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Toxicity of imidacloprid for nontarget arthropods in a laboratory experiment

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The use of systemic neonicotinoid insecticides disrupts the ecological balance in agrocenoses and is detrimental to nontarget invertebrates. Therefore, in a laboratory experiment, we evaluated the sensitivity of 50 nontarget species of invertebrates to imidacloprid. No sensitivity to this insecticide was shown by *Cylindroiulus truncorum*, *Formica rufa*, *Geophilus carpophagus*, and *Pterostichus niger* (the LC_{50} values were in the range of 10 to 166 mg/m^2). A moderate sensitivity was exhibited by *Lithobius forficatus*, *Megaphyllum* sp., *Forficula auricularia*, *Labia minor*, *Porcellio laevis*, *Notiophilus palustris*, *Harpalus rufipes*, *H. latus*, *Amara nitida*, *Ophonus rufibarbis*, *Ponera coarctata*, *Lasius fuliginosus*, *L. niger*, *L. flavus*, *Rhyparochromus phoeniceus*, *Lygus pratensis*, *Oxythyrea funesta*, and *Teuchestes fossor* (LC_{50} measuring 1 to 10 mg/m^2). Imidacloprid-sensitive species were found to be *Carabus convexus*, *C. granulatus*, *C. hortensis*, *Nebria brevicollis*, *Tachyporus hypnorum*, *Tachinus signatus*, *Drusilla canaliculata*, *Philonthus coprophilus*, *Ph. decorus*, *Ph. nitidus*, *Ph. cognatus*, *Silpha carinata*, *Phosphuga atrata*, *Aphodius foetens*, *Hister fenestus*, *Chortippus* sp., *Graphosoma italicum*, *Coreus marginatus*, *Pyrrhocoris apterus*, and *Myrmica ruginodis* (LC_{50} ranging 0.1 to 1 mg/m^2). A hypersensitivity to the studied insecticide was registered for *Ph. carbonarius*, *Xantholinus tricolor*, and *Oxytelus sculptus* (LC_{50} accounting for 0.03 to 0.08 mg/m^2). The values of median lethal concentration for some nontarget arthropods could vary by over 5,000 times. We observed no relationship between trophic specialization of the species and sensitivity to imidacloprid. The larger the invertebrate's body, the less sensitivity to the insecticide it exhibited.

Keywords: nontarget arthropods; imidacloprid; neonicotinoids; insecticide sensitivity; median lethal concentration; species survival.

Introduction

Against the background of global chemical pollution, the extensive application of neonicotinoid insecticides exacerbates the toxic loading on the environment. Although effective for plant protection, these insecticides (especially when used in excessive amounts) entail a number of detrimental effects. The most harmful one is that target species acquire resistance while nontarget species are suffering toxic impacts (Matsuda et al., 2020; Wu et al., 2021). Due to the neonicotinoids' physical and chemical properties (high solubility in water and low volatility), they infiltrate nontarget areas (soil, surface water bodies, groundwater) and concentrate there (Huseth & Groves, 2014).

Imidacloprid ($C_9H_{10}ClN_5O_2$) is a contact insecticide with a broad action range and a strong insecticidal activity. Discovered in 1984, it was the first neonicotinoid on the market and still remains the most well-known and broadly used agent of this class worldwide. Officially, the application of neonicotinoids has been registered in over 120 countries, with the main consumers located in South America, Asia, and North America (Craddock et al., 2019). Imidacloprid has a notable systemic action, and therefore is primarily used against sucking and chewing pest insects. The selective toxicity of neonicotinoids is based on targeting the nicotinergic neural pathway, typical for invertebrates. Nonetheless, there are serious concerns regarding its toxic action toward nontarget organisms and a potential threat to humans (via consumption of contaminated drinking water and plant-based products) (Han et al., 2018; Zhang et al., 2018). Imidacloprid enters the organism of invertebrates both via intestines and contact and — similarly to natural nicotine — affects the nicotinic acetylcholine receptors of the central nervous system by disrupting the signal transmission. This leads to the emergence of neurotoxic symptoms, and ultimately to paralysis and lethal outcome (Simon-Delso et al., 2015). Imidacloprid is able to remain in soil for extended periods of time, with its half-life accounting for up to 100 days. This compound exerts low or average toxicity toward vertebrates and no mutagenic, teratogenic, or carcinogenic properties. At the same time, imidacloprid is highly toxic to aquatic arthropods and nontarget terrestrial insects, especially bees (Sheets, 2010; Cresswell et al., 2012). Since 2018, its outdoor use has been prohibited in the European Union (application is permitted only in permanent greenhouse complexes) (EU, 2018/783, 2018). Nevertheless, imidacloprid-containing preparations are currenly extensively used in a number of non-European countries.

In recent decades, numerous published studies have been focused on the nontarget toxicity of neonicotinoids. Sublethal effects of neonicotinoids have been studied for some harmful and beneficial species. Most often, the negative effects manifest the insects' shorter life, lower fertility, and longer development period (Santos et al., 2016; Ullah et al., 2024). Nontarget Coleoptera are highly sensitive to the effects of neonicotinoids (Gunstone et al., 2021). Ecologically significant concentrations of imidacloprid are potentially harmful for the scarab beetles *Canthon* spp. (Cavallaro et al., 2023). These toxic compounds disrupt the functioning of the immune, reproductive, and other systems of Insecta, and are able to drastically reduce the populations of nontarget species in terrestrial settings (Pisa et al., 2021).

The literature analysis revealed that studies on the effects of this insecticide on nontarget species have been primarily focused on aquatic organisms, considering the global distribution of imidacloprid in surface waters (Borsuah et al., 2020; Malhotra et al., 2021; Nugnes et al., 2023), and terrestrial pollinator species (Hardstone & Scott, 2010; Pamminger et al., 2024). Thus, Hymenoptera were found to be negatively affected by imidacloprid even at sublethal concentrations (Gill et al., 2012; Whitehorn et al., 2012). Research has confirmed that neonicotinoids are involved in the reduction of bee populations around the globe. Fortunately, the dipteran pollinators Syrphidae were found to be less sensitive to imidacloprid (Henriques Martins et al., 2024).

Toxic impact of imidacloprid has been poorly explored for many groups of nontarget terrestrial arthropods, especially those living discreetly. Some taxa with narrow specialization remain practically unstudied, despite their vital ecosystemic functions. Another example of invertebrates underrepresented in the studies on the neonictinoids' toxicity are predatory coleopterans, such as ground beetles and staphylinids. The paucity of reports limits our understanding of how harmful substances are for communities of invertebrates, first of all in agrocenoses (Martynov & Brygadyrenko, 2017; Pearsons & Tooker, 2025).

Evaluation of the risks neonicotinoid insecticides pose to nontarget fauna requires a detailed scientific data on their toxicity. Toxic impact and sublethal effects of one or another insecticide can significantly vary depending on the species's taxonomic position. Since the data on this topic are scarce (Gunstone et al., 2021; Kang et al., 2022), our objective was to evaluate the toxic effects of imidacloprid on nontarget invertebrates in laboratory setting.

Material and methods

The field material was collected in June-August 2024 in forest and meadow biocenoses of Kaunas District (Lithuania). The arthropods were captured using generally accepted zoological methods: Barber pitfall traps, manual examination of the litter and soil, insect nets, and aspirators (Lamarre et al., 2018). In the experiments, we used 50 nontarget arthropod species representing different taxonomic groups. In the laboratory, we maintained stable conditions (21–23 °C temperature, 55–65% relative air humidity). The invertebrates were placed in plastic containers (10 × 6 × 4 cm) with lids. For the absorption of excess moisture, we put two cotton disks on the bottom of each container. Only mature invertebrates were used in the experiments. The number of individuals placed into the container depended on the body size: four individuals of large species and eight individuals of small species. Using plastic sprayers, we introduced a dose of imidacloprid (Confidor 200 SL) into each container. One dose contained 0.37 mL of aqueous solution of the insecticide at a certain concentration. During the spraying, the toxic compound with equal probability ended on the coating of the invertebrates and on the bottom and walls of the plastic container. In the experiments, we used 15 concentrations of the insecticide. The recommended dose of imidacloprid for the application in agrocenoses, according to manual, is 3.5 mg/m^2 (Table 2). The containers with invertebrates were placed for 24 hours in laboratory cabinets. Then, we counted the individuals that have survived and had died (Table 1). Based on the obtained data, we calculated median lethal concentrations. The sublethal effects on survived individuals were not studied. In the control groups of the species, where filtered water was sprayed, no mortality was observed.

The results were statistically analyzed in a set of Statistica 8.0 (StatSoft Inc., USA). The results were processed using probit analysis. Table 2 and the text present the mean values (x) ± standard error (SE) for LC_{50}.

Results

The experiments on the effects of imidacloprid on 50 nontarget terrestrial arthropods revealed a significantly varying sensitivity (Tables 1 and 2), with the the median lethal concentrations (LC_{50}) for different species varying by over 10 thousand times. Among the analyzed taxonomic groups, the highest LC_{50} values were observed in the millipedes *Cylindroiulus truncorum* and *Geophilus carpophagus*, ant *Formica rufa*, and ground beetle *Pterostichus niger*.

Table 1
Results of the laboratory experiments on the effects of imidacloprid on the invertebrates over 24 h

Species	Dosage, mg/m^2	Concentration														
		0.009	0.014	0.027	0.055	0.219	0.438	0.875	1.75	3.5	7	14	28	56	112	224
Porcellio laevis Latreille, 1804	living	8	8	8	8	8	8	8	6	5	3	3	1	0	0	0
	dead	0	0	0	0	0	0	0	2	3	5	5	7	8	8	8
Geophilus carpophagus Leach, 1815	living	8	8	8	8	8	8	8	8	7	6	3	3	2	0	0
	dead	0	0	0	0	0	0	0	0	1	2	5	5	6	8	8
Lithobius forficatus (Linnaeus, 1758)	living	8	8	8	8	8	8	8	8	6	4	3	3	1	0	0
	dead	0	0	0	0	0	0	0	0	2	4	5	5	7	8	8
Cylindroiulus truncorum (Silvestri, 1896)	living	6	6	6	6	6	6	6	6	6	6	5	4	4	2	0
	dead	0	0	0	0	0	0	0	0	0	0	1	2	2	4	6
Megaphyllum sp.	living	6	6	6	6	6	6	6	6	4	4	2	1	0	0	0
	dead	0	0	0	0	0	0	0	0	2	2	4	5	6	6	6
Forficula auricularia Linnaeus, 1758	living	8	8	8	8	8	8	8	7	6	3	3	0	0	0	0
	dead	0	0	0	0	0	0	0	1	2	5	5	8	8	8	8
Labia minor (Linnaeus, 1758)	living	8	8	8	8	8	8	5	6	3	3	2	0	0	0	0
	dead	0	0	0	0	0	0	3	2	5	5	6	8	8	8	8
Chortippus sp. 1	living	8	8	8	8	7	4	3	1	2	0	0	0	0	0	0
	dead	0	0	0	0	1	4	5	7	6	8	8	8	8	8	8
Chortippus sp. 2	living	6	6	6	6	3	2	2	1	0	0	0	0	0	0	0
	dead	0	0	0	0	3	4	4	5	6	6	6	6	6	6	6
Carabus convexus Fabricius, 1775	living	6	6	6	6	5	3	4	2	0	0	0	0	0	0	0
	dead	0	0	0	0	1	3	2	4	6	6	6	6	6	6	6
C. granulatus Linnaeus, 1758	living	8	8	8	7	4	2	3	1	0	0	0	0	0	0	0
	dead	0	0	0	1	4	6	5	7	8	8	8	8	8	8	8
C. hortensis Linnaeus, 1758	living	6	6	6	6	5	5	4	2	0	0	0	0	0	0	0
	dead	0	0	0	0	1	1	2	4	6	6	6	6	6	6	6
Pterostichus niger (Schaller, 1783)	living	6	6	6	6	6	6	6	6	5	5	4	2	0	0	0
	dead	0	0	0	0	0	0	0	0	1	1	2	4	6	6	6
P. melanarius (Illiger, 1798)	living	8	8	8	8	8	8	5	4	4	3	2	0	0	0	0
	dead	0	0	0	0	0	0	3	4	4	5	6	8	8	8	8
Poecilus versicolor (Sturm, 1824)	living	6	6	6	6	6	6	6	5	3	2	0	0	0	0	0
	dead	0	0	0	0	0	0	0	1	3	4	6	6	6	6	6
Calathus fuscipes (Goeze, 1777)	living	8	8	8	8	8	8	8	6	6	4	1	0	0	0	0
	dead	0	0	0	0	0	0	0	2	2	4	7	8	8	8	8
Nebria brevicollis (Fabricius, 1792)	living	6	6	6	6	5	4	3	1	0	0	0	0	0	0	0
	dead	0	0	0	0	1	2	3	5	6	6	6	6	6	6	6
Ophonus rufibarbis (Fabricius, 1792)	living	8	8	8	8	6	6	5	3	3	2	0	0	0	0	0
	dead	0	0	0	0	2	2	3	5	5	6	8	8	8	8	8
Leistus ferrugineus (Linnaeus, 1758)	living	6	6	6	6	6	6	4	3	2	1	0	0	0	0	0
	dead	0	0	0	0	0	0	2	3	4	5	6	6	6	6	6
Harpalus latus (Linnaeus, 1758)	living	6	6	6	6	6	6	6	4	3	1	1	0	0	0	0
	dead	0	0	0	0	0	0	0	2	3	5	5	6	6	6	6

Species	Dosage, mg/m²	Concentration														
		0.009	0.014	0.027	0.055	0.219	0.438	0.875	1.75	3.5	7	14	28	56	112	224
H. rufipes (DeGeer, 1774)	living	6	6	6	6	6	6	6	6	4	4	2	0	0	0	0
	dead	0	0	0	0	0	0	0	0	2	2	4	6	6	6	6
Notiophilus palustris (Duftschmid, 1812)	living	6	6	6	6	6	6	6	6	6	5	2	0	0	0	0
	dead	0	0	0	0	0	0	0	0	0	1	4	6	6	6	6
Amara nitida Sturm, 1825	living	8	8	8	8	8	7	4	2	2	0	0	0	0	0	0
	dead	0	0	0	0	0	1	4	6	6	8	8	8	8	8	8
Tachyporus hypnorum (Fabricius, 1775)	living	6	6	6	3	3	1	0	0	0	0	0	0	0	0	0
	dead	0	0	0	3	3	5	6	6	6	6	6	6	6	6	6
Tachinus signatus Gravenhorst, 1802	living	6	6	6	6	4	2	1	0	0	0	0	0	0	0	0
	dead	0	0	0	0	2	4	5	6	6	6	6	6	6	6	6
Drusilla canaliculata (Fabricius, 1787)	living	6	6	6	6	3	2	0	0	0	0	0	0	0	0	0
	dead	0	0	0	0	3	4	6	6	6	6	6	6	6	6	6
Xantholinus tricolor (Fabricius, 1787)	living	6	6	4	2	1	0	0	0	0	0	0	0	0	0	0
	dead	0	0	2	4	5	6	6	6	6	6	6	6	6	6	6
Philonthus coprophilus Jarrige, 1949	living	8	8	7	5	2	0	0	0	0	0	0	0	0	0	0
	dead	0	0	1	3	6	8	8	8	8	8	8	8	8	8	8
Ph. decorus (Gravenhorst, 1802)	living	8	8	8	6	3	2	0	0	0	0	0	0	0	0	0
	dead	0	0	0	2	5	6	8	8	8	8	8	8	8	8	8
Ph. nitidus (Fabricius, 1787)	living	6	6	6	4	3	1	0	0	0	0	0	0	0	0	0
	dead	0	0	0	2	3	5	6	6	6	6	6	6	6	6	6
Ph. carbonarius (Gravenhorst, 1802)	living	6	5	4	2	0	0	0	0	0	0	0	0	0	0	0
	dead	0	1	2	4	6	6	6	6	6	6	6	6	6	6	6
Ph. cognatus Stephens, 1832	living	6	6	5	3	1	1	0	0	0	0	0	0	0	0	0
	dead	0	0	1	3	5	5	6	6	6	6	6	6	6	6	6
Oxytelus sculptus Gravenhorst, 1806	living	6	6	4	3	1	0	0	0	0	0	0	0	0	0	0
	dead	0	0	2	3	5	6	6	6	6	6	6	6	6	6	6
Silpha carinata Herbst, 1783	living	8	8	8	8	6	6	3	2	0	0	0	0	0	0	0
	dead	0	0	0	0	2	2	5	6	8	8	8	8	8	8	8
Phosphuga atrata (Linnaeus, 1758)	living	6	6	6	6	5	4	2	0	0	0	0	0	0	0	0
	dead	0	0	0	0	3	4	4	6	6	6	6	6	6	6	6
Hister fenestus Erichson, 1834	living	8	8	8	5	2	2	1	0	0	0	0	0	0	0	0
	dead	0	0	0	3	6	6	7	8	8	8	8	8	8	8	8
Aphodius foetens (Fabricius, 1787)	living	8	8	8	8	6	4	4	3	0	0	0	0	0	0	0
	dead	0	0	0	0	2	4	4	5	8	8	8	8	8	8	8
Teuchestes fossor (Linnaeus, 1758)	living	8	8	8	8	8	6	5	2	2	0	0	0	0	0	0
	dead	0	0	0	0	0	2	3	6	6	8	8	8	8	8	8
Oxythyrea funesta (Poda, 1761)	living	8	8	8	8	8	7	4	4	2	0	0	0	0	0	0
	dead	0	0	0	0	0	1	4	4	6	8	8	8	8	8	8
Graphosoma italicum (Muller, 1766)	living	8	8	8	8	5	3	1	2	0	0	0	0	0	0	0
	dead	0	0	0	0	3	5	7	6	8	8	8	8	8	8	8
Lygus pratensis (Linnaeus, 1758)	living	6	6	6	6	6	6	5	2	0	0	0	0	0	0	0
	dead	0	0	0	0	0	0	1	4	6	6	6	6	6	6	6
Coreus marginatus (Linnaeus, 1758)	living	6	6	6	6	4	4	2	1	0	0	0	0	0	0	0
	dead	0	0	0	0	2	2	4	5	6	6	6	6	6	6	6
Pyrrhocoris apterus (Linnaeus, 1758)	living	8	8	8	8	5	4	2	2	1	0	0	0	0	0	0
	dead	0	0	0	0	3	4	6	6	7	8	8	8	8	8	8
Rhyparochromus phoeniceus (Rossi, 1794)	living	8	8	8	7	5	3	3	1	0	0	0	0	0	0	0
	dead	0	0	0	1	3	5	5	7	8	8	8	8	8	8	8
Myrmica ruginodis Nylander, 1846	living	8	8	8	8	5	5	4	2	1	0	0	0	0	0	0
	dead	0	0	0	0	3	3	4	6	7	8	8	8	8	8	8
Formica rufa Linnaeus, 1761	living	8	8	8	8	8	8	8	8	8	8	6	6	3	2	0
	dead	0	0	0	0	0	0	0	0	0	0	2	2	5	6	8
Ponera coarctata (Latreille, 1802)	living	8	8	8	8	8	8	8	7	6	4	4	3	2	0	0
	dead	0	0	0	0	0	0	0	1	2	4	4	5	6	8	8
Lasius flavus (Fabricius, 1782)	living	8	8	8	8	8	8	6	5	3	2	0	0	0	0	0
	dead	0	0	0	0	0	0	2	3	5	6	8	8	8	8	8
L. fuliginosus (Latreille, 1798)	living	8	8	8	8	8	8	8	6	6	3	1	0	0	0	0
	dead	0	0	0	0	0	0	0	2	2	5	7	8	8	8	8
L. niger (Linnaeus, 1758)	living	8	8	8	8	8	8	8	5	2	2	0	0	0	0	0
	dead	0	0	0	0	0	0	0	3	6	6	8	8	8	8	8

Table 2
Median lethal concentrations of imidacloprid for the arthropods in the experiment

Order	Family	Species	LC_{50} (mean ± SE), mg/m²	Average body mass (dry weight), mg	Body length, mm
Isopoda	Porcellionidae	*Porcellio laevis* Latreille, 1804	4.11 ± 0.30	29	10–20
Geophilomorpha	Geophilidae	*Geophilus carpophagus* Leach, 1815	11.84 ± 1.15	12	15–60
Lithobiomorpha	Lithobiidae	*Lithobius forficatus* (Linnaeus, 1758)	8.08 ± 0.72	21	18–30
Julida	Julidae	*Cylindroiulus truncorum* (Silvestri, 1896)	165.9 ± 23.5	42	15–20
	Julidae	*Megaphyllum* sp.	5.84 ± 0.53	47	17–22
Dermaptera	Forficulidae	*Forficula auricularia* Linnaeus, 1758	4.08 ± 0.34	29	12–14
Dermaptera	Spongiphoridae	*Labia minor* (Linnaeus, 1758)	2.45 ± 0.15	3	4–7
Orthoptera	Acrididae	*Chortippus* sp. 1	0.752 ± 0.043	72	20–28
Orthoptera	Acrididae	*Chortippus* sp. 2	0.485 ± 0.032	63	18–25
Coleoptera	Carabidae	*Carabus convexus* Fabricius, 1775	0.779 ± 0.049	120	15–18

Order	Family	Species	LC_{50} (mean ± SE), mg/m^2	Average body mass (dry weight), mg	Body length, mm
	Carabidae	*C. granulatus* Linnaeus, 1758	0.406 ± 0.027	106	17–23
	Carabidae	*C. hortensis* Linnaeus, 1758	0.911 ± 0.059	237	23–30
	Carabidae	*Pterostichus niger* (Schaller, 1783)	10.35 ± 1.11	74	15–21
	Carabidae	*P. melanarius* (Illiger, 1798)	2.33 ± 0.14	71	12–18
	Carabidae	*Poecilus versicolor* (Sturm, 1824)	2.72 ± 0.22	15	8.0–11.5
	Carabidae	*Calathus fuscipes* (Goeze, 1777)	3.45 ± 0.28	25	10–14
	Carabidae	*Nebria brevicollis* (Fabricius, 1792)	0.720 ± 0.045	29	10–14
	Carabidae	*Ophonus rufibarbis* (Fabricius, 1792)	1.185 ± 0.048	11	7.5–10.0
	Carabidae	*Leistus ferrugineus* (Linnaeus, 1758)	1.662 ± 0.105	7	6.5–8.0
	Carabidae	*Harpalus latus* (Linnaeus, 1758)	2.607 ± 0.195	12	8.0–10.5
	Carabidae	*H. rufipes* (DeGeer, 1774)	4.91 ± 0.47	47	11–16
	Carabidae	*Notiophilus palustris* (Duftschmid, 1812)	6.96 ± 0.81	5	4.5–6
	Carabidae	*Amara nitida* Sturm, 1825	1.116 ± 0.071	6	6.5–7.5
Coleoptera	Staphylinidae	*Tachyporus hypnorum* (Fabricius, 1775)	0.196 ± 0.019	0.5	3,1–4
	Staphylinidae	*Tachinus signatus* Gravenhorst, 1802	0.428 ± 0.033	0.8	5–6
	Staphylinidae	*Drusilla canaliculata* (Fabricius, 1787)	0.345 ± 0.031	0.6	4.0–4.8
	Staphylinidae	*Xantholinus tricolor* (Fabricius, 1787)	0.0632 ± 0.0073	8	9–12
	Staphylinidae	*Philonthus coprophilus* Jarrige, 1949	0.122 ± 0.013	7	6.6–8.5
	Staphylinidae	*Ph. decorus* (Gravenhorst, 1802)	0.235 ± 0.021	12	11–13
	Staphylinidae	*Ph. nitidus* (Fabricius, 1787)	0.222 ± 0.020	15	10.5–16.0
	Staphylinidae	*Ph. carbonarius* (Gravenhorst, 1802)	0.0305 ± 0.0038	1	4.3–4.9
	Staphylinidae	*Ph. cognatus* Stephens, 1832	0.116 ± 0.011	7	8–10
	Staphylinidae	*Oxytelus sculptus* Gravenhorst, 1806	0.0756 ± 0.0083	0.6	3.5–4.0
Coleoptera	Silphidae	*Silpha carinata* Herbst, 1783	0.703 ± 0.043	74	12–23
	Silphidae	*Phosphuga atrata* (Linnaeus, 1758)	0.431 ± 0.033	42	10–16
Coleoptera	Histeridae	*Hister fenestus* Erichson, 1834	0.226 ± 0.019	6	4–6
Coleoptera	Aphodiidae	*Aphodius foetens* (Fabricius, 1787)	0.698 ± 0.042	9	6.0–8.5
	Aphodiidae	*Teuchestes fossor* (Linnaeus, 1758)	1.090 ± 0.067	41	8–13
Coleoptera	Cetoniidae	*Oxythyrea funesta* (Poda, 1761)	1.224 ± 0.077	45	8–12
Hemiptera	Pentatomidae	*Graphosoma italicum* (Muller, 1766)	0.499 ± 0.035	45	8–12
	Miridae	Lygus pratensis (Linnaeus, 1758)	1.249 ± 0.105	2	5.5–7.0
	Coreidae	*Coreus marginatus* (Linnaeus, 1758)	0.611 ± 0.038	23	13–15
	Pyrrhocoridae	*Pyrrhocoris apterus* (Linnaeus, 1758)	0.624 ± 0.034	32	9–11
	Lygaeidae	*Rhyparochromus phoeniceus* (Rossi, 1794)	2.18 ± 0.13	4	7.5–9.0
Hymenoptera	Formicidae	*Myrmica ruginodis* Nylander, 1846	0.727 ± 0.038	0.7	3.0–4.5
	Formicidae	*Formica rufa* Linnaeus, 1761	82.39 ± 11.17	5	4.5–9.0
	Formicidae	*Ponera coarctata* (Latreille, 1802)	8.76 ± 0.70	0.3	2.0–4.0
	Formicidae	*Lasius flavus* (Fabricius, 1782)	1.93 ± 0.13	0.3	2.5-4.0
	Formicidae	*L. fuliginosus* (Latreille, 1798)	3.28 ± 0.26	0.5	3.5–5.5
	Formicidae	*L. niger* (Linnaeus, 1758)	2.15 ± 0.17	0.4	3.0–4.5

Note: the dose of imidacloprid recommended by manufacturer for agrocenoses is 3.5 mg/m^2.

Table 3
Distribution of arthropods in the experiments according to the level of sensitivity to imidacloprid, taking into account the taxonomic position and trophic specialization

Group	Range	Order, family	Species	Trophic specialization
Hypersensitive	LC_{50} < 0.1 mg/m^2	Coleoptera (Staphylinidae)	*Xantholinus tricolor* (Fabricius, 1787)	z
			Philonthus carbonarius (Gravenhorst, 1802)	z
			Oxytelus sculptus Gravenhorst, 1806	z
Sensitive	0.1 ≤ LC_{50} < 1 mg/m^2	Orthoptera (Acrididae)	*Chortippus sp.* 1	f
			Chortippus sp. 2	f
		Coleoptera (Carabidae)	*Carabus convexus* Fabricius, 1775	z
			C. granulatus Linnaeus, 1758	z
			C. hortensis Linnaeus, 1758	z
			Nebria brevicollis (Fabricius, 1792)	z
		Coleoptera (Staphylinidae)	*Tachyporus hypnorum* (Fabricius, 1775)	z
			Tachinus signatus Gravenhorst, 1802	z
			Drusilla canaliculata (Fabricius, 1787)	z
			Philonthus coprophilus Jarrige, 1949	z
			Ph. decorus (Gravenhorst, 1802)	z
			Ph. nitidus (Fabricius, 1787)	z
			Ph. cognatus Stephens, 1832	z
		Coleoptera (Silphidae)	*Silpha carinata* Herbst, 1783	p
			Phosphuga atrata (Linnaeus, 1758)	z
		Coleoptera (Histeridae)	*Hister fenestus* Erichson, 1834	z
		Coleoptera (Aphodiidae)	*Aphodius foetens* (Fabricius, 1787)	s
		Hemiptera (Pentatomidae)	*Graphosoma italicum* (Muller, 1766)	f
		Hemiptera (Coreidae)	*Coreus marginatus* (Linnaeus, 1758)	f
		Hemiptera (Pyrrhocoridae)	*Pyrrhocoris apterus* (Linnaeus, 1758)	p
		Hymenoptera (Formicidae)	*Myrmica ruginodis* Nylander, 1846	p
Moderately sensitive	1 ≤ LC_{50} < 10 mg/m^2	Isopoda (Porcellionidae)	*Porcellio laevis* Latreille, 1804	s
		Lithobiomorpha (Lithobiidae)	*Lithobius forficatus* (Linnaeus, 1758)	z
		Julida (Julidae)	*Megaphyllum sp.*	s
		Dermaptera (Forficulidae)	*Forficula auricularia* Linnaeus, 1758	p

Group	Range	Order, family	Species	Trophic specialization
		Dermaptera (Spongiphoridae)	*Labia minor* (Linnaeus, 1758)	p
		Coleoptera (Carabidae)	*Pterostichus melanarius* (Illiger, 1798)	z
			Poecilus versicolor (Sturm, 1824)	z
			Calathus fuscipes (Goeze, 1777)	z
			Ophonus rufibarbis (Fabricius, 1792)	f
			Leistus ferrugineus (Linnaeus, 1758)	z
			Harpalus latus (Linnaeus, 1758)	f
			H. rufipes (DeGeer, 1774)	p
			Notiophilus palustris (Duftschmid, 1812)	z
			Amara nitida Sturm, 1825	f
		Coleoptera (Aphodiidae)	*Teuchestes fossor* (Linnaeus, 1758)	s
		Coleoptera (Cetoniidae)	*Oxythyrea funesta* (Poda, 1761)	f
		Hemiptera (Miridae)	*Lygus pratensis* (Linnaeus, 1758)	f
		Hemiptera (Lygaeidae)	*Rhyparochromus phoeniceus* (Rossi, 1794)	f
		Hymenoptera (Formicidae)	*Ponera coarctata* (Latreille, 1802)	p
			Lasius flavus (Fabricius, 1782)	p
			L. fuliginosus (Latreille, 1798)	p
			L. niger (Linnaeus, 1758)	p
Insensitive	$10 \leq LC_{50} < 100$ mg/m^2	Geophilomorpha (Geophilidae)	*Geophilus carpophagus Leach, 1815*	z
		Coleoptera (Carabidae)	*Pterostichus niger* (Schaller, 1783)	z
		Hymenoptera (Formicidae)	*Formica rufa Linnaeus, 1761*	p
Resistant	$100 \leq LC_{50} < 1,000$ mg/m^2	Julida (Julidae)	*Cylindroiulus truncorum* (Silvestri, 1896)	s

Note: the dose of imidacloprid recommended by manufacturer for agrocenoses – 3.5 mg/m^2; trophic group: f – phytophages, s – saprophages, z – zoophages, p – pantophages.

For the convenience of the analysis, the arthropods we studied were divided according to the level of sensitivity to imidacloprid. Five ranges of sensitivity were designated (Table 3). The distribution of the nontarget species was uneven across the formed groups. The most diverse groups comprised moderately sensitive ($0.1 \leq LC_{50} < 10$ mg/m^2) and sensitive species ($0.1 \leq LC_{50} < 1$ mg/m^2). The moderately sensitive species included woodlice, millipedes, earwigs, the majority of ground beetles and ants, and some species of scarab beetles and heminopterans (Lygaeidae and Miridae).

The broad group ecompassing sensitive species included several species of Acrididae, large ground beetles of the *Carabus* genus, carrion beetles, and the majority of staphylinids and heminopterans that participated in the experiments. The most vulnerable group, composed of hypersensitive species, was represented by three species of Staphylinidae (*Ph. carbonarius*, *X. tricolor*, and *O. sculptus*), for which the LC_{50} values ranged 0.03–0.08 mg/m^2. We observed no relationship between the sensitivity to imidacloprid and the trophic specialization of the studied species. The zoophages were included in both the hypersensitive and insensitive groups.

Discussion

The conducted studies on the sensitivity of arthropods to imidacloprid covered a considerable fraction of taxonomic groups and revealed varying results. The semilethal concentrations of the insecticide significantly differed across the species. Especially concerning is the hypersensitivity to imidacloprid observed in staphylinids and ground beetles (the *Carabus* genus). According to our previous studies, those same groups of coleopterans are highly sensitive to cypermethrin and pirimiphos-methyl (Faly et al., 2023; Faly & Brygadyrenko, 2024). Zoophages perform an important functional role in terrestrial ecosystems, ands such a high sensitivity to toxicants indicates that in natural ecosystems these groups completely drop out of the invertebrate communities, especially in areas adjacent to treated agrocenoses (Brygadyrenko & Reshetniak, 2014; Avtaeva et al., 2021). Even when subject to low concentrations of the insecticide (due to the uneven distribution of the insecticide solution during its application in agrosystems and further degradation of the compound), nontarget invertebrates can suffer sublethal impact (Pisa et al., 2021). At the same time, the highest LC_{50} values among taxonomic groups we the analyzed, were observed for the millipedes *Cylindroiulus truncorum* and *Geophilus carpophagus*, ant *Formica rufa*, and ground beetle *Pterostichus niger*. Low sensitivity of those species to chemical means of plant protection was registered also for other classes of compounds – pyrethroids, organophosphorus insecticides (Faly et al., 2023; Faly & Brygadyrenko, 2024).

The scientific literature contains detailed data on the effects of imidacloprid at field concentrations on the life span and fertility of taget pests. Less attention has been paid to parameters such as survival of the larval stages and time of development of preimaginal phases (Ullah et al., 2024). As known, a sensitivity to imidacloprid was exhibited by harmful species of the lepidopterans Noctuidae (*Helicoverpa armigera* [Hübner, 1808[) (Nareshkumar et al., 2018), coleopterans Chrysomelidae (*Acalymma vittatum* [Fabricius, 1775]) (Jasinski et al., 2009), Curculionidae (*Rhynchophorus ferrugineus* [Olivier, 1790]) (Alzahrani, 2019), Scarabaeidae (*Popillia japonica* Newman, 1841) (Oliver et al., 2013), Carabidae (*Zabrus tenebrioides* Goeze, 1777) (Esmailpour et al., 2024), Tenebrionidae (*Tribolium confusum* Jacquelin du Val, 1863) (Saglam et al., 2013), Elateridae (*Agriotes obscurus* [Linnaeus 1758]) (Van Herk et al., 2008), hemipterans Scutelleridae (*Eurygaster integriceps* Puton, 1881) (Shekhi Garjan, Mohammadipour, 2024), Aphididae (*Metopolophium dirhodum* [Walker, 1849]) (Li et al., 2023), Aleyrodidae (*Bemisia tabaci* [Gennadius, 1889]) (He et al., 2011), Cicadellidae (*Amrasca biguttula* [Ishida, 1913] (Saeed et al., 2016), Diaspididae (*Aulacaspis tubercularis* Newstead, 1906) (Ebrahim, 2024), orthopterans Gryllotalpidae (*Scapteriscus vicinus* Scudder, 1869) (Kostromytska et al., 2011), Acrididae (*Locusta migratoria* Linnaeus, 1758) (El-Samad et al., 2022), dipterans Cecidomyiidae (*Dasineura oxycoccana* [Johnson, 1899]) (Lopez, Liburd, 2024), Anthomyiidae (*Delia antiqua* [Meigen, 1826], *D. platura* [Meigen, 1826]) (Wilson et al., 2015), Psilidae (*Diaphorina citri* Kuwayama, 1908) (Serikawa et al., 2012), Chloropidae (*Oscinella frit* [Linnaeus, 1758]) (Cheng, 2025), thrips Phlaeothripidae (*Gynaikothrips uzeli* [Zimmermann, 1900]) (Lin et al., 2018) and Thripidae (*Thrips flavus* Schrank, 1776, *Megalurothrips usitatus* [Bagnall, 1913]) (Pei et al., 2025; Yu et al., 2023), and many other groups. At the same time, over 300 species of agriculture and forestry pests displayed imidacloprid resistance. To prevent the development of resistance in harmful insects, neonicotinoids are used only once during the season. Inside this class of compounds, no cross-resistance was observed (Bass et al., 2015).

Researches have studied the toxic effects of neonicotinoid insecticides on some entomophages used in the biomethod. Field concentrations of clothianidin and thiamethoxam exerted a lethal toxicity for the imagoes of the staphylinid Dalotia coriaria (Kraatz, 1856) (Cloyd et al., 2009). Besides lethal effects, neonicotinoids can also display sublethal effects on zoophages. Those effects most often express in decline in the locomotor activity of predators, rates of consuming prey (Malaquias et al., 2014). Imidacloprid reduces the locomotor activity of nymphs and imagoes of predatory hymenopterans *Eocanthecona furcellata* (Wolff, 1811), thereby reducing the efficiency of pest control in agrocenoses in China (Chen et al., 2025). In sublethal concentrations, imidacloprid was observed to decrease the life span, number of deposited eggs, and survival of imagoes of predatory *Hippodamia variegata* (Goeze, 1777), thereby limiting the effectiveness of biological control carried out by entomophages (Skouras et al., 2019). Similar negative effects were observed for other species of Coccinellidae, including *Hippodamia undecimnotata* Schneider, 1792, and *Coccinella septempunctata* (Linnaeus, 1758) (Papachristos, Milonas, 2008; Xiao et al., 2016).

Sublethal concentrations of imidacloprid negatively affected the locomotor activity and behavior of some species of ants. Deteriorated navigation and limited success in the search for food when subject to this insecticide was described for the ants *Pogonomyrmex occidentalis* (Cresson, 1865) and *Lasius niger*. Among the *L. flavus* individuals, there was seen a manifestation of excessive aggressiveness in individuals in the nest (Thiel & Köhler, 2016; Sappington, 2018). Environmental contamination with neonicotinoids can aggravate the effects of other stress factors. For example, a study found neonicotinoids responsible for the decline in the populations of the Lampyridae beetles in North America (Lewis et al., 2020). Imidacloprid affects terrestrial Isopoda crustaceans at concentrations similar to those for insects. In laboratory experiments with the woodlouce *Porcellio scaber* Latreille, 1804, imidacloprid significantly reduced its feeding activity (Drobne et al., 2008).

The comparison of the effects of several neonicotinoids (imidacloprid and thiamethoxam) on the aphid parasitoid *Aphidius colemani* Viereck, 1912, revealed significant differences in their toxic actions. Thiamethoxam caused a high mortality of the parasitoid, while imidacloprid had only a low effect (Ricupero et al., 2020). At the same time, the literature has described positive effects of neonicotinoids (Qu et al., 2015; Guedes et al., 2022). For example, studies of the effects of low and moderate doses of imidacloprid on *Trichogramma chilonis* Ishii, 1941 revealed a stimulating effect – hormesis. In the first generation of the parasitoid, there were significant changes in the demographic characteristics. In the following generations, hormetic effects were observed. The application of certain low doses of imidacloprid is recommended for mass cultivation of egg parasitoids (Ray et al., 2022). However, those are exceptional cases and in general neonicotinoids are toxic to arthropods.

The effects of sublethal intoxication of the system with neonicotinoids can potentially spread via food chains. The experiments on the effects of sublethal doses of imidacloprid on nontarget trophic model system, including a plant, a phytophage, and a predator revealed mixed results. The phytophage, *Nemobius sylvestris* (Bosc, 1792), was observed to have reduced mobility and gain of body mass. However, the insecticide had no effect on the life span and did not increase the success of predation in spiders (*Pisaura mirabilis* [Clerck, 1757]) (Uhl et al., 2015). Neonicotinoid insecticides decreased the number of zoophage arthropods. The toxicity of neonicotinoids for predatory insects through their prey has been poorly studied. On the example of thiamethoxam action toward the three-component trophic system, it was demonstrated that the insecticide concentration decreases as it travels further in food chain. Nonetheless, the amount of toxic compound accumulated in the phytophages was high enough to harm the predatory beetles of *Chlaenius tricolor* Dejean, 1826 (Douglas et al., 2015).

Conclusion

In the laboratory conditions, we evaluated the sensitivity of 50 nontarget species of arthropods to imidacloprid. The studied species belonged to various taxonomic groups. The diplopod *Cylindroiulus truncorum* was observed to exhibit the highest resistance to the insecticide, the median lethal concentration accounting for over 100 mg/m^2. Other insensitive species were the ant Formica rufa (82.39 mg/m^2), the millipede *Geophilus carpophagus* (11.84 mg/m^2), and the ground beetle *Pterostichus niger* (10.35 mg/m^2). The moderately sensitive species, for which LC_{50} measured 1 to 10 mg/m^2, included millipede *Lithobius forficatus*, *Megaphyllum* sp., woodlice *Porcellio laevis*, ground beetles *Notiophilus palustris*, *Harpalus rufipes*, *H. latus*, *Amara nitida*, and *Ophonus rufibarbis*, carabeed beetles *Oxythyrea funesta* and *Teuchestes fossor*, earwigs *Forficula auricularia* and *Labia minor*, ants *Ponera coarctata*, *Lasius fuliginosus*, *L. niger*, and *L. flavus*, and heteropterans *Rhyparochromus phoeniceus* and *Lygus pratensis*. A greater sensitivity to imidacloprid was displayed by the ground beetles *Carabus convexus*, *C. granulatus*, *C. hortensis*, and *Nebria brevicollis*, staphylinids *Tachyporus hypnorum*, *Tachinus signatus*, *Drusilla canaliculata*, *Philonthus coprophilus*, *Ph. decorus*, *Ph. nitidus*, and *Ph. cognatus*, carrion beetles *Silpha carinata* and *Phosphuga atrata*, carrabid beetle *Aphodius foetens*, hister beetle *Hister fenestus*, ant *Myrmica ruginodis*, orthopteran *Chortippus* sp., and heteropterans *Graphosoma italicum*, *Coreus marginatus*, and *Pyrrhocoris apterus*. The LC_{50} values for these species were within the range of 0.1–1.0 mg/m^2. It was found that the most vulnerable group among the nontarget arthropods is Staphylinidae. An ultrasensitivity to imidacloprid was observed in *Ph. carbonarius*, *Xantholinus tricolor*, and *Oxytelus sculptus*: for these coleopterans, the median lethal concentrations were no higher than 0.08 mg/m^2.

The studies revealed no relationship between the trophic specialization of the species and sensitivity to imidacloprid. The larger the body of the nontarget arthropods, the lower was their sensitivity to the insecticide, with the exception of ground beetles, particularly those of the *Carabus* genus. Our laboratory experiments demonstrated that invertebrates belonging to different taxonomic groups significantly vary in the sensitivity to neonicotinoids. Poor practice of using systemic neonicotinoids in agrosystems leads to a drastic impoverishment of the nontarget entomofauna. Adequate design of complex programs of combating pests includes an assessment of side-effects of the insecticides for nontarget species, including entomophages and parasitoids. Therefore, further studies are required to explore the toxic sensitivity of arthropods to popular agricultural insecticides.

References

Alzahrani, A. M. (2019). Ultrastructural damage and biochemical alterations in the testes of red palm weevils (*Rhynchophorus ferrugineus*) exposed to imidacloprid. Environmental Science and Pollution Research, 26(16), 16548–16555.

Avtaeva, T., Petrovičová, K., Langraf, V., & Brygadyrenko, V. (2021). Potential bioclimatic ranges of crop pests Zabrus tenebrioides and *Harpalus rufipes* during climate change conditions. Diversity, 13, 559.

Bass, C., Denholm, I., Williamson, M. S., & Nauen, R. (2015). The global status of insect resistance to neonicotinoid insecticides. Pesticide Biochemistry and Physiology, 121, 78–87.

Borsuah, J. F., Messer, T. L., Snow, D. D., Comfort, S. D., & Mittelstet, A. R. (2020). Literature review: Global neonicotinoid insecticide occurrence in aquatic environments. Water, 12(12), 3388.

Brygadyrenko, V. V., & Reshetniak, D. Y. (2014). Trophic preferences of *Harpalus rufipes* (Coleoptera, Carabidae) with regard to seeds of agricultural crops in conditions of laboratory experiment. Baltic Journal of Coleopterology, 14(2), 179–190.

Cavallaro, M. C., Hladik, M. L., Hittson, S., Middleton, G., & Hoback, W. W. (2023). Comparative toxicity of two neonicotinoid insecticides at environmentally relevant concentrations to telecoprid dung beetles. Scientific Reports, 13(1), 8537.

Chen, G., Chen, Z., Ding, Y. S., Wu, Z. Y., He, W. D., Ren, W., ... & Guo, K. F. (2025). Acute exposure to imidacloprid impairs walking behavior of *Eocanthecona furcellata* (Hemiptera: Pentatomidae). Journal of Entomological Science, 60(4), 567–575.

Cheng, Z. (2025). Management of frit fly (*Oscinella frit*), a challenging turfgrass insect pest in Hawaii. International Turfgrass Society Research Journal, 15(1), 1110–1112.

Cloyd, R. A., Timmons, N. R., Goebel, J. M., & Kemp, K. E. (2009). Effect of pesticides on adult rove beetle *Atheta coriaria* (Coleoptera: Staphylinidae) survival in growing medium. Journal of Economic Entomology, 102(5), 1750–1758.

Craddock, H. A., Huang, D., Turner, P. C., Quirós-Alcalá, L., & Payne-Sturges, D. C. (2019). Trends in neonicotinoid pesticide residues in food and water in the United States, 1999–2015. Environmental Health, 18(1), 7.

Cresswell, J. E., Page, C. J., Uygun, M. B., Holmbergh, M., Li, Y., Wheeler, J. G., ... & Tyler, C. R. (2012). Differential sensitivity of honey bees and bumble bees to a dietary insecticide (imidacloprid). Zoology, 115(6), 365–371.

Douglas, M. R., Rohr, J. R., & Tooker, J. F. (2015). Neonicotinoid insecticide travels through a soil food chain, disrupting biological control of non-target pests and decreasing soya bean yield. Journal of Applied Ecology, 52(1), 250–260.
Drobne, D., Blažič, M., Van Gestel, C. A., Lešer, V., Zidar, P., Jemec, A., & Trebše, P. (2008). Toxicity of imidacloprid to the terrestrial isopod *Porcellio scaber* (Isopoda, Crustacea). Chemosphere, 71(7), 1326–1334.
Ebrahim, Y. N. (2024). Field efficacy of insecticides for suppressing white mango scale insect (*Aulacaspis tubercularis* Newstead) (Hemiptera: Diaspididae) in Southwest Ethiopia. Heliyon, 10(18), e38156.
El-Samad, L. M., El-Gerbed, M. S., Hussein, H. S., Flaven-Pouchon, J., El Wakil, A., & Moussian, B. (2022). Imidacloprid-induced pathophysiological damage in the midgut of *Locusta migratoria* (Orthoptera: Acrididae) in the field. Environmental Science and Pollution Research, 29, 57644–57655.
Esmailpour, N., Nozari, J., & Allahyari, H. (2024). Effect of nutrition by fertilizing, plant density, and seed treatment with imidacloprid on grain yield, population density, and damage rate of the cereal ground beetle, *Zabrus tenebrioides* in rain-fed wheat. Iranian Journal of Plant Protection Science, 54(2), 391–406.
Faly, L., & Brygadyrenko, V. (2024). Effects of pirimiphos-methyl on non-target invertebrates. Biology, 13(10), 823.
Faly, L., Brygadyrenko, V., Orzekauskaite, A., & Paulauskas, A. (2023). Sensitivity of non-target groups of invertebrates to cypermethrin. Biosystems Diversity, 31(3), 393–400.
Gill, R. J., Ramos-Rodriguez, O., & Raine, N. E. (2012). Combined pesticide exposure severely affects individual-and colony-level traits in bees. Nature, 491(7422), 105–108.
Guedes, R. N. C., Rix, R. R., & Cutler, G. C. (2022). Pesticideinduced hormesis in arthropods: Towards biological systems. Current Opinion in Toxicology, 29, 43–50.
Gunstone, T., Cornelisse, T., Klein, K., Dubey, A., & Donley, N. (2021). Pesticides and soil invertebrates: A hazard assessment. Frontiers in Environmental Science, 9, 643847.
Han, W., Tian, Y., & Shen, X. (2018). Human exposure to neonicotinoid insecticides and the evaluation of their potential toxicity: An overview. Chemosphere, 192, 59–65.
Hardstone, M. C., & Scott, J. G. (2010). Is Apis mellifera more sensitive to insecticides than other insects? Pest Management Science, 66(11), 1171–1180.
He, Y., Zhao, J., Wu, D., Wyckhuys, K. A., & Wu, K. (2011). Sublethal effects of imidacloprid on *Bemisia tabaci* (Hemiptera: Aleyrodidae) under laboratory conditions. Journal of Economic Entomology, 104(3), 833–838.
Henriques Martins, C. A., Azpiazu, C., Bosch, J., Burgio, G., Dindo, M. L., Francati, S., ... & Sgolastra, F. (2024). Different sensitivity of flower-visiting Diptera to a neonicotinoid insecticide: Expanding the base for a multiple-species risk assessment approach. Insects, 15(5), 317.
Huseth, A. S., & Groves, R. L. (2014). Environmental fate of soil applied neonicotinoid insecticides in an irrigated potato agroecosystem. PloS One, 9(5), e97081.
Jasinski, J., Darr, M., Ozkan, E., & Precheur, R. (2009). Applying imidacloprid via a precision banding system to control striped cucumber beetle (Coleoptera: Chrysomelidae) in cucurbits. Journal of Economic Entomology, 102(6), 2255–2264.
Kang, Y., Koo, H.-N., Kim, H.-K., & Kim, G.-H. (2022). Analysis of the feeding behavior and life table of *Nilaparvata lugens* and *Sogatella furcifera* (Hemiptera: Delphacidae) under sublethal concentrations of imidacloprid and sulfoxaflor. Insects, 13(12), 1130.
Kostromytska, O. S., Buss, E. A., & Scharf, M. E. (2011). Toxicity and neurophysiological effects of selected insecticides on the mole cricket, *Scapteriscus vicinus* (Orthoptera: Gryllotalpidae). Pesticide Biochemistry and Physiology, 100(1), 27–34.
Lamarre, G. P. A., Juin, Y., Lapied, E., Le Gall, P., & Nakamura, A. (2018). Using field-based entomological research to promote awareness about forest ecosystem conservation. Nature Conservation, 29, 39–56.
Lewis, S. M., Wong, C. H., Owens, A. C., Fallon, C., Jepsen, S., Thancharoen, A., ... & Reed, J. M. (2020). A global perspective on firefly extinction threats. BioScience, 70(2), 157–167.
Li, X., Li, Y., Zhu, X., Li, X., Cheng, D., & Zhang, Y. (2023). Effects of imidacloprid-induced hormesis on the development and reproduction of the rose-grain aphid *Metopolophium dirhodum* (Hemiptera: Aphididae). Frontiers in Physiology, 14, 1113464.
Lin, Y., Chen, F., Lin, S., Huang, P., Akutse, K. S., Yu, D., & Gao, Y. (2018). Imidacloprid pesticide regulates *Gynaikothrips uzeli* (Thysanoptera: Phlaeothripidae) host choice behavior and immunity against *Lecanicillium lecanii* (Hypocreales: Clavicipitaceae). Journal of Economic Entomology, 111(5), 2069–2075.
Lopez, M., & Liburd, O. E. (2024). Assessing the effectiveness of selected reduced-risk insecticides and malathion on blueberry gall midge (Diptera: Cecidomyiidae) and key parasitoids. Crop Protection, 185, 106890.
Malaquias, J. B., Ramalho, F. S., Omoto, C., Godoy, W. A. C., & Silveira, R. F. (2014). Imidacloprid affects the functional response of predator *Podisus nigrispinus* (Dallas) (Heteroptera: Pentatomidae) to strains of *Spodoptera frugiperda* (JE Smith) on Bt cotton. Ecotoxicology, 23(2), 192–200.
Malhotra, N., Chen, K. H. C., Huang, J. C., Lai, H. T., Uapipatanakul, B., Roldan, M. J. M., ... & Hsiao, C. D. (2021). Physiological effects of neonicotinoid insecticides on non-target aquatic animals – an updated review. International Journal of Molecular Sciences, 22(17), 9591.
Martynov, V. O., & Brygadyrenko, V. V. (2017). The influence of synthetic food additives and surfactants on the body weight of larvae of *Tenebrio molitor* (Coleoptera, Tenebrionidae). Biosystems Diversity, 25(3), 236–242.
Matsuda, K., Ihara, M., & Sattelle, D. B. (2020). Neonicotinoid insecticides: Molecular targets, resistance, and toxicity. Annual Review of Pharmacology and Toxicology, 60(1), 241–255.
Nareshkumar, B., Akbar, S. M., Sharma, H. C., Jayalakshmi, S. K., & Sreeramulu, K. (2018). Imidacloprid impedes mitochondrial function and induces oxidative stress in cotton bollworm, *Helicoverpa armigera* larvae (Hubner: Noctuidae). Journal of Bioenergetics and Biomembranes, 50(1), 21–32.
Nugnes, R., Russo, C., Orlo, E., Lavorgna, M., & Isidori, M. (2023). Imidacloprid: Comparative toxicity, DNA damage, ROS production and risk assessment for aquatic non-target organisms. Environmental Pollution, 316, 120682.
Oliver, J. B., Ranger, C. M., Reding, M. E., Moyseenko, J. J., Youssef, N. N., & Bray, A. M. (2013). Preharvest quarantine treatments of chlorantraniliprole, clothianidin, and imidacloprid-based insecticides for control of Japanese beetle (Coleoptera: Scarabaeidae) and other scarab larvae in the root zone of field-grown nursery trees. Journal of Economic Entomology, 106(3), 1190–1199.
Pamminger, T., Basley, K., Goulson, D., & Hughes, W. O. (2024). Potential acetylcholine-based communication in honeybee haemocytes and its modulation by a neonicotinoid insecticide. PeerJ, 12, e17978.
Papachristos, D. P., & Milonas, P. G. (2008). Adverse effects of soil applied insecticides on the predatory coccinellid *Hippodamia undecimnotata* (Coleoptera: Coccinellidae). Biological Control, 47(1), 77–81.
Pearsons, K. A., & Tooker, J. F. (2025). Acute toxicity of neonicotinoid insecticides to ground beetles (Coleoptera: Carabidae) from Pennsylvania. Environmental Entomology, 54(3), 574–584.
Pei, T., Wang, L., Zhao, Y., Shi, S., & Gao, Y. (2025). Toxicity and efficacy of thirty insecticides against Thrips flavus in Northeast China: Laboratory, semifield, and field trials. Insects, 16(4), 405.
Pisa, L., Goulson, D., Yang, E. C., Gibbons, D., Sánchez-Bayo, F., Mitchell, E., ... & Bonmatin, J. M. (2021). An update of the worldwide integrated assessment (WIA) on systemic insecticides. Part 2: Impacts on organisms and ecosystems. Environmental Science and Pollution Research, 28(10), 11749–11797.
Qu, Y., Xiao, D., Li, J., Chen, Z., Biondi, A., Desneux, N., … Song, D. (2015). Sublethal and hormesis effects of imidacloprid on the soybean aphid *Aphis glycines*. Ecotoxicology, 24(3), 479–487.
Ray, A., Gadratagi, B. G., Rana, D. K., Ullah, F., Adak, T., Govindharaj, G. P. P., ... & Rath, P. C. (2022). Multigenerational insecticide hormesis enhances fitness traits in a key egg parasitoid, *Trichogramma chilonis* Ishii. Agronomy, 12(6), 1392.
Ricupero, M., Desneux, N., Zappala, L., & Biondi, A. (2020). Target and non-target impact of systemic insecticides on a polyphagous aphid pest and its parasitoid. Chemosphere, 247, 125728.
Saeed, R., Razaq, M., & Hardy, I. C. (2016). Impact of neonicotinoid seed treatment of cotton on the cotton leafhopper, *Amrasca devastans* (Hemiptera: Cicadellidae), and its natural enemies. Pest Management Science, 72(6), 1260–1267.
Saglam, O., Athanassiou, C. G., & Vassilakos, T. N. (2013). Comparison of spinetoram, imidacloprid, thiamethoxam and chlorantraniliprole against life stages of *Tribolium confusum* Jacquelin du Val (Coleoptera: Tenebrionidae) on concrete. Crop Protection, 53, 85–95.
Santos, M. F., Santos, R. L., Tomé, H. V. V., Barbosa, W. F., Martins, G. F., Guedes, R. N. C., & Oliveira, E. E. (2016). Imidaclopridmediated effects on survival and fertility of the Neotropical brown stink bug *Euschistus heros*. Journal of Pest Science, 89(1), 231–240.
Sappington, J. D. (2018). Imidacloprid alters ant sociobehavioral traits at environmentally relevant concentrations. Ecotoxicology, 27, 1179–1187.
Serikawa, R. H., Backus, E. A., & Rogers, M. E. (2012). Effects of soil-applied imidacloprid on Asian citrus psyllid (Hemiptera: Psyllidae) feeding behavior. Journal of Economic Entomology, 105(5), 1492–1502.
Sheets L. P. (2010). Imidacloprid: A neonicotinoid insecticide. In: Krieger, R. (Ed.). Hayes' handbook of pesticide toxicology. Academic Press. Pp. 2055–2064.
Shekhi Garjan, A., & Mohammadipour, A. (2024). Are insecticidal seed treatments effective on overwintered adults of Sunn pest, *Eurygaster integri-*

ceps (Hemiptera: Scutelleridae)? Journal of Entomological Society of Iran, 44(2), 181–187.
Simon-Delso, N., Amaral-Rogers, V., Belzunces, L. P., Bonmatin, J. M., Chagnon, M., Downs, C., & Wiemers, M. (2015). Systemic insecticides (neonicotinoids and fipronil): Trends, uses, mode of action and metabolites. Environmental Science and Pollution Research International, 22(1), 5–34.
Skouras, P. J., Brokaki, M., Stathas, G. J., Demopoulos, V., Louloudakis, G., & Margaritopoulos, J. T. (2019). Lethal and sub-lethal effects of imidacloprid on the aphidophagous coccinellid *Hippodamia variegata*. Chemosphere, 229, 392–400.
Thiel, S., & Köhler, H. R. (2016). A sublethal imidacloprid concentration alters foraging and competition behaviour of ants. Ecotoxicology, 25, 814–823.
Uhl, P., Bucher, R., Schäfer, R. B., & Entling, M. H. (2015). Sublethal effects of imidacloprid on interactions in a tritrophic system of non-target species. Chemosphere, 132, 152–158.
Ullah, F., Güncan, A., Abbas, A., Gul, H., Guedes, R. N. C., Zhang, Z., ... & Lu, Y. (2024). Sublethal effects of neonicotinoids on insect pests. Entomologia Generalis, 44(5), 1145–1160.
Van Herk, W. G., Vernon, R. S., Tolman, J. H., & Ortiz Saavedra, H. (2008). Mortality of a wireworm, *Agriotes obscurus* (Coleoptera: Elateridae), after topical application of various insecticides. Journal of Economic Entomology, 101(2), 375–383.
Whitehorn, P. R., O'connor, S., Wackers, F. L., & Goulson, D. (2012). Neonicotinoid pesticide reduces bumble bee colony growth and queen production. Science, 336(6079), 351–352.
Wilson, R. G., Orloff, S. B., & Taylor, A. G. (2015). Evaluation of insecticides and application methods to protect onions from onion maggot, *Delia antiqua*, and seedcorn maggot, *Delia platura*, damage. Crop Protection, 67, 102–108.
Wu, C., Zhang, H., He, M., Dong, F., Xu, J., Wu, X., ... & Liu, X. (2021). Toxicity of neonicotinoid insecticides on key non-target natural predator the larvae of *Coccinella septempunctata* in environmental. Environmental Technology and Innovation, 23, 101523.
Xiao, D., Zhao, J., Guo, X., Chen, H., Qu, M., Zhai, W., Desneux, N., Biondi, A., Zhang, F., & Wang, S. (2016). Sublethal effects of imidacloprid on the predatory seven-spot ladybird beetle *Coccinella septempunctata*. Ecotoxicology, 25(10), 1782–1793.
Yu, X. R., Tariq, T., Guo, L. H., Wu, S. Y., Tang, L. D., & Zang, L. S. (2023). Assessing the effectiveness of imidacloprid and thiamethoxam via root irrigation against *Megalurothrips usitatus* (Thysanoptera: Thripidae) and its residual effects on cowpea. Journal of Economic Entomology, 116(5), 1767–1775.
Zhang, Q., Li, Z., Chang, C. H., Lou, J. L., Zhao, M. R., & Lu, C. (2018). Potential human exposures to neonicotinoid insecticides: A review. Environmental Pollution, 236, 71–81.