced sucrose responsiveness, poly(methyl methacrylate) MP had no effect (*Bombus terrestris*, Cappa et al. 2025). In terms of physico-chemically mediated differences in uptake frequency, *Apis mellifera* workers show a reduced uptake of food spiked with polystyrene (fragments, Al Naggar et al. 2023), but no similar behaviour is observed for polyester-spiked food (fibers, Buteler et al. 2022). Due to their distinct physico-chemical properties, the investigation of TWP could be particularly interesting, especially given their high environmental relevance as major MP source.

Among insects, bumblebee species like *B. terrestris*, could be particularly negatively affected by TWP. *B. terrestris* is a generalist pollinator that forages in diverse habitats (Goulson et al. 2010), including urban areas (Theodorou et al. 2020). Especially in urban areas large amounts of TWP are produced (Stalnaker et al. 1996) and likely frequently encountered by *B. terrestris*, including also recently generated TWP. These recently generated particles are likely to contain higher concentrations of harmful substances, such as heavy metals like zinc, cadmium, or lead (Councell et al. 2004; Hwang and Young 2004), as limited exposure to environmental weathering has not yet allowed substantial leaching of contaminants. In *A. mellifera* workers, exposure to lead has been observed to impair cognition, memory, and long-term recall and learning (Monchanin et al. 2021). Similar adverse health effects could affect bumblebee workers. Since *B. terrestris* are social insects, pollutants such as TWPs could additionally affect not just foragers, but all nest mates. If workers ingest TPW during foraging, they likely pass on these particles to their brood during cooperative brood care, which we already observed in *B. terrestris* for another MP type (polystyrene MP, Kühn et al. 2026a). Therefore, the health effects could not only manifest at the individual, but also at the colony level (e.g. Botías et al. 2020; Feldhaar and Otti 2020; Alma et al. 2023).

Thus, physico-chemical properties may affect uptake and distribution of MP within colonies of *B. terrestris*, consequently leading to MP-specific hazard and risk. We therefore compared uptake and trophic transfer to brood of polystyrene MP (PS-MP) and TWP within bumblebee colonies. To this end we exposed queenright colonies of *B. terrestris* to 0.4% (w/v of either PS-MP or TWP of similar size distributions in sugar water for four weeks. Afterwards, we analysed workers, larvae, and pupae as well as the nesting material (wax and honeypot contents) for the presence of MP particles using stereo microscopy.

Materials and methods

Production and characterization of experimental MP particles

We used irregularly shaped fluorescent PS-MP particles labelled with rhodamine-b (λ_{max} = 544 nm) for feeding trials. Fluorescent plastic granules (Magic Pyramid Brücher & Partner KG, Frechen, Germany) were milled (centrifugal mill ZM 200, RETSCH GmbH, Haan, Germany; rotor: 24Z; sieve: distance sieve 120 µm) and subsequently sieved to achieve a particle size class where 50% of the particles had a diameter (d_{50}) smaller than 163 µm (d_{10} = 95.74 µm, d_{90} = 303.6 µm, Fig. 1a, c). The sizes were determined by a Microtrac Sync particle analyser (Microtrac RETSCH GmbH, Haan, Germany).

TWP were provided by Continental AG from tires of a passenger car with a known composition (see Table 3), representing a real-life tire tread material. TWP were generated by Continental AG using a tire buffing machine. Particles were sieved (Hosokawa Alpine air jet sieve e200 LS; Hosokawa Alpine AG, Augsburg, Germany) in the central service project Z01 of the CRC 1357 Microplastics at the University of Bayreuth to obtain defined size fractions. We used a size distribution with a d_{50} of 147.9 µm (d_{10} = 94.41 µm, d_{90} = 214.6 µm, Fig. 1b, d), similar to the one of the PS-MP. We again determined the size distribution with the Microtrac Sync particle analyzer.

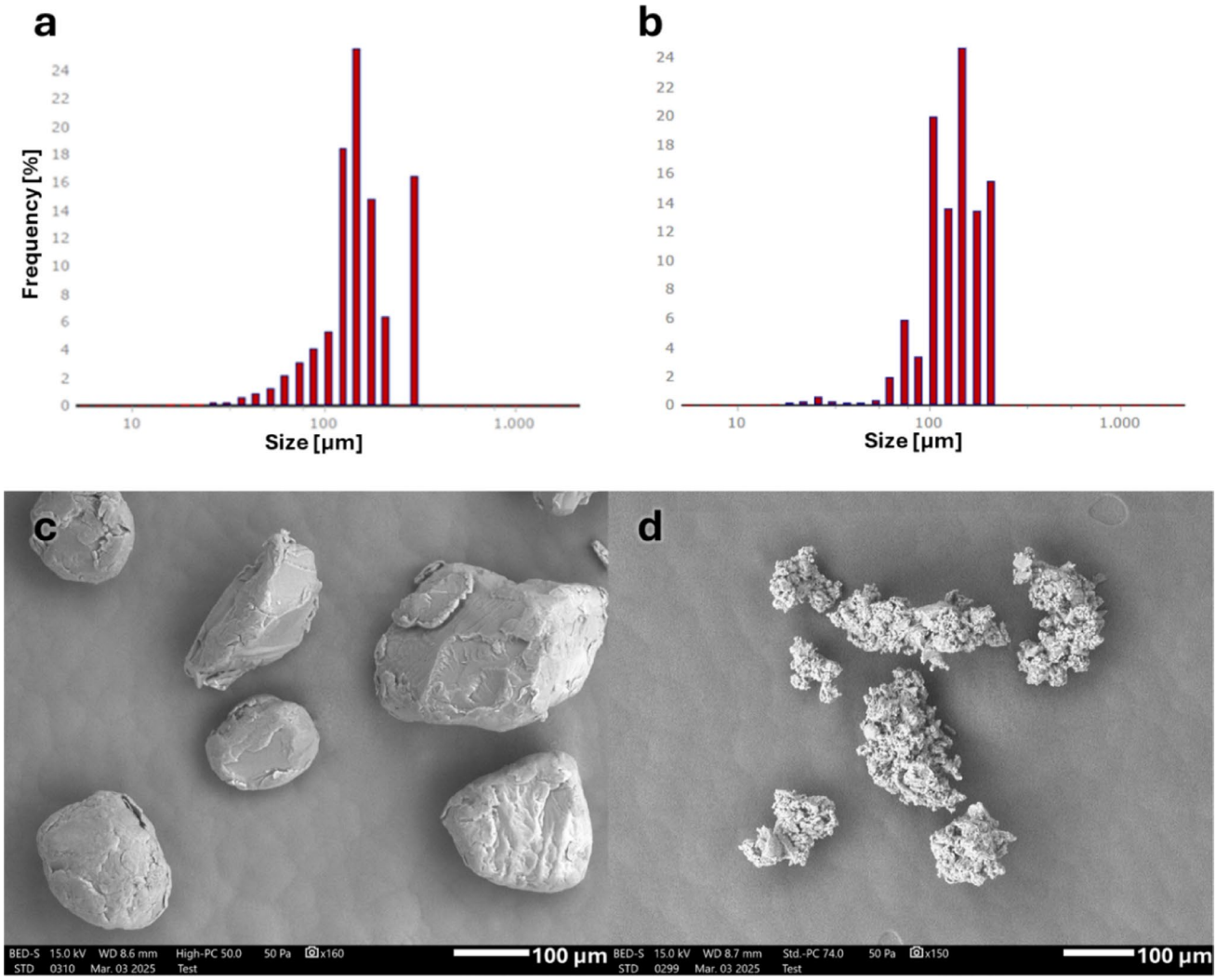

Fig. 1 Size distribution of **a** polystyrene microplastic (PS-MP) particles and **b** tire wear particles (TWP) and electron microscopic images of the respective particles: **c** PS-MP fragments (fluorescence rhodamine-b tagged, λ_{max} = 544 nm; d_{10} = 95.74 µm, d_{90} = 303.6 µm) and **d** TWP (passenger car, provided by Continental Reifen Deutschland GmbH, Hannover; d_{10} = 94.41 µm, d_{90} = 214.6 µm). Electron microscopic Images were taken (a: High-PC: 50.0, b: Std.-PC: 74.0; 15.0 kV) at **c** 160x and **d** 150x magnification with a JSM-IT500 SEM (JEOL, Akishima, Japan)

Animal husbandry

We ordered nine queenright *B. terrestris* colonies from Biobest (Westerlo, Belgium). Upon arrival, we kept the colonies in their original boxes in a climate chamber at a constant temperature of 26 °C and 70% humidity under an inverted 12:12 h dark: light cycle. We fed the colonies three times per week with approximately 10 g of pollen (Imkerpur, Osnabrück, Germany) and sugar water (1:1 ratio of water to Apiinvert (Südzucker AG, Mannheim, Germany)) *ad libitum*.

MP exposure of B. terrestris colonies

We randomly assigned three colonies each to one of the three treatments: control, PS-MP and TWP. Over a period of 4 weeks, we provided the colonies with treatment solutions/suspensions next to an *ad libitum* sugar water supply, enabling the bumblebees to choose their food freely and thus also avoid contaminated food. The treatment solution for the control-colonies consisted of sugar water and 0.02% (v/v) of Tween 80. Tween 80 is a surfactant necessary to break the surface tension and ensure suspension of the hydrophobic MP particles in the sugar water in the MP treatments. The treatment suspensions for the MP treatments were additionally spiked with 0.4% (w/v) of the respective MP particles, PS-MP or TWP. We provided the

treatment solutions/suspensions from 2-mL reservoirs, that we placed in the feeding area of the colonies, close to the wick from the additional *ad libitum* sugar water supply (see Fig. 3). The reservoirs were connected to 20-mL syringes from which they could be refilled easily. As the wick from the sugar water tank and the reservoir were placed underneath the bottom grid of the colony boxes, the bumblebee workers could reach them with their mouth parts only (see Fig. 3, for a schematic drawing of the bumblebee colony set up see Kühn et al. 2026a). Thus, we prevented them from spreading particles throughout the colony via body contact. We refilled the reservoirs four times a day to ensure a steady provisioning of the treatment solutions/suspensions. Thus, we provided each colony with approximately 8 mL of treatment solution/suspension per day. During the refilling of the reservoirs the MP was resuspended to keep the particles permanently accessible. We refreshed and refilled the syringes providing the treatment solutions/suspension three times per week. Additionally, we fed the colonies with approximately 10 g of pollen. We cleaned and refilled the sugar water tanks once a week.

At the end of the 4-week experimental period, we anesthetised the colonies with CO_2 from dry ice and collected workers, larvae, and pupae for analyses. Then we euthanized all animals in the freezer at -20 °C overnight and stored the individuals for analyses at the same temperature.

Detection of MP particles in B. terrestris workers, larvae, and pupae

We analysed 15 workers, 15 larvae and 9 pupae per colony (except for one of the PS-MP colonies where only 3 pupae were available; and one of the TWP colonies where no pupae were available). Before dissection we checked the body surface of the specimen for MP to prevent contamination using a Leica M205 FCA fluorescence stereo microscope (Leica Microsystems GmbH, Wetzlar, Germany) equipped with a Leica DBC6200 camera and the Leica Application Suite X software (version 3.8.2.27713). If we found MP on the body surface, we removed it with 70% EtOH. Only then we dissected the digestive system from workers and larvae and analysed them for the presence of MP. For the dissection, we placed individuals in Petri dishes and covered them with 70% EtOH. Then we opened the individuals ventrally using micro-scissors (in the case of workers, only in the abdominal region) and carefully cut the digestive system at the oesophagus and rectum before removing it from the body cavity. We then transferred the isolated digestive system into a fresh Petri dish and covered it with 70% EtOH before opening it to examine the contents for the presence of MP. For detecting fluorescent PS-MP, we used the fluorescence setting of the stereo microscope with an excitation wavelength of 650 nm (emission $\lambda_{max} = 544$ nm for rhodamine-b, exemplary image of fluorescent particles of different sizes in Fig. 4). We detected TWP using visible light, and confirmed found TWP under a microscope (Leitz Laborlux K Mikroskop, Leica Microsystems GMBH, Wetzlar, Germany, 200-fold magnification). Due to their black colour TWP could be differentiated from the rest of the gut content, tissue or nesting material. Both MP types were controlled for contaminations by also using the other light setting (visible light for PS-MP individuals, and fluorescent light for TWP individuals, control individuals were analysed with both light settings). As pupae do not have a developed digestive system during metamorphosis, we instead crushed them and analysed the whole body for the presence of MP. If specimens were damaged during handling, they were excluded from the analysis (1 worker and 1 larva, both from the TWP treatment).

Detection of MP particles in nesting material

To qualitatively analyse if *B. terrestris* workers incorporate MP particles in the nesting material (wax containing structures and honeypot contents), upon the end of the experiment we took wax and honeypot content samples (~2 cm^2 wax per colony from different locations within the colony, ~ 3 ml of honeypot contents from multiple honeypots per colony) and investigated them under the fluorescence stereo microscope.

Statistical analysis

All statistical analyses were conducted using R 4.5.1 (R Core Team 2025). We created and arranged the barplots with the *ggplot2* (ver. 3.5.2, Wickham 2016) and the *ggpubr* (ver. 0.6.0, Kassambara 2023) packages. To assess the effect of the treatment (control, PS-MP, TWP) on the probability of MP presence in the digestive system of individuals, we fitted generalised linear models (GLMs) with a binomial error distribution and logit link function to account for the binary presence-absence data. We modelled the response variable as the number of individuals with MP in their digestive system and the number of individuals without MP in their digestive system, aggregated per colony and with individual models per life stage (worker or larva, *dplyr* package, ver. 1.1.4, Wickham et al. 2023). To account for the sometimes strong imbalance in the presence-absence proportions, we introduced conservative dummy variables (i.e. variables that reduce the actual difference without altering the number of observations). Since no MP was detected in pupae, no model was fitted for this life stage. We visually inspected the model residuals using simulated residuals plots (*DHARMa* package, ver. 0.4.7., Hartig 2024). For

workers and larvae, we conducted post-hoc pairwise comparisons between the treatments using estimated marginal means (*emmeans* package, ver. 2.0.1, Lenth and Piaskowski 2025) on the response scale with Tukey´s method to control for multiple comparisons.

Results

Although the bumblebees were able to choose between pure sugar water and treatment solutions/suspensions, they always emptied the treatment solutions or suspensions that were provided in all treatment groups (personal observation). However, the detection of MP particles in the specimens differed among treatments and life stages. The model for the bumblebee workers revealed a significant effect of treatment on MP particle presence (ANOVA, χ^2 = 98.9, df = 2, $p < 0.001$). With post-hoc pairwise comparisons we detected a significantly higher proportion of particle containing workers in the TWP treatment compared to the control (post-hoc pairwise comparison, $p < 1 \cdot 10^{-4}$, Table 1) or the PS-MP treatment (post-hoc pairwise comparison, $p < 1 \cdot 10^{-4}$). We found TWP in the digestive systems of 36 out of 44 workers throughout all three colony replicates. In contrast, we found no MP particles in the digestive systems of workers from the control or the PS-MP treatment (Figs. 2a and 5a-i).

The model for the larvae also revealed a significant effect of treatment on MP particle presence (ANOVA, χ^2 = 121.8, df = 2, $p < 0.001$). With post-hoc pairwise comparisons we detected a significantly higher proportion of larvae containing particles in the TWP treatment compared to the control (post-hoc pairwise comparison, $p < 1 \cdot 10^{-4}$, Table 2) and the PS-MP treatment (post-hoc pairwise comparison, $p < 1 \cdot 10^{-4}$, Table 2). We found TWP in the digestive systems of 41 out of 44 larvae throughout all three colony replicates, and PS-MP in the digestive system of two out of 45 larvae in two of the three colony replicates. None of the digestive systems of larvae form the control treatment contained any MP particles (Figs. 2b and 5j-r).

None of the pupae of all three treatments contained particles.

In the nesting material (wax-containing structures and honeypot contents) of control colonies we found no MP particles (Fig. 6a, b, g, h). In colonies confronted with PS-MP we found particles only in the wax of one colony (Fig. 6c,

Table 1 Pairwise comparisons between treatments for the microplastics (MP) presence-absence ratio in workers

Comparison	Odds ratio	Standard error	z-ratio	*p*-value
Control – PS-MP	1.000	1.430	0.000	1.000
Control – TWP	0.005	0.005	-4.878	**$<1 \cdot 10^{-4}$**
PS-MP – TWP	0.005	0.005	-4.878	**$<1 \cdot 10^{-4}$**

Counts were aggregated per colony and treatment. Significant differences (Tukey-adjusted $p < 0.05$) are indicated by bold print. The underlying proportions, along with standard errors and confidence intervals, are reported in Table 4

Table 2 Pairwise comparisons between treatments for the microplastics (MP) presence-absence ratio in larvae

Comparison	Odds ratio	Standard error	z-ratio	*p*-value
Control – PS-MP	0.489	0.608	-0.576	0.833
Control – TWP	0.002	0.002	-5.446	**$<1 \cdot 10^{-4}$**
PS-MP – TWP	0.003	0.003	-6.055	**$<1 \cdot 10^{-4}$**

Counts were aggregated per colony and treatment. Significant differences (Tukey-adjusted $p < 0.05$) are indicated by bold print. The underlying proportions, along with standard errors and confidence intervals, are reported in Table 5

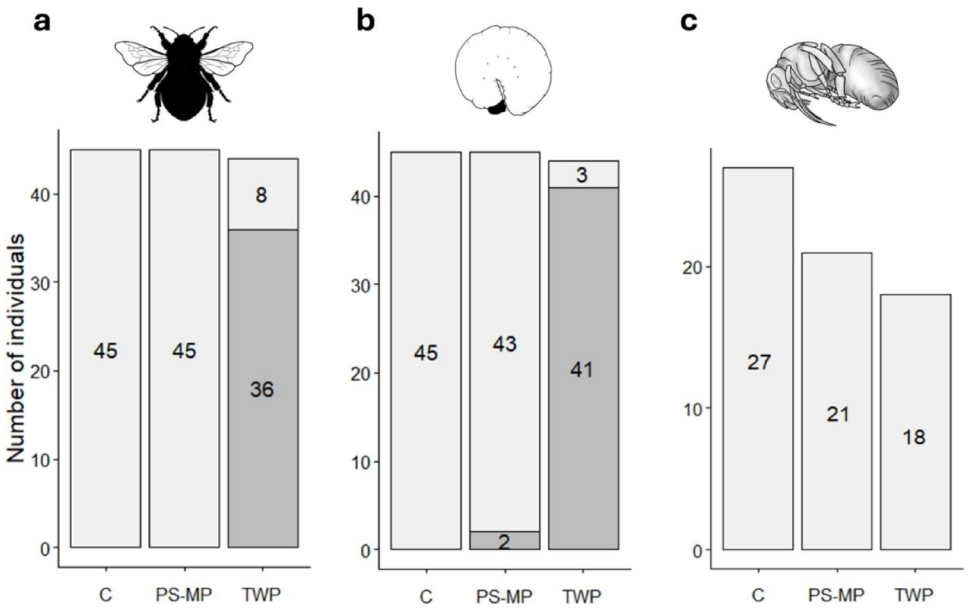

Fig. 2 Results for microplastics (MP) detection in bumblebee workers, larvae, and pupae. Number of individuals with (dark grey) and without (light grey) MP particles detected **a** in bumblebee workers, **b** bumblebee larvae, and **c** bumblebee pupae from colonies fed with control solution (C), fluorescent polystyrene MP suspension (PS-MP), or tire wear particles suspension (TWP)

d) but not in the honeypot contents (Fig. 6i, j). In contrast, in all colonies confronted with TWP we found the particles in both, wax and honeypot contents (see Fig. 6e, f, k, l).

Discussion

Our study showed that the distribution patterns of PS-MP and TWP provided with food differ significantly within colonies, with TWP being present in a significantly larger number of workers and larvae than PS-MP. In addition, we detected TWP in both, wax and honeypot contents, while PS-MP was only detectable in wax but not honeypot contents. We must emphasise that our findings are based on a restricted number of truly independent replicates (i.e., bumblebee colonies). However, we consider this to affect the validity of our qualitative results only negligibly.

We did not detect PS-MP particles in the digestive systems of *B. terrestris* workers, but we found them in a small number of larvae. Given that larvae are fed via regurgitated food from workers, this suggests that workers may have ingested PS-MP at low frequencies. Ingested MP could adversely affect bumblebee worker health by increasing the mortality (Cappa et al. 2025; Kühn et al. 2026b) or interfering with memory (Cappa et al. 2025), as found for *B. terrestris* in previous studies. Here, the ingestion frequencies of the PS-MP by *B. terrestris* workers were potentially too low to be detected in the share of workers of a colony we analysed. We previously found bumblebee workers to ingest PS-MP and transfer it to brood, albeit of a smaller size distribution (d_{50}=40.5 µm, d_{10}=26.86 µm, d_{90}=127.1 µm in contrast to d_{50}=163 µm, d_{10}=95.74 µm, d_{90}=303.6 µm used here; Kühn et al. 2026a). The size of this smaller PS-MP is comparable to that of pollen naturally gathered by *B. terrestris* (e.g. Kämper et al. 2016), suggesting that these MP particles may be misidentified as pollen and inadvertently ingested. Given its larger size, the PS-MP used in this study may be easier to recognise possibly leading to an avoidance of the PS-MP particles contained in the treatment suspension. However, since all treatment solutions/suspensions were ingested to the same extend across all treatments (personal observation), the low frequency at which we detected PS-MP does not seem to be due to an avoidance of the contaminated treatment solution per se, but the bumblebees seem to be able to avoid ingesting PS-MP particles with food via a behaviour or mechanism that needs to be further researched. Size-related physical constraints, however, are unlikely to explain the absence of the larger PS-MP in workers as 80% of the workers from the TWP treatment group contained similarly large particles in their digestive system.

Instead, we hypothesise, that other physico-chemical properties such as the texture or surface structure of the TWP could potentially explain the differences in particle uptake. While the PS-MP particles are solid and with a relatively smooth surface (Fig. 1c), the TWP are softer and sponge-like with a rough surface (Fig. 1d). This could possibly make a discrimination against the TWP in the feeding suspension difficult, as they may soak up sugar water. The assumed ability of TWP to soak up sugar water is in line with our observation of initially floating TWP sinking down after incubation in sugar water for several hours. Consequently, TWP could potentially be 'masked' by sugar water and may not be recognised as non-food particles, which could result in the more frequently observed uptake. Regardless of the mechanism underlying the higher uptake rate of TWP compared to PS-MP, this could mean that TWP may pose a greater health risk to bumblebees.

Furthermore, the effects could extend beyond the worker level, as we detected MP in the digestive systems of bumblebee larvae. A transfer of MP to brood was already observed in other bee species (e.g. *Apis mellifera*; Alma et al. 2023). However, in our study the detection frequency varied significantly between the two MP types with TWP being present in over 90% of larval digestive systems and PS-MP particles in only 4%. This disparity likely reflects differences in uptake frequency by workers discussed above. Our finding of a trophic transfer of MP from workers to larvae is particularly significant in the light of a recent study on metal avoidance during cooperative brood care in bumblebees (Gekière et al. 2025). In this study, bumblebees appear to recognise metal pollution in food. While workers ingest contaminated food when not performing brood care, they actively avoid feeding it to the brood. In contrast, in our study the bumblebees did not avoid passing on MP contamination during cooperative brood care, even though they had the opportunity to avoid MP in our experimental set-up. This supports our assumption, that bumblebees are unable to recognise TWP in sugar water as a pollutant. The adverse health effects of MP could manifest themselves not only at the individual level of workers and larvae, but consequently also at the colony level. Not only increased worker mortality, but also sublethally impaired workers could weaken the colony, for example through reduced foraging performance due to a cognitive impairment as observed for *A. mellifera* after exposure to lead (Monchanin et al. 2021), a contaminant of TWP. Consequently, colonies could become more

vulnerable to other stressors such as pathogens or pesticides (Feldhaar and Otti 2020) to which bumblebees are realistically exposed in a multi-stressor environment.

We detected no MP particles of either type in pupae. This is possibly due to the complete emptying of the digestive system prior to metamorphosis (Pereboom 2001). This process could therefore potentially act as a mechanism that effectively eliminates particulate pollutants such as MPs and thus protects developing bumblebees from physical damage during this sensitive stage.

MP particles were incorporated into the nesting material (wax and honeypot contents, see Fig. 6), which has already been observed in other bee species (e.g. Shavali Gilani et al. 2025). We found TWP in the wax of all three bumblebee colonies confronted with TWP, while we found the PS-MP particles in only one out of three. Furthermore, we found TWP but not PS-MP in the honeypot contents (Fig. 6k). From the honeypot contents, TWP and chemicals that could possibly leach from them (e.g. Müller et al. 2022) could be ingested by non-foraging workers and fed to larvae, potentially resulting in negative health effects on the colony level.

We fed our bumblebees a TWP concentration of 0.4% (w/v, in sugar water), which could exceed the TWP concentration of a naturally occurring uptake. So far for water bodies close to roads maximum TWP concentrations of approximately 0.005% (w/v), have been measured (reviewed by Sun et al. 2025). In soils next to roads, TWP pollution can reach concentrations of over 3% (w/w; Wagner et al. 2018). This illustrates that road verges represent a hotspot for TWP pollution. The particles freshly generated on the roads or resuspended by the airflow of passing cars could settle on flowers and contaminate pollen and nectar or contaminate water sources. Therefore, pollinators such as *B. terrestris* may come into contact with high concentrations of TWP while foraging in these areas. This is also the exposure scenario we simulated in our study. Concentrations in the environment will likely steadily increase due to the longevity of the particles and the constant generation of new particles. Currently studies quantifying the settlement of TWP on flowers are lacking. Likewise, no data are currently available on the amount of TWP that bumblebees ingest during foraging in such habitats, which calls for further studies. Nevertheless, our results show that TWP were readily taken up, transferred to brood, and incorporated into nesting material, which we assume will also happen at lower TWP concentrations. Ultimately, finding TWP significantly more frequently than PS-MP in workers, brood, and nesting material of bumblebee colonies suggests that TWP have a greater potential for harm compared to other MP types.

Conclusion

In our study comparing the ingestion and transfer of two MP types in *B. terrestris* colonies, we found that TWP were substantially more frequently ingested by bumblebee workers than similar-sized PS-MP. This difference is likely driven by particle-specific physico-chemical properties. Once ingested however, PS-MP and TWP were transferred from workers to larvae during cooperative brood care in similar proportions to the frequency found in workers. This suggests that the workers lacked mechanisms to prevent the transfer of MP to offspring. Our study highlights the particular hazard potential of TWP pollution in the environment, as bumblebees were taking up and transferring TWP at much higher frequency in comparison to PS-MP of similar size. As TWP may contain high levels of harmful substances and *B. terrestris* is commonly found in urban environments with potentially high TWP pollution, our findings highlight an underestimated risk to pollinator health in human-altered landscapes.

Appendix

See Tables 3, 4, 5 and Figs. 3, 4, 5 and 6.

Table 3 Composition of ingredients of the tire wear used

Ingredient	PassCar in phr
Natural rubber	10
Styrene-butadiene-rubber	90
Silica	95
Mineral oil softener	35
Anti-aging component	4
Zinc oxide	2.5
Stearic acid	2.5
Silane	6.7
Vulcanisation system	6

PassCar = passenger car (type of tire), phr = parts per hundred rubber

Table 4 Proportion of workers that contained microplastics (MP) to workers that did not contain MP and according standard error and lower and upper confidence intervals

Treatment	Proportion	Standar error	Lower conf. int.	Upper conf. int.
Control	NA	NA	NA	NA
PS-MP	NA	NA	NA	NA
TWP	0.818	0.058	0.677	0.906

For the control and the PS-MP treatment the values do not refer to the original data and are therefore not representative, which is why they are not included. Conf. int. = confidence interval

Table 5 Proportion of larvae that contained microplastics (MP) to larvae that did not contain MP and according standard error and lower and upper confidence intervals

Treatment	Proportion	Standar error	Lower conf. int.	Upper conf. int.
Control	NA	NA	NA	NA
PS-MP	0.044	0.031	0.011	0.161
TWP	0.932	0.038	0.809	0.978

For the control treatment the values do not refer to the original data and are therefore not representative, which is why they are not included. Conf. int. = confidence interval

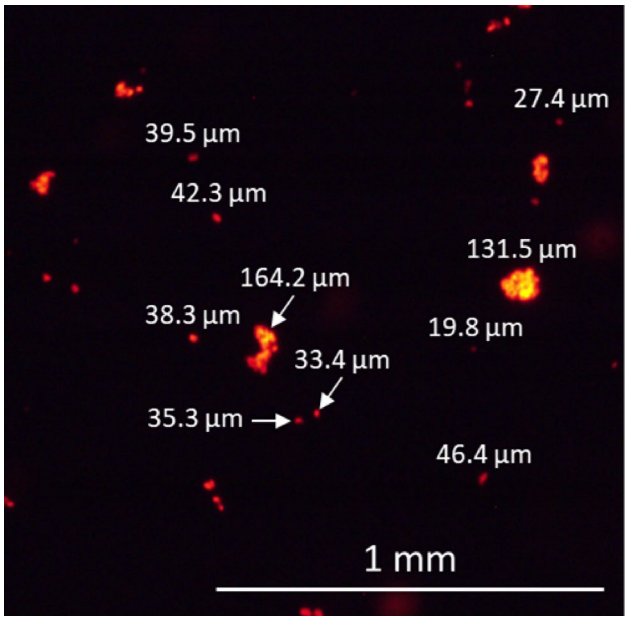

Fig. 4 Exemplary image of fluorescent polystyrene microplastic (PS-MP) particles of different sizes taken with the fluorescence setting of the stereo microscope (excitation wavelength: 650 nm, emission λ_{max} = 544 nm for rhodamine-b)



Fig. 3 Experimental setup of the modified feeding area of a colony. A bumblebee worker is standing on the bottom grid and drinking pure sugar water from the wick (connected to the sugar water tank below the colony) on the left. Indicated by a red arrow, on the right there is the reservoir (made from a cut upper part of the cylinder of a 10-ml syringe) from which the treatment solution is provided, in this case it contains tire wear particles (TWP) visible as black dots

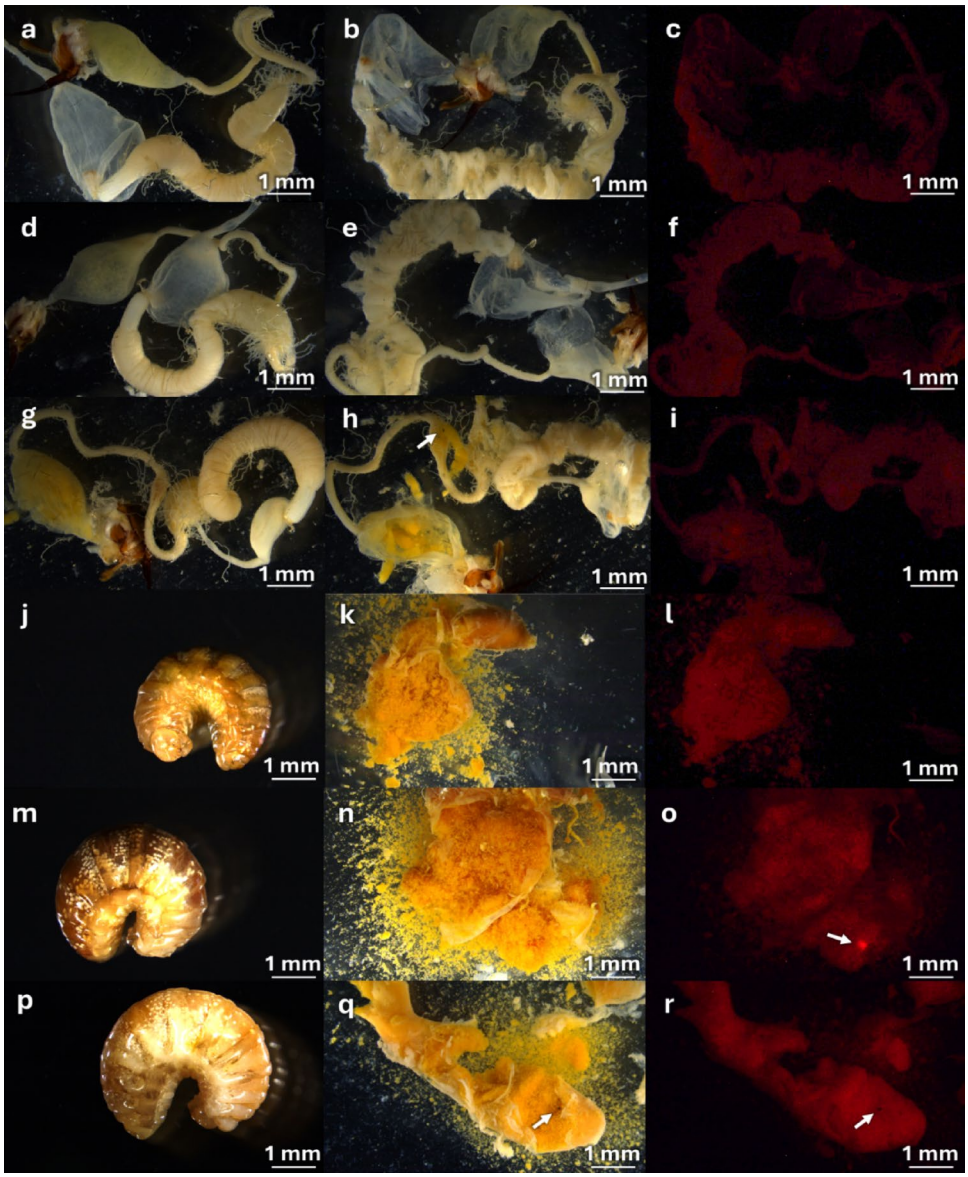

Fig. 5 *Bombus terrestris* workers and larvae from colonies fed with control solution (**a**, **b**, **c**; **j**, **k**, **l**) fluorescent polystyrene microplastics (PS-MP) suspension (**d**, **e**, **f**; **m**, **n**, **o**), or tire wear particles (TWP) suspension (**g**, **h**, **i**; **p**, **q**, **r**). From each individual pictures were taken from the intact digestive system (**a**, **d**, **g**) for workers and complete body (**j**, **m**, **p**) for larvae. Furthermore, pictures were taken from the opened digestive system with light (**b**, **e**, **h**, **k**, **n**, **q**) and with fluorescence (**c**, **f**, **i**, **l**, **o**, **r**) microscopy, to detect PS-MP and TWP particles. For better visibility, particles are indicated by white arrows. Less bright and less sharply defined fluorescence, which can also be seen on images without fluorescent MP particles, is caused by autofluorescence of the individuals' own body structures or pollen in the gut contents

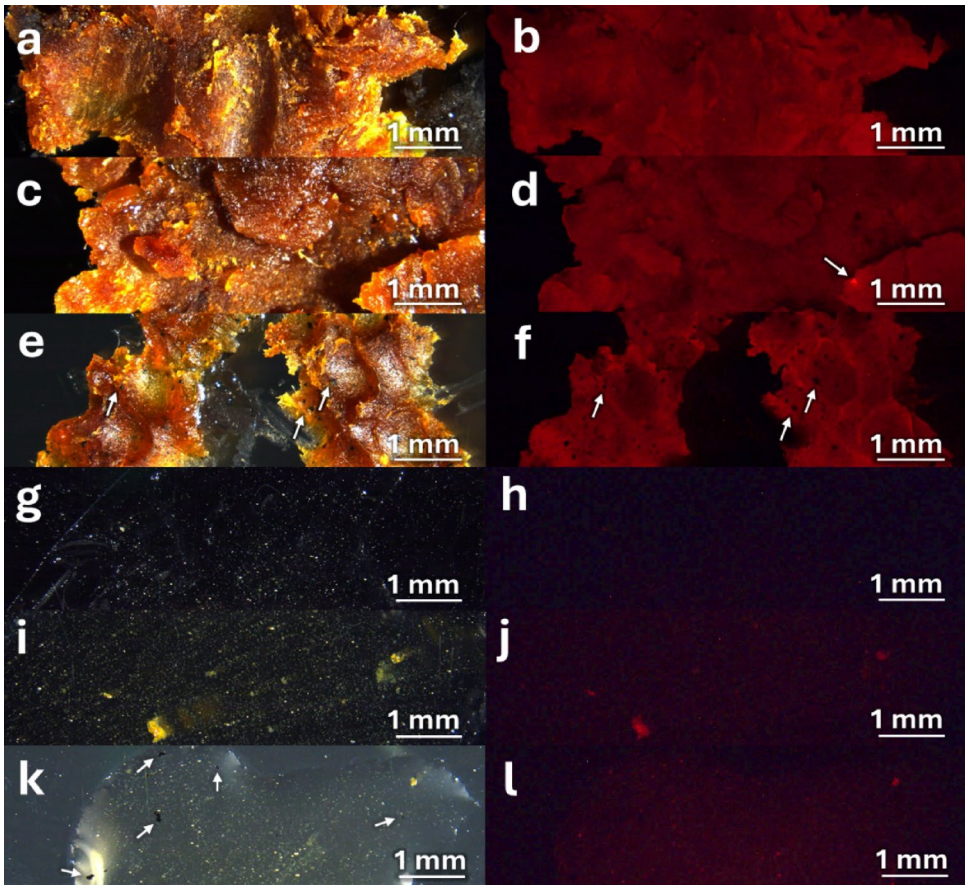

Fig. 6 Wax (**a**, **b**, **c**, **d**, **e**, **f**) and honeypot content (**g**, **h**, **i**, **j**, **k**, **l**) samples from colonies fed with control solution (**a**, **b**; **g**, **h**), polystyrene microplastic (PS-MP) suspension (**c**, **d**; **i**, **j**), or tire wear particles (TWP) suspension (**e**, **f**; **k**, **l**). From each sample a picture was taken with light (**a**, **c**, **e**; **g**, **i**, **k**) and fluorescent (**b**, **d**, **f**; **h**, **j**, **l**) microscopy, to detect fluorescent MP particles. For better visibility, some particles are indicated by white arrows. Less bright and less sharply defined fluorescence, which can also be seen on images without fluorescent MP particles, is caused by autofluorescence of the wax, or in honeypot content pictures by wax and pollen grains

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Declarations

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

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References

Al Naggar Y, Sayes CM, Collom C, Ayorinde T, Qi S, El-Seedi HR, Paxton RJ, Wang K (2023) Chronic exposure to polystyrene microplastic fragments has no effect on honey bee survival, but reduces feeding rate and body weight. Toxics 11:100

Alma AM, de Groot GS, Buteler M (2023) Microplastics incorporated by honeybees from food are transferred to honey, wax and larvae. Environ Pollut 320:121078

Balzani P, Galeotti G, Scheggi S, Masoni A, Santini G, Baracchi D (2022) Acute and chronic ingestion of polyethylene (PE) microplastics has mild effects on honey bee health and cognition. Environ Pollut 305:119318

Botías C, Jones JC, Pamminger T, Bartomeus I, Hughes WO, Goulson D (2020) Multiple stressors interact to impair the performance of bumblebee *Bombus terrestris* colonies. J Anim Ecol 90:415–431

Buteler M, Alma AM, Stadler T, Gingold AC, Manattini MC, Lozada M (2022) Acute toxicity of microplastic fibres to honeybees and effects on foraging behaviour. Sci Total Environ 822:153320

Cappa F, Pasquini E, Ibraliu A, Muti G, Ferrante F, Baracchi D (2025) Revealing antagonistic interactions in the adverse effects of polystyrene and poly(methyl methylacrylate) microplastics in bumblebees. *Proceedings of the Royal Society B* 292:20250047

Councell TB, Duckenfield KU, Landa ER, Callender E (2004) Tire-wear particles as a source of zinc to the environment. Environ Sci Technol 38:4206–4214

Feldhaar H, Otti O (2020) Pollutants and their interaction with diseases of social hymenoptera. Insects 11:153

Ferrante F, Pasquini E, Cappa F, Bellocchio L, Baracchi D (2024) Unravelling the microplastic menace: different polymers additively increase bee vulnerability. Environ Pollut 352:124087

Gekière A, Snowden T, Masson T, Brown MJF, Tougeron K (2025) Risk-averse parenting: bumble bees prioritize metal avoidance over sugar intake to safeguard offspring. *Proceedings of the Royal Society B Biological Sciences* 292:20251598

Goulson D, Lepais O, O'Connor S, Osborne JL, Sanderson RA, Cussans J, Goffe L, Darvill B (2010) Effects of land use at a landscape scale on bumblebee nest density and survival. J Appl Ecol 47:1207–1215

Grenis K, Murphy SM (2019) Direct and indirect effects of light pollution on the performance of an herbivorous insect. Insect Sci 26:770–776

Hartig F (2024) DHARMa: residual diagnostics for hierarchical (multi-level / mixed) regression models. R package version 0.4.7. https://CRAN.R-project.org/package=DHARMa

Hwang H-M, Young T (2004) Organic contaminants from highway stormwater runoff. SETAC North America 25th annual meeting, Portland, Oregon, USA

International Standard ISO (2023) 24187. Principles for the analysis of microplastics present in the environment

Kämper W, Werner PK, Hilpert A, Westphal C, Blüthgen N, Eltz T, Leonhardt SD (2016) How landscape, pollen intake and pollen quality affect colony growth in *Bombus terrestris*. Landscape Ecol 31:2245–2258.

Kassambara A (2023) Ggpubr: 'ggplot2' based publication ready plots. R package version

Knight LJ, Parker-Jurd FNF, Al-Sid-Cheikh M, Thompson RC (2020) Tyre wear particles: an abundant yet widely unreported microplastic? Envrionmental Sci Pollution Res 27:18345–18354

Kovochich M, Liong M, Parker JA, Oh SC, Lee JP, Xi L, Kreider ML, Unice KM (2021) Chemical mapping of tire and road wear particles for single particle analysis. Sci Total Environ 757:144085

Kühn G, Döring VR, Wedel Jv, Ritschar S, Ter-Heide A, Dittmann V, Steinbrenner L, Laforsch C, Feldhaar H (2026a) The fate of orally ingested microplastics during cooperative brood care in two social Hymenoptera species. Ecol Evol 16:e74006

Kühn G, Rupprecht MM, Mair MM, Stöckl JB, Kröger F, Schieder A, Nölscher A, Fröhlich T, Feldhaar H (2026b) Negative effects of increased ozone concentrations and heat stress on bumblebees are exacerbated by microplastics. Preprint Reseach Square. https://doi.org/10.21203/rs.3.rs-9320368/v1

Lau WWY, Yonathan S, Richard B, Cook ME, Martin S, Julia RK, Costas V, Linda AG, Julien B, Margaret M, Richard BT, Emilia CJ, Arturo Castillo C, Toby P, Ben DD, Laura K, Edward K, Enzo F, Jutta G, Sarah B, Meera A, David EF, Kevin H, Milan KP, Rashid MSU, Emily N, Mark B, Keith VL, James P E (2020) Evaluating scenarios toward zero plastic pollution. Science 369:1455–1461

Lenth R, Piaskowski J (2025) emmeans: estimated marginal means, aka least-squares means. R package version 2.0.1. https://CRAN.R-project.org/package=emmeans

Li H, Feng W, An T, Dai P, Liu Y-J (2025) Polystyrene microplastics reduce honeybee survival by disrupting gut microbiota and metabolism. Environ Toxicol Pharmacol 116:104704

Manzoor S, Naqash N, Rashid G, Singh R (2022) Plastic material degradation and formation of microplastic in the environment: a review. Mater Today: Proc 56:3254–3260

Mattsson K, de Lima JA, Wilkinson T, Järlskog I, Ekstrand E, Sköld YA, Gustafsson M, Hassellöv M (2023) Tyre and road wear particles from source to sea. Microplastics Nanoplastics 3:1–11

Monchanin C, Blanc-Brude A, Drujont E, Negahi MM, Pasquaretta C, Silvestre J, Baqué D, Elger A, Barron AB, Devaud J-M, Lihoreau M (2021) Chronic exposure to trace lead impairs honey bee learning. Ecotoxicol Environ Saf 212:112008

Müller K, Hübner D, Huppertsberg S, Knepper TP, Zahn D (2022) Probing the chemical complexity of tires: identification of potential tire-borne water contaminants with high-resolution mass spectrometry. Sci Total Environ 802:149799

Pasquini E, Ferrante F, Passaponti L, Pavone FS, Costantini I, Baracchi D (2024) Microplastics reach the brain and interfere with honey bee cognition. Sci Total Environ 912:169362

Patra I, Huy DTN, Alsaikhan F, Opulencia MJC, van Tuan P, Nurmatova KC, Majdi A, Shoukat S, Yasin G, Margiana R, Walker TR, Karbalaei S (2022) Toxic effects on enzymatic activity, gene expression and histopathological biomarkers in organisms exposed to microplastics and nanoplastics: a review. Environ Sci Europe 34:1–17

Pereboom J (2001) Size dimorphism in bumblebees: a result of caste specific differences in fat body metabolism? Neth J Zool 51:323–333

R Core Team (2025) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Shavali Gilani PS, Moradian M-H, Tajdar-Oranj B, Basaran B, Peivasteh-Roudsari L, Javanmardi F, Khodaei SM, Alizadeh AM (2025) Microplastics comprehensive review: impact on honey bee, occurrence in honey and health risk evaluation. J Appl Ecol 62:1772–1794

Stalnaker D, Turner J, Parekh D, Whittle B, Norton R (1996) Indoor simulation of tire wear: some case studies. Tire Sci Technol 24:94–118

Suman TY, Li W-G, Alif S, Faris VRP, Amarnath DJ, Ma J-G, Pei D-S (2020) Characterization of petroleum-based plastics and their absorbed trace metals from the sediments of the Marina Beach in Chennai, India. Environ Sci Europe 32:1–10

Sun W, Wang B, Ouyang W, Liu Z, Zhang H (2025) Tire wear particles in aquatic environments: a systematic review of sources, detection, distribution, and toxicological impacts. Ecotoxicol Environ Saf 305:119236

Theodorou P, Radzevičiūtė R, Lentendu G, Kahnt B, Husemann M, Bleidorn C, Settele J, Schweiger O, Grosse I, Wubet T, Murray TE, Paxton RJ (2020) Urban areas as hotspots for bees and pollination but not a panacea for all insects. Nat Commun 11:576

Thimmegowda GG, Mullen S, Sottilare K, Sharma A, Mohanta SS, Brockmann A, Dhandapany PS, Olsson SB (2020) A field-based quantitative analysis of sublethal effects of air pollution on pollinators. Proc Natl Acad Sci USA 117:20653–20661

Thompson RC, Courtene-Jones W, Boucher J, Pahl S, Raubenheimer K, Koelmans AA (2024) Twenty years of microplastic pollution research-what have we learned? Science 386:eadl2746

Wagner DL (2020) Insect declines in the anthropocene. Ann Rev Entomol 65:457–480

Wagner DL, Grames EM, Forister ML, Berenbaum MR, Stopak D (2021) Insect decline in the anthropocene: death by a thousand cuts. Proc Natl Acad Sci USA 118:e2023989118

Wagner S, Hüffer T, Klöckner P, Wehrhahn M, Hofmann T, Reemtsma T (2018) Tire wear particles in the aquatic environment - a review on generation, analysis, occurrence, fate and effects. Water Res 139:83-100

Wang Q, Liu G, Yan L, Xu W, Hilton DJ, Liu X, Pei W, Li X, Wu J, Zhao H, Zhang D, Elgar MA (2023) Short-term particulate matter contamination severely compromises insect antennal olfactory perception. Nat Commun 14:4112

Wickham H (2016) Ggplot2: elegant graphics for data analysis. Springer-, New York

Wickham H, François R, Henry L, Müller K, Vaughan D (2023) dplyr: a grammar of data manipulation. R package version 1.1.4. https://CRAN.R-project.org/package=dplyr

Wu W, Ma J, Liu D, Xu Q, Li G (2023) Scientific knowledge mapping and thematic evolution for tire wear particles. Sustainability 15:583

Xing Z, Fu W, Li L, Wu S (2025) Bibliometric analysis of microplastics research: advances and future directions (2020–2024). Cont Shelf Res 285:105371

Zilnik G, Bergeron PE, Chuang A, Diepenbrock L, Hanel A, Middleton E, Moretti E, Schmidt-Jeffris R (2023) Meta-analysis of herbicide non-target effects on pest natural enemies. Insects 14:787

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