species and have a smaller foraging radius than honeybees. Moreover, due to their social lifestyle and the large number of workers inside the hive, honeybees can often compensate for PPP effects. This is not possible for solitary wild bees. In addition, nurse bees can filter larval food before feeding honeybee larvae, so fewer PPPs are ingested by them. Particularly at the individual level, honeybees and wild bees also exhibit different sensitivities to PPPs (Drossart and Gérard, 2020; Thompson, 1999; Wood et al., 2020). This was already shown by investigating the effect of a neonicotinoid to three different bee species. The solitary wild bee *O. bicornis* was most sensitive to the insecticide clothianidin, followed by the social wild bee *B. terrestris* and finally the honeybee *A. mellifera*. Synergistic effects were also most evident in *O. bicornis* (Sgolastra et al., 2017). Wild bees, such as the bumblebee, also have different activity patterns compared to honeybees. They show higher activity in the morning and in the evening while honeybees display their activity peak in the midday. In addition, wild bees often fly in unfavorable weather conditions. These different flight times can also lead to higher exposure to PPPs for wild bees, as regulations for PPP application are usually based on honeybee activity (Thompson, 1999).

Wild bees are indispensable pollinators of crops but especially of wild plants. At the same time, they suffer from a significant decline. Thus, it is important to focus research on stressors and their effects on pollinators not only on the honeybee but also on wild bees (Drossart and Gérard, 2020).

5. Conclusion

A correct evaluation of food sources is crucial for the foraging success of a honeybee, as the nectar concentration determines whether a food source should be exploited (Seeley, 1995; von Frisch, 1965). Furthermore, individual responsiveness to sucrose has a direct impact on the learning behavior (Scheiner et al., 2005, 2001). A good learning performance also maximizes the foraging success, as honeybees have to learn important features of the food source like the shape, the color or the odor and have to be able to orient themselves to the sun compass and to landmarks. Sharing this information with other foragers increases the foraging efficiency (Menzel, 1993). Accordingly, adverse effects of PPPs on learning behavior or sucrose responsiveness would have far-reaching consequences for the honeybee colony.

Our behavioral experiments revealed no negative effects of a field-realistic treatment with the fungicide Cantus® Gold, the insecticide Mospilan® or the mixture of both PPPs on sucrose responsiveness or learning performance of honeybees. Nevertheless, the mortality rate was synergistically affected.

Although our finding suggests that the PPPs tested do not have a sublethal effect on the honeybees in the field realistic concentrations, this does not mean that higher concentrations would not have negative side effects. But our experiments were based on a field-realistic situation in Europe and should be interpreted in this background.

Additionally, the interaction of PPPs needs to be addressed further, because we could only test one combination of fungicides and a neonicotinoid, but other combinations of different PPPs are also frequent. In fact, future studies should try to investigate a matrix of different PPPs and their interaction using more concentrations to estimate the real threat of PPP mixtures on honeybee behavioral performance and cognition.

Since honeybees differ from wild bees in many aspects, no direct comparisons can be made with wild bees. However, as wild bees are suffering from a significant decline, further studies with different wild bee species are inevitable. Also other non-target organisms should be examined in more detail since negative effects of PPPs can occur (Drossart and Gérard, 2020; Thompson, 1999; Willow et al., 2019; Wood et al., 2020).

Ethical approval

Our protocols comply with standard welfare practice in our field. The experiment involved bees from an apiary dedicated to research.

Funding

This work was supported by a grant from the Bavarian State Ministry of the Environment and Consumer Protection (TGC01GCU-75253) to RS in the research network BayÖkotox (TP 2 Honig- und Wildbienen unter Stress) and by a grant of the German Federal Environmental Foundation to AS. This publication was supported by the Open Access Publication Fund of the University of Wuerzburg.

CRediT authorship contribution statement

Antonia Schuhmann: Data acquisition, Visualization, Writing – original draft, Writing – review & editing. **Ricarda Scheiner:** Conceptualization, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

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

Data availability

The raw data for the mortality studies, the PER tests and the learning experiments is available on Mendeley Data (doi: 10.17632/4r839t38sb.1).

Acknowledgements

We would like to thank Anna Paulina Schmid, Sarah Manzer and Valerie Finke for their methodological support. We thank Dirk Ahrens for beekeeping. We would like to thank the Bavarian State Ministry of the Environment and Consumer Protection (research network BayÖkotox, TP 2 Honig- und Wildbienen unter Stress) and the German Federal Environmental Foundation for funding resources. This publication was supported by the Open Access Publication Fund of the University of Wuerzburg.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2023.114850.

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