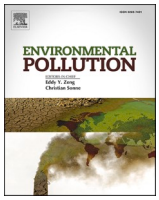
Environmental Pollution 345 (2024) 123466



Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol





Pesticide residues in ornamental plants marketed as bee friendly: Levels in flowers, leaves, roots and soil☆

Tove Porseryd [a,b,*], Kristina Volkova Hellström [b], Patrik Dinnétz [a]

[a] School of Natural Sciences, Technology and Environmental Studies, Södertörn University, Huddinge, Sweden
[b] The Swedish Society for Nature Conservation, Stockholm, Sweden

ARTICLE INFO

Keywords:
Pesticides
Ornamental flowers
Environmental exposure
Bee friendly
Non-target organisms
Floriculture

ABSTRACT

Ornamental plants rich in pollen and nectar are often marketed as "pollinator-friendly" by flower retailers. However, even though the plants are attractive from a foraging perspective, i.e pollen and nectar rich, bees and other pollinating insects could be at risk from exposure of pesticide residues on the plants or from pesticide used during production. Pesticides used in ornamental plant production could lead to environmental emissions both during cultivation, at retailer displays and when planted in gardens by the consumers. This study aims to investigate what pesticides that are used in the production of perennial ornamental plants sold in Sweden and if the residues could pose a risk for wild pollinators. We analyze an array of 536 pesticides in whole flowers, leaves, roots and soil of 54 individual (46 had flowers) perennial plants specifically marketed as "bee friendly". In addition, seeds from 65 seed bags were analyzed for the same pesticides. Our result show for the first time the distribution of pesticide residues between flowers, leaves, roots and soils of ornamental plants. We also show that all ornamental plants analyzed contained at least one pesticide, and that some samples contained up to 19 different substances.

1. Introduction

Pollinating insect populations around the world are facing noticeable declines (Potts et al., 2010; Zattara and Aizen, 2021), ascribed primarily to factors such as habitat loss and degradation, pathogens, and the widespread use of pesticides (Dicks et al., 2021; Goulson et al., 2015; LeBuhn and Vargas Luna, 2021). Specifically, use of neonicotinoids has been cited as one of the main causes for bee population declines. Neonicotinoids are widely used in agriculture around the world, and found in pollen, nectar of crop plants as well as nearby wildflowers (Cecala and Wilson Rankin, 2020). EU recently banned 3 neonicotinoids for all outdoor use due to the negative effects on bees. While the effects of certain neonicotinoids on bees are relatively well-studied, a recent systematic review (Dirilgen et al., 2023) highlighted that the effects of other insecticides are still understudied. There is also emerging evidence that both fungicides and herbicides have negative effects on bees (Cullen et al., 2019). Many studies have focused on insecticides since they are designed specifically to target the biology of insects (Dirilgen et al., 2023). Even if studies of the effects of pesticides on non-target organisms are increasing, there are still many knowledge gaps. For example, we lack studies on the use of synthetic non-neonicotinoid insecticides, bees other than honeybees, sub-lethal effects, and combination effects of pesticides (Dirilgen et al., 2023).

Bees can be exposed to pesticides in several ways when they are foraging and pollinating flowers in agricultural areas. Pesticides have been measured in bees and their colonies in agricultural areas from all around the world. In western France, 37 pesticides, insecticides and fungicides were found in honeybees as well as in honey and in pollen from the hive (Lambert et al., 2013). In 96 %, 72 % and 59 % of the honeybee, honey, and pollen samples, respectively, measurable traces of at least one of the 80 compounds analyzed were found. In North America and Canada, 121 different pesticides and metabolites were found within wax, pollen, bee and associated hive samples from migratory and other beekeepers in 23 states with an average of 6.2 detections per sample. Notable levels up to 214 ppm were found in pollen (Mullin et al., 2010). A study from the UK found that flowering crops and nearby wildflowers were contaminated with a broad range of pesticides, and that the levels were reflected in the honeybees and bumblebees to similar complex mixtures. Pollen collected by both bee species also contained a wide range of pesticides, including fungicides and neonicotinoids. In

☆ This paper has been recommended for acceptance by Jiayin Dai.

* Corresponding author. School of Natural Sciences, Technology and Environmental Studies, Södertörn University, Huddinge, Sweden
E-mail address: tove.porseryd@sh.se (T. Porseryd).

https://doi.org/10.1016/j.envpol.2024.123466
Received 8 December 2023; Received in revised form 24 January 2024; Accepted 28 January 2024
Available online 29 January 2024
0269-7491/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

bumblebees, some fungicides were present at concentrations up to 73 ng/g (David et al., 2016). Adding to the complexity of exposure, different bee species have different foraging patterns, different levels of sociality, floral preference, and nesting behaviors that can affect the risk of exposure to pesticides (Knapp et al., 2023).

Ornamental plant nurseries represent an agricultural sector that remains rather uninvestigated in terms of its impact on local insect populations and compliance with pesticide regulation (Cecala and Wilson Rankin, 2020). Ornamental plants rich in pollen and nectar are often marketed as "pollinator-friendly" by flower retailers (Garbuzov et al., 2017). A survey study from the US showed that labeling the flower with terms such as "bee-friendly" may provide the possibility of setting premium prices. The authors conclude that the marketing phrase "bee-friendly'' has great impact on plant purchases and was the best understood term of those presented (Wollaeger et al., 2015). There are also other studies finding that consumers are willing to pay premium prices for pollinator-friendly attributes (Campbell et al., 2017). Gardening with ornamental plants to attract pollinators is a popular activity for homeowners, organizations, and public authorities (Campbell et al., 2017; Davies et al., 2009; Kalaman et al., 2020). In the face of decreased habitat quality due to urban area expansion into rural environments and agricultural intensification, urban green spaces are becoming progressively more important for native biodiversity. Gardens cover a significant part of urban areas, ranging from 16 % to 36 % (Goddard et al., 2010), and private gardens and public green spaces gardens offer beneficial habitats for pollinators increasing the abundance and activity of insects (Langellotto et al., 2018; Palmersheim et al., 2022; Persson et al., 2023).

Even though ornamental flowers planted to help pollinators can serve as pollinator refuges and are attractive from a foraging perspective to the bees and other insects, they could also be an exposure route of pesticide residues used during their production. There is little information concerning pesticide residues in ornamental plants at the time of purchase, or if pesticide residues pose a threat to pollinating insects or the people handling them. A recent study from the UK investigated 8 insecticides and 16 fungicides in pollen and nectar of 29 different 'bee-friendly' plants. The pesticides analyzed were chosen based on data from local authorities and a report of pesticides commonly detected in greenhouse crops grown or exported to the UK. In this study, only two of the 29 plants were completely free from any of the 24 pesticides that were analyzed. On 23 of the plants more than one pesticide was detected, some with mixtures of up to 10 insecticides and fungicides. Neonicotinoids were detected in over 70 % of the analyzed plants, chlorpyrifos and pyrethroid in 10 % and 7 % respectively. Boscalid, spiroxamine and DMI-fungicides were detected in 40 % of the plants (Lentola et al., 2017).

Pesticides use in floriculture seems to be higher than in food crops and the reasons for this has been cited as differences in pest management goals, application methods and the lack of MRLs (Cecala and Wilson Rankin, 2020; Pereira et al., 2021). For example, neonicotinoids tend to be applied at higher levels in ornamental crops than in food crops (Krischik et al., 2015). A study from Sweden found that greenhouse agriculture contributes to significant environmental levels of pesticides in surface water (Boye et al., 2022). The production of ornamental plants generally appeared to contribute more often to the occurrence of pesticides compared to vegetable greenhouse production. The study concludes that floriculture utilizes higher frequency of pesticide applications and number of substances used, in addition to the year-round production of ornamental plants.

In this study we analyze an array of 537 pesticides in whole flowers buds, leaves, roots and pot-soil respectively, in perennial plants specifically marketed as "bee friendly". This study aims to investigate what pesticides are used in the production of perennial ornamental plants sold in Sweden and if the residues could pose a risk for wild pollinators.

2. Methods

2.1. Choice of plants and sampling

Perennial plants and seeds marketed as "bee friendly" were purchased in June 2022 from 3 different retailers of flowers in the South of Stockholm. One was a local garden center (A), one a commercial chain garden center (B) and one food supermarket with flowers on retail (C). Each plant was bought in duplicates rendering 27 x 2 = 54 flowers (see Table S1). "Bee friendly" was defined as pictures or text depicting the plants as positive for bees. The individual plants with most flowers/flower buds of the plants on display were purchased and brought to the laboratory. All plants were kept at room temperature until the following day when flowers (whole flowers or flower buds) and leaves from each plant were sampled. The plants were afterwards kept in a cool room with a temperature of 6 °C. On day 3 roots and soil from each plant were sampled. Roots were cut off with scissors and the top soil was sampled with a spoon, at least 0.5 g of each was sampled. The samples were kept on ice before being stored in −80 C until analysis.

22 different seed variants in packages were purchased at retailers A, B and C. The seed packages were produced by three different manufacturers, E, F and G (See Table S2). All packages were marketed as bee friendly. Each seed variant/mixture was bought in replicates of two, four or five depending on weight to be able to pool the samples if necessary. However, the content of each seed package was enough to perform individual analysis hence some variants have five replicates. The total number of seed packages that were analyzed individually added up to 65.

2.2. Choice of pesticides

536 pesticide and metabolite substances were included in the analysis (see Table S3 for all substances and respective detection limits, LOQ). The analysis package used was developed by Eurofins food and feed testing Sweden AB for fruits, vegetables, juices, and canned food based on the pesticides that are approved for use in Sweden, approved active substance in the EU, presence on the priority list and substances found in the coordinated European control program. Since there is no comprehensive information of pesticides used in the floriculture sector we made the assumption that this package described above can detect most of the pesticides used in floriculture.

2.3. Pesticide analysis

The pesticides included in the multimethod are detected by GC-MSMS, GC-ECD and LC-MSMS according to the NMKL Method No 195 mod (NMKL, n.d.) In short, after homogenization, extractions are made with ethyl acetate followed by analysis with liquid chromatography (LC) and gas chromatography (GC) allowing for chromatography with tandem mass spectrometric determination. The multi residue method has no need of sample clean-up. To improve the recovery of basic pesticides the addition of sodium hydrogen carbonate (NaHCO3) has been made to all matrices. For detection limit for all pesticides see Supplementary Information Table S1. All sample preparation and chemical analysis were conducted by Eurofins food and feed testing Sweden AB. The laboratories are accredited by SWEDAC (The Swedish board for Accreditation and Conformity Assessment) according to the ISO 17025 standard.

2.4. Categorization and classification of pesticides

2.4.1. CMR

The substances were defined as Cancerogenic (C), Mutagenic (M) or Toxic for Reproduction (R) according to EUs harmonized classification in the CLP Regulation (EC) No 1272/2008.

2.4.2. Authorized for use within the EU

The pesticides were also categorized as: authorized in the EU, not authorized at time of sample purchase, and never been authorized.

2.4.3. Target pests

The pesticides were classified by the intended targeted pest's insecticide, herbicide, arachnicide, growth retardant, or multi if multiple categories of pests are targeted when used. One pesticide, Piperonylbutoxide, was categorized as a synergist. Several metabolites are included in the analysis. The metabolites are not classified further in the analysis except Oxychlordane, the metabolite of Chlordane, which was classified as insecticide.

2.4.4. Harmful to bees

To classify if the substances detected on the plants were harmful to bees several data bases were used. The PPDB: Pesticide Properties Data Base (Lewis, 2011) was screened and the most conservative value from each type of test, oral LD50, contact LD50 and chronic LD50 for all tested bee species was used. For the data sheet from Lewis and Tzilivakis (2019); Lewis and Tzilivakis (2019) data relating to the acute toxicity of pesticides to wild bee species (both topical and oral exposure) from published regulatory documents and peer reviewed literature were presented. To evaluate if a substance was harmful to bees the classification from US EPAs Guidance for Assessing Pesticide Risks to Bees (US EPA, 2014) was used. If any LD50 value found for any of the bee species was under 11 μg/bee the substance was classified as harmful to bees (moderately toxic or highly toxic). US EPA has not extended the classification scheme to also include acute oral endpoints for regulatory purposes, but we have applied also oral data to the scheme. The metabolites are not classified in the analysis. In addition, data from the Swedish chemical agency's (KEMI) risk assessment was also used. If a substance was classified as harmful to bees by KEMI it was considered harmful to bees also in this study, regardless of the published LD50 value in literature.

2.5. Statistical analyses

Data on all detected substances was analyzed both as the mean concentration of each single substance found in the different plant parts [flower, leaf, root, seed, soil], and as the number of substances found on each plant part. Differences in concentrations of all substances among the different plant parts and the soil was analyzed in a general linear mixed models with plant parts and soil as fixed explanatory variable and individual plant and substances as random factors. To allow for better visualization all diagrams presenting mean concentrations are shown with a square root transformed y-axis. We show mean concentrations for all substances with a concentration above the detection limit found on the different plant parts and in the soil in the flowerpots. In these diagrams we also indicate if a substance is bee-friendly, or if the substance is authorized by EU.

Differences in number of substances among plant parts [flower, leaf, root, seed, soil] and among substance type [herbicide, fungicide, insecticide, acaricide, multiple use, avian repellent or synergist, growth regulator, metabolite] was analyzed with generalized linear mixed models assuming Poisson distributed residuals. Flower parts and substance type were included as fixed variables and individual plant was used as random factor to control for dependence among repeated measurements from the same individual plant.

All statistical analyses and visualization were performed in R (R Core Team, 2022) and RStudio using the packages lme4 (Bates et al., 2015), reshape2 (Wickham H, 2016), ggeffects (Lüdecke, 2018), ggplot2 (Wickham H, 2016), Rmisc (Hope, 2022), and doBy (Halekoh, 2023).

3. Results

Out of the 536 pesticides and metabolites analyzed on the plant flowers, leaves, roots, seeds and soil, 61 pesticides and 7 metabolite substances were detected. All plants but one in this study contained at least one substance in either flower, leaf, root or soil. Of the 68 substances detected 21 were categorized as harmful to bees. In addition, 2 pesticides have chronic 10-day LC50 or LDD50 values under 11 μg/bee. Also, one of the metabolites, oxychlordane, a metabolite of chlordane, was only found as a metabolite. Chlordane is regarded harmful to bees with a contact acute LD_{50} 0.6 μg bee^{-1}. In addition, chlordane is listed as a POP under the Stockholm Convention. 23 of the substances found are categorized as CMR; 13 of the cancerogenic, 2 mutagenic and 12 with reproductive toxicity, see Table 1. 15 of the active substances are currently not authorized to be used within the EU, with two of the approvals ceasing in 2021. In addition, 3 of the detected metabolites were of prochloraz which was one of the substances with approval ceasing in 2021. For two of the unauthorized pesticides, thiacloprid and imidacloprid, emergency authorizations were granted by some EU member states in 2021 and 2022 respectively, for use in plants that can be considered ornamental (*Amelanchier alnifolia* and *Helianthus annuus*). However, none of these plants were included in this study. The concentrations from analysis of each plant part and substance are found in Table S5.

The most common group of pesticides found was fungicides followed by insecticides. 29 different fungicides and 20 different insecticides were found across the samples, see Table 2.

The most commonly detected pesticide was the fungicide boscalid, which was found in 97 of the 216 plant and soil samples, and 9 of the seed samples. It was followed by the insecticide pirimicarb, which was found in 35 plant samples and 10 seed samples, and the fungicide pyraclostrobin which was found in 33 plant samples and 2 seed samples (see Table S5).

The sum of the number of substances found in each sample as well as the total concentration of substances per sample and plant are shown in Table S4. The highest number of pesticides found in a single sample was 19, found in the soil of *Buddleja davidii.* Followed by 16 found in the soil of *Gaura lindheimeri.* The highest concentrations of pesticides were in the flower of *Lavendula augustifola* with as much as 159 mg/kg of total pesticides in the flowers. Only one plants sample did not have any measurable pesticides in soil, roots, leaves or flower and that was one sample of Nepeta × faassenii. The other Nepeta × faassenii replicate from the same retailer only contained levels of Boscalid in the soil.

The generalized linear mixed model showed that the number of pesticides differed significantly among plant parts with significantly more pesticides in the soil than in the plant parts or seeds, and significantly less in the seeds than the plant parts or soil (Fig. 1A, Chisq = 151.29, df = 4, $p < 0.001$, Poisson regression with LR-test). There was also a significant difference in number of pesticides per sample among the different pesticide types (Fig. 2, Chisq = 714.86 < 0.001, Poisson regression with LR-test).

There were no significant differences in total pesticide concentrations among the different plant parts or soil (Chisq = l7.696, df = 4, p = 0.103). The main reason for the non-significant result is that the variation in pesticide concentration is very large among the flower samples. Looking at the mean pesticide concentrations per plant part or soil and their standard errors (Fig. 1B), we can see that even if concentrations in roots and seed are not significantly different from concentrations in flowers, they still have much lower concentrations than leaves and soil. The seeds generally contained less pesticide residues than the plant samples, 46 out of 65 samples did not contain any measurable residues at all. The largest number of substances found in the same sample of seeds was 4.

For individual pesticides the concentrations found were highest on flowers followed by leaves, soil, roots, and seeds (Figs. 3 and 4A). However, the number of different pesticides found was highest in the soil followed by roots, leaves, flowers, and seeds (Figs. 3 and 4A). Of the 24 pesticides found on flowers 6 (25 %) where classified as Bee-toxic (Fig. 3A). On leaves there was 10 (31 %) Bee-toxic out of 32 pesticides

Table 1
All the 68 substances that were found in plants, either flower, leaf, root or soil, bought in commercial stores marketed as "bee friendly". The substances were classified as harmful to bees if a LD50, contact or oral, is under 11μ/bee for all bees studied or if it is classified as harmful to bees by the Swedish chemical's agency under their risk assessment. The Substances were also classified as CMR, cancerogenic, mutagenic or reproductive toxicity according to the harmonized classification under Regulation (EC) No 1272/2008 - classification, labelling and packaging of substances and mixtures (CLP). The regulatory status of the metabolites is not classified, hence NA.

Substance	Pests controlled	Harmful to bees	CMR	Regulatory Status in EU
2.4.6-Trichlorophenol	Multiple use		C	Never been authorized
Acetamiprid	Insecticide	YES	R	Authorized
Acetamiprid-N-desmethyl	Metabolite			NA
Anthraquinone	Avian repellant		C	Never been authorized
Avermectin B1a	Insecticide		R	Authorized
Azadirachtin	Insecticide			Authorized
Azoxystrobin	Fungicide			Authorized
Bifenazate	Acaracide	YES		Authorized
Bifenyl	Fungicide			Never been authorized
Boscalid	Fungicide			Authorized
BTS-44595	Metabolite			NA
BTS-44596	Metabolite			NA
Carbendazim	Fungicide		M, R	Not authorized (since 2016)
Cyantraniliprole	Insecticide	YES		Authorized
Cyazofamid	Fungicide			Authorized
Cyprodinil	Fungicide			Authorized
Deltamethrin	Insecticide	YES		Authorized
Difenoconazole	Fungicide			Authorized
Dimethenamid-P	Herbicide			Authorized
Dimethomorph	Fungicide		R	Authorized
Diuron	Herbicide		C	Not authorized (since 2020)
Fenhexamid	Fungicide			Authorized
Fenpyroximate	Insecticide	YES		Authorized
Flonicamid	Insecticide	YES		Authorized
Fludioxonil	Fungicide			Authorized
Fluopyram	Fungicide			Authorized
Flupyradifurone	Insecticide	YES		Authorized
Fluvalinate, tau-	Insecticide			Authorized
Folpet	Fungicide		C	Authorized
Formetanate	Insecticide	YES		Authorized
Imidakloprid	Insecticide	YES		Not authorized (since 2020)
Indoxacarb	Insecticide	YES		Not authorized (since 2021)
Iprodione	Fungicide	YES	C	Not authorized (since 2017)
Isoxaben	Herbicide			Authorized
Lambda-cyhalothrin	Insecticide	YES		Authorized
Lenacil	Herbicide		C	Authorized
mandipropamid	Fungicide			Authorized
Mepanipyrim	Fungicide		C	Authorized
Metalaxy	Fungicide			Authorized
Metazachlor	Herbicide			Authorized
Oxychlordane[a]	Insecticide	YES		NA
Paclobutrazol	Growth regulator	YES	R	Authorized
Penconazole	Fungicide	YES		Authorized
Permethrin	Herbicide	YES	R	Authorized
Pendimethalin	Insecticide			Never been authorized
Piperonyl-butoxide	Synergist			NA
Pirimicarb	Insecticide	YES	C	Authorized
Pirimicarb-desmethyl	Metabolite			NA
Pirimifos-methyl	Insecticide	YES		Authorized
Prochloraz	Fungicide			Not authorized (since 2021)
propamocarb	Fungicide			Authorized
Propiconazole	Fungicide		R	Not authorized (since 2018)
Propyzamide	Herbicide		C	Authorized
Prothioconazole-desthio	Fungicide			NA
Pyraclostrobin	Fungicide			Authorized
Pyrazophos	Fungicide	YES		Never been authorized
Pyretrins	Insecticide	YES		Authorized
Pyrimethanil	Fungicide			Authorized
Quinoclamine	Herbicide		C, R	Not authorized (since 2018)
Spinosad	Insecticide	YES		Authorized
Spirodiclofen	Acaracide		C, R	Not authorized (since 2020)
Tebuconazole	Fungicide		R	Authorized
Tetraconazole	Fungicide			Authorized
TFNA	Metabolite			NA
Thiacloprid	Insecticide	YES	C, R	Not authorized (since 2020)
Thiophanate-methyl	Fungicide		C, M	Not authorized (since 2020)
Tolclofos-methyl	Fungicide			Authorized
Trifloxystrobin	Fungicide			Authorized

[a] Oxychlordane is a metabolite of Chlordane, which is classified as harmful to bees. Chlordane is considered harmful to bees, hence Oxychlordane is considered harmful to bees in this study.

Table 2
Number of pesticide substances grouped by what type of pest/function they have that are found in the plant, either flower, leaf, root or soil and seed samples.

Pest controlled/function	Number of substances found (all samples)
Acaracide	2
Avian repellent	1
Fungicide	29
Growth regulator	1
Herbicide	8
Insecticide	20
Metabolite	5
Multiple use	1
Synergist	1

(Fig. 3B). The percentage of Bee-toxic pesticides was highest in seeds with 42 % (Fig. 4A). The substance with highest mean concentration was Folpet, a fungicide found in high concentrations in flowers and leaves (Fig. 3A and B). Of the 24 pesticides found on flowers 4 was non-authorized by EU (Figure S1A). The two un-authorized substances with the highest mean concentrations were 2.4.6.Trichlorophenol and prochloraz (Figure S1A).

4. Discussion

With this study we show that pesticide application seems to be common practice in the floriculture industry, causing transfer of pesticides to private gardens and public green spaces. In this study. All ornamental plant samples, except for one, from commercial retailers in Sweden contained at least one active substance residue in either flowers, leaves, roots or soil.

This and other studies show that bees are at risk of exposure to a plethora of different pesticides when they forage or nest either in the vicinity of agricultural areas or in gardens. It is known that insecticides can have negative effects on bees (Dirilgen et al., 2023) but evidence suggests that also fungicides and herbicides can have negative effect on bees (Cullen et al., 2019). In this study, 18 of the detected substances were classified as harmful to bees. Two were fungicides and one is a growth inhibitor, the rest were insecticides or acaracides. There is also

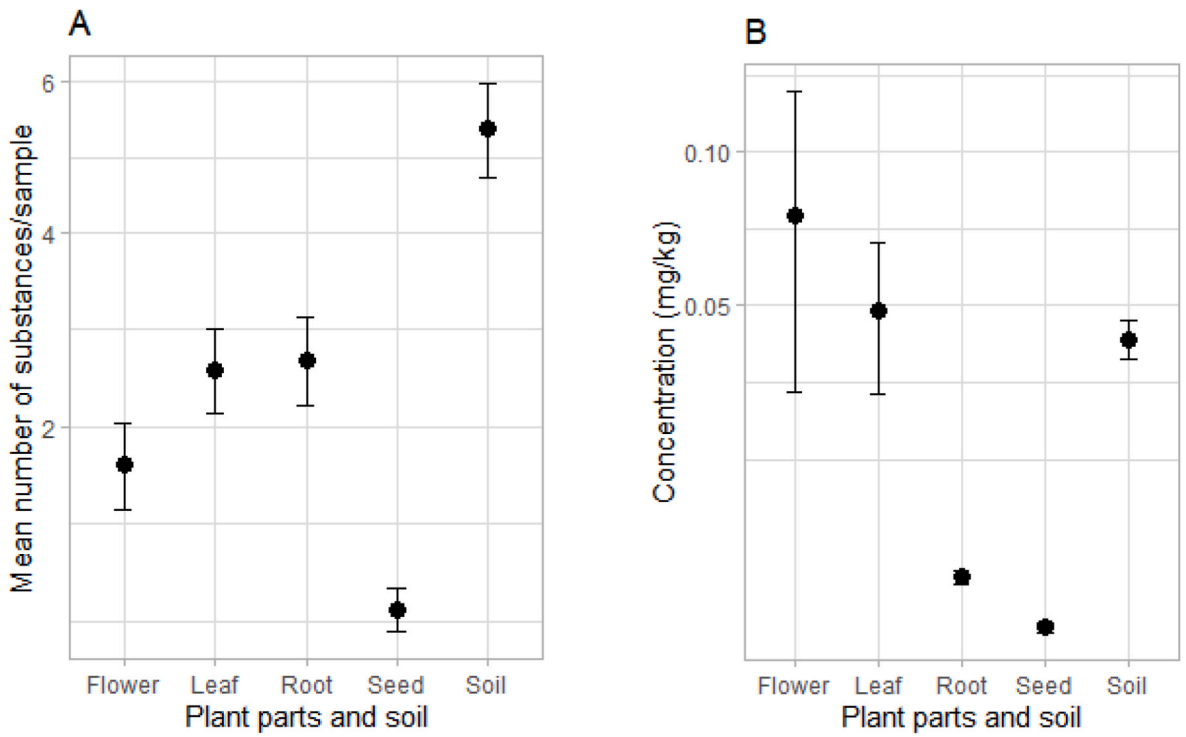


Fig. 1. Mean number of substances found in the flowers, leaves, roots, seed and soil (A). Mean concentration (mg/kg) of all substances found in flowers, leaves, roots, seeds, and soil (B). Error bars denote SE.

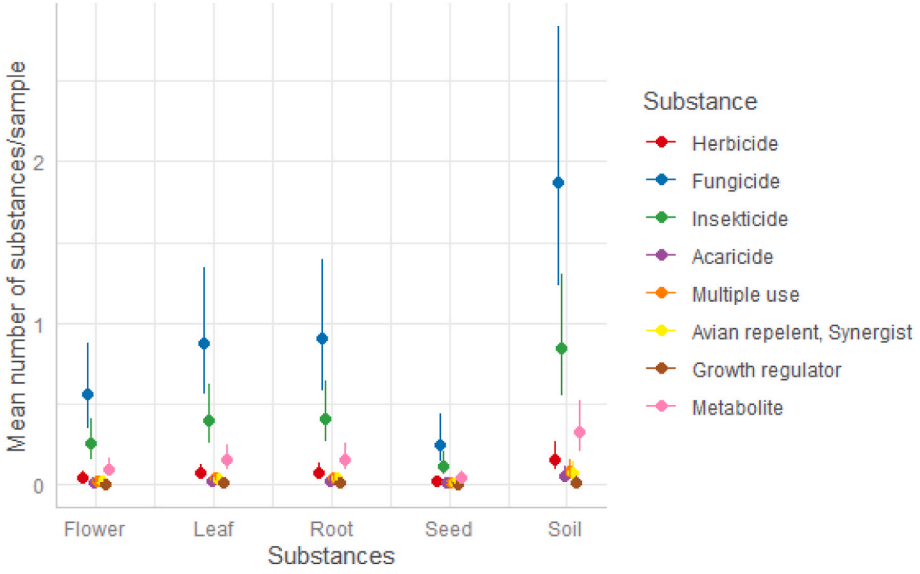


Fig. 2. Mean number of substances found on different plant parts [flowers, leaves, roots, seeds, soil] for different types of pesticide function. Error bars denote 95 % CI.

evidence that pesticides act synergistically and additively (Carnesecchi et al., 2019; Spurgeon et al., 2020). Nicholson et al. (2023) recently showed that in a natural setting the use of pesticides in agriculture results in bumble bees being exposed to several pesticides that reduce colony performance during crop bloom. They also showed a significantly higher risk for negative effects with increasing number of pesticides that the bumble bee colony encountered (Nicholson et al., 2023). In our study we found that one single plant could contain up to 20 different substances several which are considered harmful to bees such as acetamiprid, cyantraniliprole and spinosad. This indicates that also ornamental garden plants substantially can add to the chemical threats to pollinators.

Oxychlordane, a metabolite to chlordane listed in Annex A in the Stockholm convention (UNEP, 2001), was found in several samples of soil and roots of four different plant species. One has a known origin from Denmark, one is from the Netherlands and two are of unknown origin. The fact that oxychlordane was found only in roots and soil could indicate that the substance is a legacy from previous farming, but it cannot be ruled out that use has been intentional during the present plant production. Regardless of why, it is concerning that the metabolite was found in up to 200 ng/g (0.2 mg/kg) in the roots and soil of commercial plants. Previous studies of chlordane in agricultural soils show

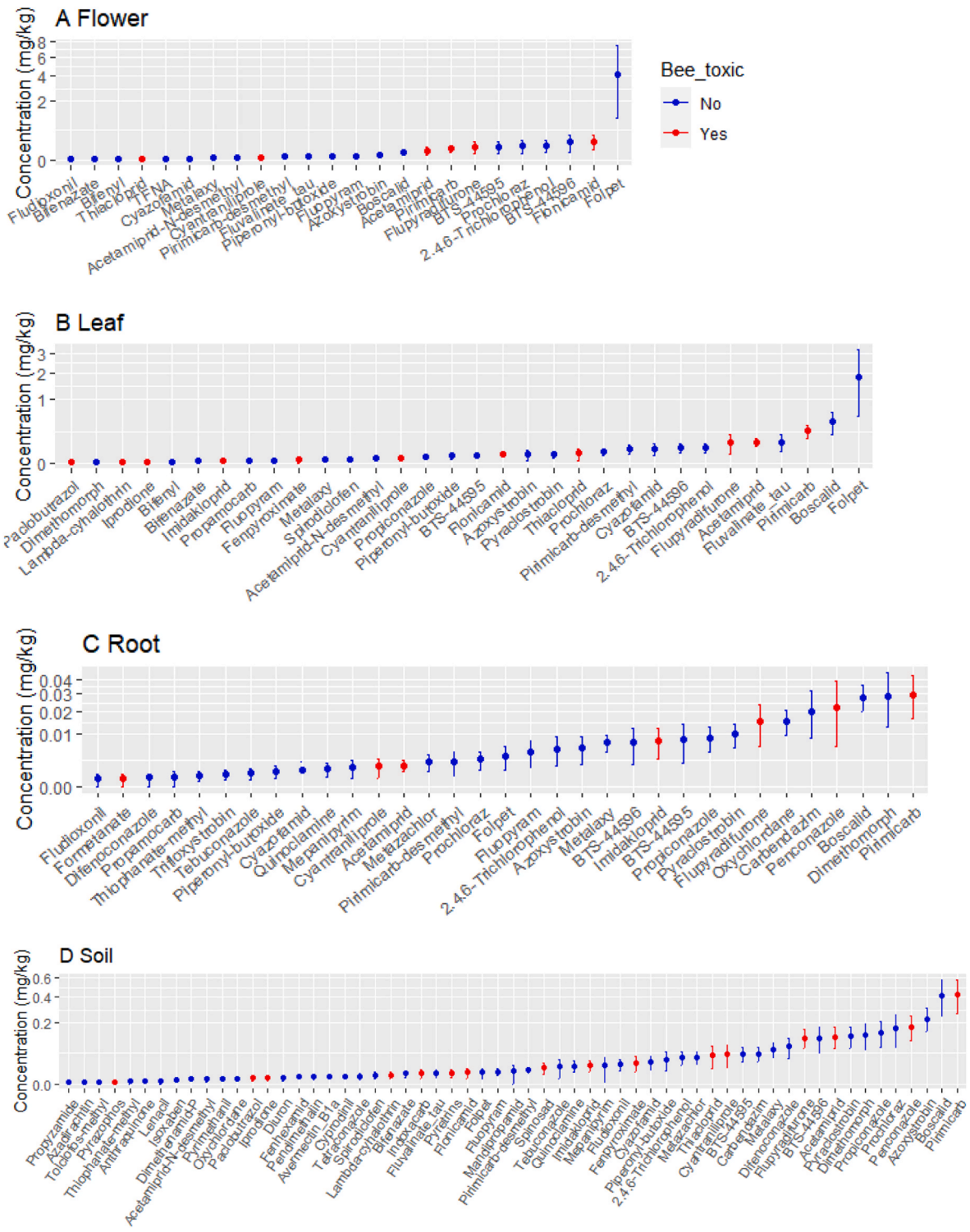


Fig. 3. Concentrations of pesticides found in (A) flowers, (B) leaves, (C) roots, and (D) soil. Pesticides classified according to Bee toxicity [No,Yes]. Error bars denote SE.

legacy residues of 0.2–1.4 ng/g (Kafaei et al., 2020). This may indicate intentional use of chlordane in ornamental plant production. All earlier measures are from agricultural fields growing crops for food consumption suggesting chlordane use has been lower in agriculture than in floriculture due to the MRLs for food. There were 15 substances in this study that are not authorized to be used within the EU. There were no registered emergency authorizations granted by EU member states in 2021 and 2022 for use in plant species that were included in this study. The substances were detected in all parts of the plants and the soil. This indicates that the levels found are not only legacy compounds from previous use, but that the unauthorized substances are used either within the EU or in the exporting third countries. Some of the unauthorized substances were systemic. The presence in leaves and flowers could possibly be explained by uptake through the roots from contaminated soil, and does not necessarily prove intentional use, However, not all of the unauthorized substances were systemic and their presence in

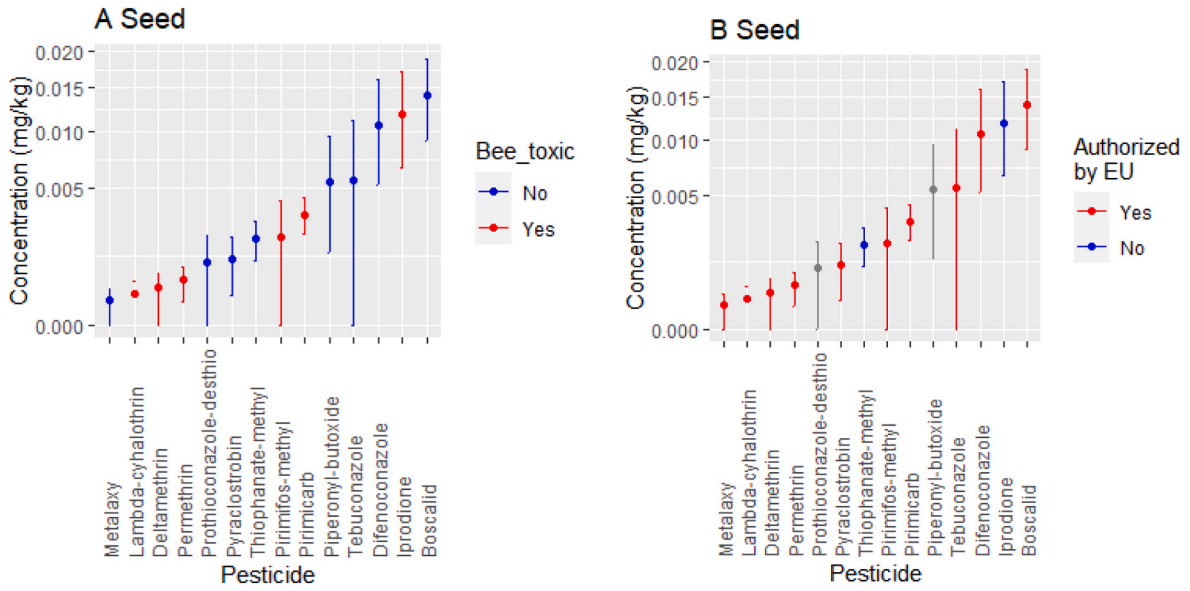


Fig. 4. Concentrations of pesticides found in seeds. (A) Pesticides classified according to Bee toxicity [No,Yes]. (B) Pesticides classified according to authorization to be used in EU [Yes,No], metabolites shown in grey. Error bars denote SE.

leaves and flowers indicates intentional use.

Pirimicarb was found in concentrations up to 4.8 mg/kg in soil, but the most concerning fact was that concentrations of pirimicarb and its metabolite of 3.5 mg/kg were found in leaves of the edible basil, *Ocimum basilicum*. Pirimicarb is not only classified in this study as harmful to bees, but it is also classified by the EU harmonized classification and labelling to be cancerogenic and persistent. The MRL for edible basil in the EU is 0.8 mg/kg. The two basil variants were the only plants marketed as edible in this study.

Carbendazim found in 15 root and soil samples from retailer A has not been authorized for use within the EU since 2014. Carbendazim is not only considered mutagenic and toxic for reproduction (CLP) it was also considered to be toxic to earth worms according to the Swedish Chemicals' Agency. A problem with the contaminated soil in our study material is that the soil samples are from plants that often are replanted in open fields, in gardens and other urban areas together with the soil it is planted in. In general, the soil samples of the plants in this study contained a larger number of pesticides than the rest of the plant parts analyzed. This could be due to the use of different pesticides applied on the plant during different stages of the cultivation period being rinsed off to the soil by irrigation and rain. Still, the highest concentrations of different pesticides were found on leaves and flowers, indicating recent direct application during the latter part of the cultivation period. An additional concern regarding the distribution of the substances is that nine of the substances detected in this study are PFAS according to the OCED definition (Wang et al., 2021). flonicamid, flupyradifurone, indoxacarb and lambda-cyhalothrin are also classified as harmful to bees and as almost all PFAS they are also extremely persistent.

Two neonicotinoids, thiacloprid and imidacloprid, that are banned from use in the EU were found on several plants, both considered as extremely harmful to bees. Thiacloprid was found on the leaves of *B. davidii* in concentrations up to 1.44 mg/kg and in the soil up to 1.40 mg/kg on a plant originating from Denmark. Imidacloprid was found in three plant species with the highest concentration of 0.5 mg/kg in the soil. Acetamiprid, a neonicotinoid substance that is still authorized for use within the EU, was found on 8 plants in concentrations up to 1.4 mg/kg on leaves and 2.4 mg/kg in soil. In this study we classified Acetamiprid as harmful to bees due to the low contact LD50 of 1.72 μg/bee tested for the solitary bee species *Osmia bicornis* (Lewis and Tzilivakis, 2019).

In an earlier study by Lentola et al. (2017) the systemic pesticides found in ornamental plants had a higher detection frequency in pollen compared with leaves, but the concentrations were similar (Lentola et al., 2017). This indicates that systemic pesticides can contaminate pollen, even if the plant was not flowering at the time of applications. Several of the pesticide residues in this study are systemic, but we do not have enough information to estimate the direct risk to bees and other pollinators. The concentrations found in our study are likely not expected to be lethal, but the levels exceed levels that have been found to cause negative non-lethal effects on bees. For example, bumble bee nests fed with pollen and sugar water containing 7 ng/g imidacloprid had a reduced worker foraging efficiency (Feltham et al., 2014) and significantly reduced growth rate as well as reduction in production of new queens (Whitehorn et al., 2012). In our study we found concentrations on leaves of the neonicotinoids imidacloprid and thiacloprod as high as 200 ng/g and 33 ng/g respectively. In the studies of Lentola et al. (2017), the concentrations were similar in pollen and in leaves. We only did whole flower analysis which could have masked the concentrations in pollen by a dilution effect. Therefore bees collecting pollen and nectar could in fact be exposed to higher levels than our analyses indicates.

Several studies from Belgium have shown that the concentration of pesticide residues on cut flowers are high and frequent and pose a risk for florists handling the flowers (Toumi et al., 2020, 2017). Active substances on cut roses reached concentrations about a thousand times higher than the Maximum Residue Limits (MRLs) for the active substances on food stuff (Toumi et al., 2016a) with an average of 14 substances detected per sample (Toumi et al., 2016b). The pesticide residue concentrations found on the cut flowers are similar to the pesticide concentrations on the ornamental plants in this study. The highest concentrations found in this study was Folpet with 137 mg/kg on the flowers of lavender. Folpet is a fungicide and is classified as cancerogenic (CLP). The global decline of pollinators has been explained to be caused partly by the use of pesticides (Dicks et al., 2021; Goulson et al., 2015; LeBuhn and Vargas Luna, 2021). The widespread presence of pesticides in the ornamental plants tested in this study indicates a risk of exposure for non-target organisms such as bees and other pollinators as well as organisms living in the soil in the vicinity of the production site or in the garden where they are planted. Bees could be exposed to the pesticide residues as adults or larvae by ingestion of contaminated pollen and nectar or thorough direct contact on the flowers and leaves. Bumble bees and other bees can nest in the soil or use mud as nesting material. Gardening to promote wildlife such as pollinators including

planting flowers that are friendly for bees is a popular activity (Palmersheim et al., 2022; Persson et al., 2023). The ornamental plants in this study were all marketed by the retailers as "bee friendly". Bee friendly plants are often rich in pollen and nectar and are especially attractive for bees. This study shows that several of the "Be friendly" the plants contained a complex mixture of different pesticides, some at worrying levels. Citizens can act as a positive driver for the very important ecosystem function of pollination and contribute to biodiversity conservation (Patel et al., 2021). Their efforts should not be diminished by pesticide use. The exact consequences for bees exposed to the pesticides through the cultivation of ornamental plants are, cannot be concluded by this study but warrants further investigation.

Ornamental plant nurseries represent an agricultural sector that remains unexplored regarding its support of local insect populations and compliance to pesticide regulation (Cecala and Wilson Rankin, 2020). Previous studies have shown that agricultural greenhouses used for production of ornamental flowers are associated with larger emissions than greenhouse production of vegetable crops (Boye et al., 2022). The larger emissions of pesticides to nearby surface waters were explained to likely be due to a higher frequency of pesticide applications and a higher number of substances used. In addition to the year-round production, in comparison to the more seasonal production of vegetables. There is a lack of legal limits on pesticide residues in ornamental plants which can explain the frequent use of pesticides in floriculture, as well as the transfer of contaminated products between countries (Pereira et al., 2021). In addition, the strict regulation of pest control on imported flowers is most likely acting as a potential driver for overuse of pesticides in floriculture.

5. Conclusions

The results show that ornamental plants marketed as bee friendly on display for sale contain a plethora of pesticide residues. Residues of multiple pesticides are found in flowers, leaves, roots and the soil of the potted plants as well as seeds. Our conclusion is that pesticides that are harmful to bees, unauthorized to be used in the EU and classified as CMR are widely used in the production of ornamental plants. The severity of the risk for bees and other non-target organisms caused by planting purchased ornamental plants cannot be assessed by this study but warrants further investigation.

Funding

The funding for this study was received from an anonymous donor through the Swedish Society for Nature Conservation. The donation was made specifically for this analysis.

CRediT authorship contribution statement

Tove Porseryd: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Kristina Volkova Hellström:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Patrik Dinnétz:** Writing – review & editing, Visualization, Methodology, Formal analysis.

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

Data will be made available on request.

Acknowledgement

We acknowledge the anonymous donor for funding this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.123466.

References

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67, 1–48. https://doi.org/10.18637/jss.v067.i01.
Boye, K., Boström, G., Jonsson, O., Gönczi, M., Löfkvist, K., Kreuger, J., 2022. Greenhouse production contributes to pesticide occurrences in Swedish streams. Sci. Total Environ. 809, 152215 https://doi.org/10.1016/j.scitotenv.2021.152215.
Campbell, B., Khachatryan, H., Rihn, A., 2017. Pollinator-friendly plants: reasons for and barriers to purchase. HortTechnology 27, 831–839. https://doi.org/10.21273/HORTTECH03829-17.
Carnesecchi, E., Svendsen, C., Lasagni, S., Grech, A., Quignot, N., Amzal, B., Toma, C., Tosi, S., Rortais, A., Cortinas-Abrahantes, J., Capri, E., Kramer, N., Benfenati, E., Spurgeon, D., Guillot, G., Dorne, J.L.C.M., 2019. Investigating combined toxicity of binary mixtures in bees: meta-analysis of laboratory tests, modelling, mechanistic basis and implications for risk assessment. Environ. Int. 133, 105256 https://doi.org/10.1016/j.envint.2019.105256.
Cecala, J.M., Wilson Rankin, E.E., 2020. Mark–recapture experiments reveal foraging behavior and plant fidelity of native bees in plant nurseries. Ecology 101. https://doi.org/10.1002/ecy.3021.
Cullen, M.G., Thompson, L.J., Carolan, J.C., Stout, J.C., Stanley, D.A., 2019. Fungicides, herbicides and bees: a systematic review of existing research and methods. PLoS One 14, e0225743. https://doi.org/10.1371/journal.pone.0225743.
David, A., Botías, C., Abdul-Sada, A., Nicholls, E., Rotheray, E.L., Hill, E.M., Goulson, D., 2016. Widespread contamination of wildflower and bee-collected pollen with complex mixtures of neonicotinoids and fungicides commonly applied to crops. Environ. Int. 88, 169–178. https://doi.org/10.1016/j.envint.2015.12.011.
Davies, Z.G., Fuller, R.A., Loram, A., Irvine, K.N., Sims, V., Gaston, K.J., 2009. A national scale inventory of resource provision for biodiversity within domestic gardens. Biol. Conserv. 142, 761–771. https://doi.org/10.1016/j.biocon.2008.12.016.
Dicks, L.V., Breeze, T.D., Ngo, H.T., Senapathi, D., An, J., Aizen, M.A., Basu, P., Buchori, D., Galetto, L., Garibaldi, L.A., Gemmill-Herren, B., Howlett, B.G., Imperatriz-Fonseca, V.L., Johnson, S.D., Kovács-Hostyánszki, A., Kwon, Y.J., Lattorff, H.M.G., Lungharwo, T., Seymour, C.L., Vanbergen, A.J., Potts, S.G., 2021. A global-scale expert assessment of drivers and risks associated with pollinator decline. Nat. Ecol. Evol. 5, 1453–1461. https://doi.org/10.1038/s41559-021-01534-9.
Dirilgen, T., Herbertsson, L., O'Reilly, A.D., Mahon, N., Stanley, D.A., 2023. Moving past neonicotinoids and honeybees: a systematic review of existing research on other insecticides and bees. Environ. Res. 235, 116612 https://doi.org/10.1016/j.envres.2023.116612.
Feltham, H., Park, K., Goulson, D., 2014. Field realistic doses of pesticide imidacloprid reduce bumblebee pollen foraging efficiency. Ecotoxicol. Lond. Engl. 23, 317–323. https://doi.org/10.1007/s10646-014-1189-7.
Garbuzov, M., Alton, K., Ratnieks, F.L.W., 2017. Most ornamental plants on sale in garden centres are unattractive to flower-visiting insects. PeerJ 5, e3066. https://doi.org/10.7717/peerj.3066.
Goddard, M.A., Dougill, A.J., Benton, T.G., 2010. Scaling up from gardens: biodiversity conservation in urban environments. Trends Ecol. Evol. 25, 90–98. https://doi.org/10.1016/j.tree.2009.07.016.
Goulson, D., Nicholls, E., Botías, C., Rotheray, E.L., 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science 347, 1255957. https://doi.org/10.1126/science.1255957.
Halekoh, S.H., 2023. doBy: groupwise statistics, LSmeans, linear estimates. Utilities.
Hope, R.M., 2022. Rmisc: Ryan Miscellaneous.
Kafaei, R., Arfaeinia, H., Savari, A., Mahmoodi, M., Rezaei, M., Rayani, M., Sorial, G.A., Fattahi, N., Ramavandi, B., 2020. Organochlorine pesticides contamination in agricultural soils of southern Iran. Chemosphere 240, 124983. https://doi.org/10.1016/j.chemosphere.2019.124983.
Kalaman, H., Knox, G.W., Wilson, S.B., Wilber, W., 2020. A master gardener survey: promoting pollinator-friendly plants through education and outreach. HortTechnology 30, 163–167. https://doi.org/10.21273/HORTTECH04460-19.
Knapp, J.L., Nicholson, C.C., Jonsson, O., de Miranda, J.R., Rundlöf, M., 2023. Ecological traits interact with landscape context to determine bees' pesticide risk. Nat. Ecol. Evol. 7, 547–556. https://doi.org/10.1038/s41559-023-01990-5.
Krischik, V., Rogers, M., Gupta, G., Varshney, A., 2015. Soil-applied imidacloprid translocates to ornamental flowers and reduces survival of adult coleomegilla maculata, Harmonia axyridis, and Hippodamia convergens lady beetles, and larval Danaus plexippus and Vanessa cardui butterflies. PLoS One 10, e0119133. https://doi.org/10.1371/journal.pone.0119133.
Lambert, O., Piroux, M., Puyo, S., Thorin, C., L'Hostis, M., Wiest, L., Buleté, A., Delbac, F., Pouliquen, H., 2013. Widespread occurrence of chemical residues in beehive matrices from apiaries located in different landscapes of Western France. PLoS One 8, e67007. https://doi.org/10.1371/journal.pone.0067007.

Langellotto, G.A., Melathopoulos, A., Messer, I., Anderson, A., McClintock, N., Costner, L., 2018. Garden pollinators and the potential for ecosystem service flow to urban and peri-urban agriculture. Sustainability 10, 2047. https://doi.org/10.3390/su10062047.

LeBuhn, G., Vargas Luna, J., 2021. Pollinator decline: what do we know about the drivers of solitary bee declines? Curr. Opin. Insect Sci., Special Section on Pollinator decline. human and policy dimensions * Social insects 46, 106–111. https://doi.org/10.1016/j.cois.2021.05.004.

Lentola, A., David, A., Abdul-Sada, A., Tapparo, A., Goulson, D., Hill, E.M., 2017. Ornamental plants on sale to the public are a significant source of pesticide residues with implications for the health of pollinating insects. Environ. Pollut. Barking Essex 228, 297–304. https://doi.org/10.1016/j.envpol.2017.03.084, 1987.

Lewis, 2011. The pesticide Properties DataBase. Chem. Int. – Newsmag. IUPAC 33, 30–31. https://doi.org/10.1515/ci.2011.33.3.30.

Lewis, K.A., Tzilivakis, J., 2019. Wild bee toxicity data for pesticide risk assessments. Data 4, 98. https://doi.org/10.3390/data4030098.

Lüdecke, D., 2018. Ggeffects: tidy data frames of marginal effects from regression models. J. Open Source Softw. 3, 772. https://doi.org/10.21105/joss.00772.

Mullin, C.A., Frazier, M., Frazier, J.L., Ashcraft, S., Simonds, R., vanEngelsdorp, D., Pettis, J.S., 2010. High levels of miticides and agrochemicals in north American apiaries: implications for honey bee health. PLoS One 5, e9754. https://doi.org/10.1371/journal.pone.0009754.

Nicholson, C.C., Knapp, J., Kiljanek, T., Albrecht, M., Chauzat, M.-P., Costa, C., De la Rúa, P., Klein, A.-M., Mänd, M., Potts, S.G., Schweiger, O., Bottero, I., Cini, E., de Miranda, J.R., Di Prisco, G., Dominik, C., Hodge, S., Kaunath, V., Knauer, A., Laurent, M., Martínez-López, V., Medrzycki, P., Pereira-Peixoto, M.H., Raimets, R., Schwarz, J.M., Senapathi, D., Tamburini, G., Brown, M.J.F., Stout, J.C., Rundlöf, M., 2023. Pesticide use negatively affects bumble bees across European landscapes. Nature 1–4. https://doi.org/10.1038/s41586-023-06773-3.

NMKL, n.d, 2013. Nordic Committee on Food Analysis, NMKL Method No 195.

Palmersheim, M.C., Schürch, R., O'Rourke, M.E., Slezak, J., Couvillon, M.J., 2022. If you grow it, they will come: ornamental plants impact the abundance and diversity of pollinators and other flower-visiting insects in gardens. Horticulturae 8, 1068. https://doi.org/10.3390/horticulturae8111068.

Patel, V., Pauli, N., Biggs, E., Barbour, L., Boruff, B., 2021. Why bees are critical for achieving sustainable development. Ambio 50, 49–59. https://doi.org/10.1007/s13280-020-01333-9.

Pereira, P.C.G., Parente, C.E.T., Carvalho, G.O., Torres, J.P.M., Meire, R.O., Dorneles, P. R., Malm, O., 2021. A review on pesticides in flower production: a push to reduce human exposure and environmental contamination. Environ. Pollut. Barking Essex 1987 289, 117817. https://doi.org/10.1016/j.envpol.2021.117817.

Persson, A.S., Hederström, V., Ljungkvist, I., Nilsson, L., Kendall, L., 2023. Citizen science initiatives increase pollinator activity in private gardens and green spaces. Front. Sustain. Cities 4.

Potts, S.G., Biesmeijer, J.C., Kremen, C., Neumann, P., Schweiger, O., Kunin, W.E., 2010. Global pollinator declines: trends, impacts and drivers. Trends Ecol. Evol. 25, 345–353. https://doi.org/10.1016/j.tree.2010.01.007.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL. https://www.R-project.org/.

Spurgeon, D., Lahive, E., Robinson, A., Short, S., Kille, P., 2020. Species sensitivity to toxic substances: evolution, ecology and applications. Front. Environ. Sci. 8.

Toumi, K., Joly, L., Vleminckx, C., Schiffers, B., 2020. Biological monitoring of exposure to pesticide residues among Belgian florists. Hum. Ecol. Risk Assess. 26, 636–653. https://doi.org/10.1080/10807039.2018.1528860.

Toumi, K., Joly, L., Vleminckx, C., Schiffers, B., 2017. Risk assessment of florists exposed to pesticide residues through handling of flowers and preparing bouquets. Int. J. Environ. Res. Publ. Health 14, 526. https://doi.org/10.3390/ijerph14050526.

Toumi, K., Vleminckx, C., Van Loco, J., Schiffers, B., 2016a. A survey of pesticide residues in cut flowers from various countries. Commun. Agric. Appl. Biol. Sci. 81.

Toumi, K., Vleminckx, C., van Loco, J., Schiffers, B., 2016b. Pesticide residues on three cut flower species and potential exposure of florists in Belgium. Int. J. Environ. Res. Publ. Health 13, 943. https://doi.org/10.3390/ijerph13100943.

UNEP, 2001. Stockholm Convention on Persistent Organic Pollutants (POPs). UNEP Chemicals, Geneva.

US EPA, 2014. Guidance for Assessing Pesticide Risks to Bees. Office of Chemical Safety and Pollution Prevention Office of Pesticide Programs Environmental Fate and Effects Division, Environmental Protection Agency, Washington DC; Environmental Assessment Directorate, Pest Management Regulatory Agency, Health Canada. California Department of Pesticide Regulation, Ottawa, CN.

Wang, Z., Buser, A.M., Cousins, I.T., Demattio, S., Drost, W., Johansson, O., Ohno, K., Patlewicz, G., Richard, A.M., Walker, G.W., White, G.S., Leinala, E., 2021. A new OECD definition for per- and polyfluoroalkyl substances. Environ. Sci. Technol. 55, 15575–15578. https://doi.org/10.1021/acs.est.1c06896.

Whitehorn, P.R., O'Connor, S., Wackers, F.L., Goulson, D., 2012. Neonicotinoid pesticide reduces bumble bee colony growth and queen production. Science 336, 351–352. https://doi.org/10.1126/science.1215025.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wollaeger, H.M., Getter, K.L., Behe, B.K., 2015. Consumer preferences for traditional, neonicotinoid-free, bee-friendly, or biological control pest management practices on floriculture crops. Hortscience 50, 721–732. https://doi.org/10.21273/HORTSCI.50.5.721.

Zattara, E.E., Aizen, M.A., 2021. Worldwide occurrence records suggest a global decline in bee species richness. One Earth 4, 114–123. https://doi.org/10.1016/j.oneear.2020.12.005.