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Pesticide usage practices and the exposure risk to pollinators: A case study in the North China Plain

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ABSTRACT

Due to the frequent pesticide applications, bees are suffered from pesticide exposure risks via consumption and direct contact with sprayed drifts. However, if pesticides are misused and the potential exposure risk to bees based on realistic pesticide application data are still little reported. In this study, pesticide application patterns in wheat-maize rotation system, vegetable and apple producing areas, was studied by interviewing farmers in Quzhou County, the North China Plain. The pesticide use status was evaluated by the recommended and actual applied dose and risk quotient (RQ) based Bee-REX model was used to assess the exposure risks of pesticide to bees based on the collected pesticide application data. The results showed that over half (52 %) of farmers in selected sites misused pesticides and orchard owners were frequently misused pesticides. Positive correlations were found between pesticide usage performance and farmers' specialized training experience. Pesticides applied in orchards have caused higher exposure risks to bees with the mean of RQs exceed 120 and 1880 via acute contact and dietary routes, respectively. Pesticide misuse significantly elevates the exposure risk to bees that the mean RQ under misuse scenarios was 5.8 times than that of correct use. Abamectin, fipronil and neonicotinoids contributed most to the pesticide exposure risk to bees. The main findings of this study imply that more sustainable pest and pollinator management strategies, including the moratorium high-risk insecticides and providing diverse flower resources and habitats, are highly needed. Additionally, measures such as implementing farmer educating and training programs should also be put on the agenda.

1. Introduction

Pesticides are used to prevent yield losses caused by pests, weeds and plant diseases and have been widely used worldwide, especially in developing countries (Cooper and Dobson, 2007; Sexton, 2007). Due to the limited knowledge and insufficient training of farmers in developing countries, very few are able to follow the instructions printed on pesticide labels allowing them to handle the pesticides properly (Akter et al., 2018; Sharafi et al., 2018). Consequently, pesticides are often misused by farmers in some ways that frequently apply either excessive or insufficient amounts of these compounds, or using pesticides have been forbidden/restricted by the government.

Bees such as honeybees play an essential role in maintaining diversity of plant species and help to produce valuable products such as jelly, yet the population of bees has been declined over the past decades driven by multiple stressors including pesticides, parasites and limited flowers (Calderone 2012; Goulson et al., 2015; Jiang et al., 2018). The use of pesticides could cause direct toxic effects on bees. Being exposed to insecticides, such as neonicotinoids, can affect bees' ability of disease tolerance and thus makes bees more susceptible to pathogens and other toxic substances (Boncristiani et al., 2012; Di Prisco et al., 2013). It has been proved that the co-occurrence of multiple pesticides, such as

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fungicides and neonicotinoids, can synergistically cause greater toxic effects to bees (Sgolastra et al., 2020). The application of herbicides can reduce the diversity and availability of flowers, leading to monotonous diets of bees that indirectly causing population decline (Goulson et al., 2015). Furthermore, the misuse of pesticides might have higher level of exposure risk to bees. In this case, systemic risk assessment for bees based on the realistic pesticide field application patterns is highly needed.

Bees can be exposed to pesticides in several ways. Pesticides can be sprayed directly on the pollinators or pesticides can drift to pollinator attractive crops (PAC) during periods when bees are likely foraging. Some persistent pesticides sprayed during the pre-bloom foliar applications on PAC may eventually be transferred to pollen and nectar, thus exposing pollinators (EPA, 2014). The abundance of possible exposure routes makes determining total pesticide exposure very difficult. Attempting to track routes via tracing devices or biomonitoring experiments is far too complex for most studies (Colosio et al., 2012). Hence, predictive and quantitative models have been developed to estimate pesticide exposure. PRIMET is one model used to quantify the exposure risk to bees via in-crop and off-crop exposure prediction (PRIMET, 2021). This method was updated by the EU and further revised by the European Food Safety Authority (EFSA) and now provides a cost-effective hazard quotient (HQ) based assessment model for the exposure estimation for honeybees, bumble bees and solitary bees (EFSA, 2013). Another RQ-based model called the Bee REX model estimates exposure through direct contact and dietary processes and was adopted as an exposure risk assessment tool for bees by the Kenyan government and the Environmental Protection Agency (EPA) in the United States (Horst et al., 2019). In the assessment, honeybees (A. mellifera) are selected as surrogates for *Apis* bees and other pollinating insects. This method does not require a complex set of input parameters and can provide estimated HQs for different ages of honeybees and for different exposure routes.

Recent studies found that pesticide misuse has been common in China, particularly in several provinces in south-eastern and southern China in several cereal, vegetable and fruit producing systems (Sun et al., 2019; Zhang et al., 2015a, 2015b). As a major intensive crop production area in China, it is essential for the government and farmers to understand pesticide usage patterns, including the proper use of pesticides, in order to establish more sustainable plant protection strategies. Considering the fact that multiple pesticides are often mixed and sprayed simultaneously, causing exposure risks to pollinators, a comprehensive risk assessment for pollinators based on actual pesticide field spraying patterns is urgently needed. Thus, the main objectives of this study were to: (1) investigate pesticide usage patterns and examine if pesticides were misused in major cropping systems in Quzhou, the NCP; (2) identify the potential driving factors of pesticide misuse and (3) assess the exposure risk of pesticides to pollinators in different cropping systems by Bee-REX model. Based on the risk assessment results, the exposure risks posed to bees from pesticides correctly used and misused were compared.

2. Materials and methods

2.1. Study area

Quzhou county (36°34′45″ N - 36°57′57″ N, 114°50′30″ E - 115°13′30″ E) is a typical agricultural county with a total area of 667 km^2 with farmland accounting for 82.5 % of the area. Located centrally in the North China Plain, the area has a subtropical humid monsoon climate with an annual mean temperature of 13.4 ℃ and an annual average precipitation of 556.2 mm. Grain crops, such as maize and wheat, and vegetables are the dominant crop producing systems. Apple orchards also can be found in a few villages.

2.2. Farmer interviews and data collection

In this study, a standardized questionnaire containing questions related to personal data (Table S1), cropping system, pesticide application pattern, pesticide storage and disposal was used for data collection. In total, 197 farmers growing grain crops, vegetables and apple orchards in 7 villages in Quzhou (Fig. 1) were selected and interviewed in December 2019. In the pesticide application pattern section, respondents were asked to name 1–3 most common pests or plant diseases and further describe how pesticides were used to handle these crop protection issues, including applied dose, active substance concentrations of used pesticides, frequency and application interval. The application rates (AR) were then calculated separately for knapsack spraying farmers and vehicle-mounted pump spraying farmers based on the equations below. To ensure data quality, the application doses were double checked with farmers and incomplete responses were excluded from this study.

$$AR_{Knapsack} = AD_{bottle} \times n \times Fre \times ASC \times 15 \div 1000 \quad (1)$$

$$AR_{Vehicle-pump} = AD_{pump} \times Fre \times ASC \times 15 \div 1000 \quad (2)$$

Here, AD_{bottle} (g or mL, depending on the formulation type) represents applied dose per bottle (15L knapsack) per mu (15 mu equals 1 hectare), $AD_{vehicle\text{-}pump}$ (g or mL) represents the applied dose for one application event for the vehicle-mounted pump, n means number of bottles of mixed solvents applied to treated crops per mu, Fre means the number of times of certain pesticide has been applied in a growing season, ASC represents active substance concentration, 15 is the transfer coefficient of treated area from mu to hectare, 1000 is transfer coefficient from g to kg.

2.3. Pesticide misuse classification

In this study, a set of completed pesticide application data was defined as a case. If the application rate larger than or less than the recommended range, or farmers using forbidden pesticides with high toxicity, the case was then defined as misuse. To better address to what extent pesticides were misused in specific cases, four scenarios related to pesticide use behaviours were established: S1, correct use; S2, only one ingredient was misused; S3, more than one ingredient was misused and S4, forbidden or restricted ingredients were used. To ensure the results representative enough, only the plant protection purposes (PPPs) with 3 or more cases were included in further exposure analysis.

Calculated ARs were compared with the recommended safe ranges found on the labels of the pesticide products. Label information can be found on the information platform (ICAMA, 2020) powered by the Institute Control of Agrochemicals, Ministry of Agriculture and Rural Affairs, P.R. China (ICAMA).

2.4. The Bee-REX model

The exposure risk for pollinators was assessed using the USEPA Bee-REX model (USEPA, 2014). In this study, the assessment procedure included 4 steps: (1) problem formulation, (2) exposure analysis (Tier I assessment), (3) risk characterization and (4) assessment of uncertainties, possible risk mitigation strategies and the need for Tier II assessment. In the Tier I assessment, pesticide application rate and toxicity data such as LD_{50} and no-observed allowance effect level (NOAEL) for bees were used in the model. The risk quotients (RQs) were used as quotients for estimated exposure. Among the calculated RQs for bees in different classes and ages, the highest value was chosen to represent the most conservative exposure risk assessment. Detailed descriptions can be found in the supplementary information (Text S1). Despite the standardized protocol for pesticide chronic exposure test on bees was developed (OECD, 2017), the chronic exposure parameters such as NOAELs (No Observed Adverse Effect Levels) of commonly used

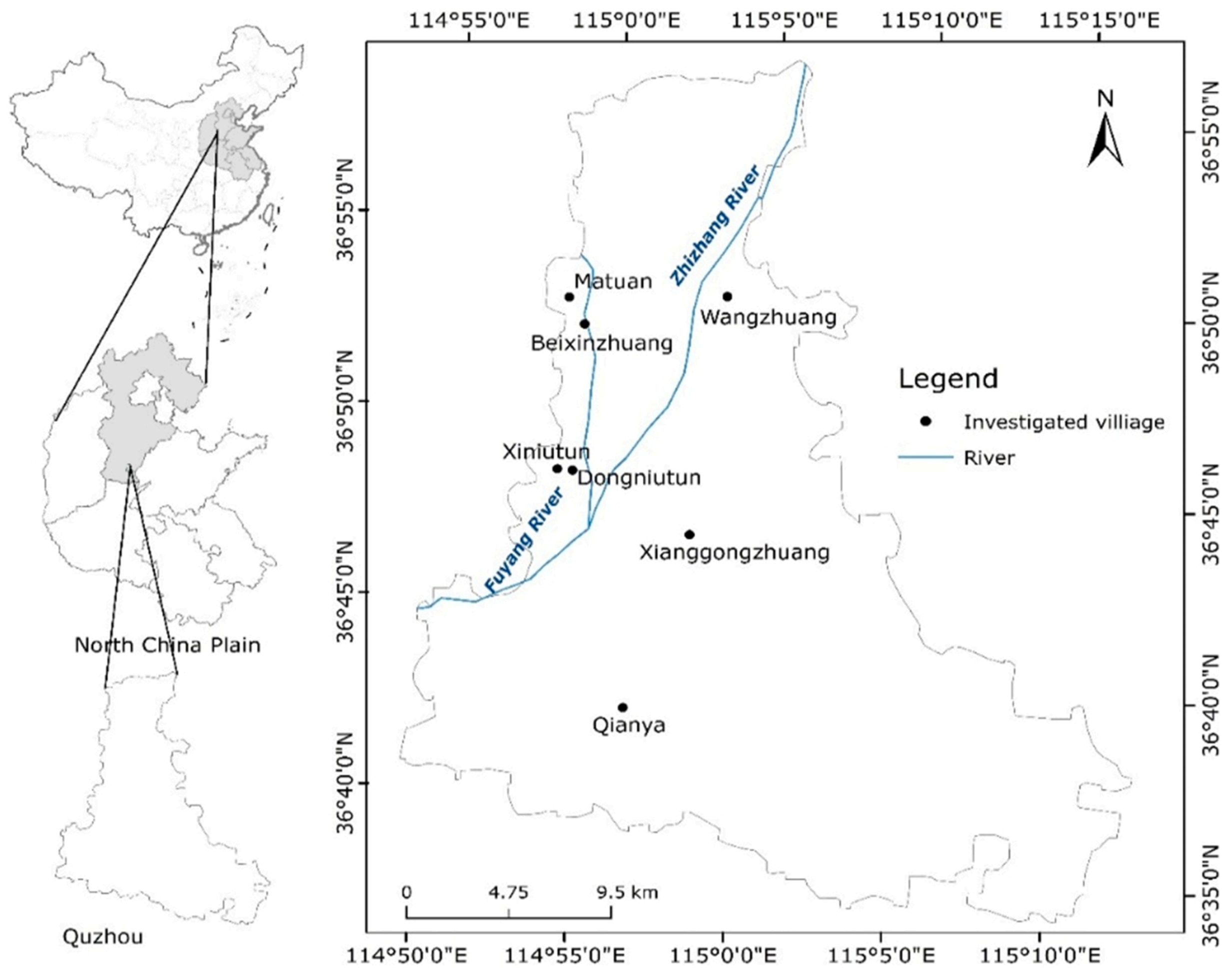

Fig. 1. Study area and the locations of investigated villages in Quzhou county, Hebei province.

pesticides on bees are limited. Thus, in this study, only acute contact and adult dietary exposure for bees could be calculated and assessed. For cases that multiple pesticides were collectively used, the RQs for each pesticide were summed up follow the concentration-addition method, which has been widely used in the ecological risk assessment for multiple pollutants based on the assumption that all the co-exposure effects among pesticide mixtures were addictive effect (Bhandari et al., 2021; Tian et al., 2018). The highest RQs derived from Bee-REX model were then further compared with the level of concern (LOC) value which was 0.4 for acute exposure scenarios. For RQs exceed the LOC, a potential exposure risk can be expected (USEPA, 2014).

To understand possible pesticide exposure risks to pollinators, the degree of hazard of commonly used pesticides was summarized in Table S4. All pesticides listed were found to be hazardous to pollinators via acute exposure and dietary routes. Required toxicity parameters such as LD50 (μg a.s./bee) for acute contact and dietary contact derived from the Pesticide Properties Data Base (PPDB, 2019) are listed in Table S5.

The contributions (%) of each pesticide to the exposure risks were further examined to identify the major risk contributors.

$$Contribution \quad (\%) = \frac{RQ_{mean,\quad i}}{RQ_{total}} \tag{3}$$

Here the $RQ_{mean,i}$ refers to the average RQ for pesticide i, the RQ_{total} refers to the sum of RQs of all involved pesticides.

2.5. Statistical analysis

The Kolmogorov-Smirnov test was performed to identify the normality of the data. The Mann-Whitney U test and t test were conducted to compare the means of ARs of pesticides applied in different cropping systems and RQs posed by each pesticide, exposure routes and pesticide usage scenarios and pesticides applied in different cropping systems.

As a useful tool to extract correlations among or common sources of multivariable by dimension reduction method (Barbieri et al., 2021; Zhuang et al., 2020), principal component analysis (PCA) was performed to identify potential driving factors of pesticide misuse in the present study.

3. Results

3.1. Overview of pesticide usages in Quzhou

In total, 27 insecticides, 8 herbicides and 7 fungicides were used by the interviewed farmers. Spraying a single pesticide to address a specific crop issue was the most common application method used by most farmers in this study. Two or three pesticides were found to be used in cocktails in 35.3 % and 6 % of the collected pesticide application cases.

The fifteen most-used pesticides in this study are listed in Table 1, which includes 10 insecticides, 2 herbicides and 3 fungicides. Among the applied active substances, dimethoate, omethoate and chlorpyrifos were classified as restricted pesticides by the government (MOA, 2017 and 2019). The top five commonly used insecticides cypermethrin

Table 1
Application rates of most-used pesticides for major crop systems based on the farmer interview results.

Pesticide	Chemical group	Use frequency (%)	Application rate (kg a.s. /ha/yr)							
			Overall		Wheat/maize rotation		Vegetables		Orchards	
			Misuse rate (%)	Mean (Range)	Mean (Recommended range)	n	Mean (Recommended range)	n	Mean (Recommended range)	n
I: Cypermethrin	Pyrethroid	55.3	35	0.30 (0.01–2.25)	0.16 (0.02–0.16) b	31	0.41 (0.02–0.20) a	16	0.50 (0.07–0.41) a	13
I: Imidacloprid	Neonicotinoid	51.3	59	0.39 (0.01–2.52)	0.12 (0.02–0.12) b	21	0.67 (0.01–0.18) a	31	0.31 (0.12–0.15) b	9
I: Acetamiprid	Neonicotinoid	41.1	89	0.42 (0.01–2.1)	0.30 (0.03–0.07) a	10	0.44 (0.02–0.11) a	18	0.59 (0.02–0.10) a	10
I: Emamectin Benzoate	Micro-organism derived	32.5	34	0.08 (0.01–0.42)	0.06 (0.02–0.1) b	6	0.11 (0.02–0.1) a	31	0.11 (0.02–0.1) a	7
I: Abamectin	Micro-organism derived	27.4	56	0.11 (0.01–0.58	0.18 (0.018–0.023) a	9	0.16 (0.008–0.011) b	21	0.08 (0.02–0.05) b	6
F: Carbendazim	Benzimidazole	15.7	50	6.52 (1.2–24)	–	–	2.18 (2.04–4.5) a	3	7.30 (0.23–9) a	17
F: Mancozeb	Carbamate	13.2	36	13.35 (7.2–43.2)	–	–	13.13 (1.85–7.11) a	4	13.38 (0.45–14.4) a	10
I: Dimethoate	Organophosphate	13.2	32	1.4 (0.3–5.76)	0.65 (0.45–1.8) b	13	3.84 (0.45–1.8) a	4	–	–
I: Omethoate*	Organophosphate	12.7	75	3.54 (0.24–18)	1.53 (0.6–1.35) a	7	5.60 (NA) a	9		
I: Chlorpyrifos*	Organophosphate	10.2	88	3.61 (0.18–7.2)	0.30 (0.54–1.44) b	3	6.00 (NA)	1	4.94 (0.9–1.2) a	4
F: Tebuconazole	Triazole	8.1	69	6.37 (0.06–19.5)	0.06 (0.08–0.30)	1	1.20 (0.11–0.34) a	3	8.79 (0.30–1.13) a	9
H: Nicosulfuron	Sulfonylurea	8.1	58	0.11 (0.01–0.22)	0.14 (0.05–0.06)	11	–	–	0.09 (0.05–0.06)	1
H: Tribenuron-methyl	Sulfonylurea	7.6	63	0.05 (0.01–0.09)	0.05 (0.01–0.02)	8	–	–	–	–
I: Chlorfenapyr	Pyrrole	7.1	50	0.56 (0.01–1.5)	–	–	0.40 (0.14–0.36) a	8	0.98 (0.11–0.14) a	2
I: Thiamethoxam	Neonicotinoid	7.1	83	0.91 (0.01–2.16)	0.64 (0.54–0.72)	2	0.88 (0.01–0.05) a	8	1.64 (0.05–0.28) a	2

Notation:
I, H and F represent the type of pesticide, namely insecticide, herbicide and fungicide.
*, restricted pesticides that have been banned to be used in vegetable fields.
The recommended application range was derived from label information of pesticide products (ICAMA, 2020).
NA, data not available.

(pyrethroid), imidacloprid (neonicotinoid), acetamiprid (neonicotinoid), emamectin benzoate (Micro-organism derived compounds) and abamectin (Micro-organism derived compounds) were all used by over 25 % of the respondents in all three cropping systems, showing that pest control was the major concern for local farmers in terms of crop protection.

3.2. Pesticide misuse classification

3.2.1. Pesticide misuse in different cropping systems and crop protection purposes

Generally, acetamiprid, omethoate, chlorpyrifos and thiamethoxam were most frequently misused by farmers with the misuse rates above 75 % (Table 1). As shown in Fig. 2, roughly 50 % of farmers growing grain crops and vegetables could spray approved pesticides in a safe range while only 42.9 % of orchard owners could do so. When spraying pesticide cocktails to handle crop issues, around 7 % of grain farmers and 10 % of orchards owners misused all of the ingredients they applied, while the figure for vegetable growers was 15 % (Fig. 2). Also, forbidden/restricted pesticides were used in 8.3 % of the cases of vegetable cultivation. When only one ingredient was used, farmers growing vegetables maintained better habits with regards to pesticide application, using the correct rates, roughly 6 % and 11 % higher than grain crop farmers and orchard owners, respectively (Fig. S1). In cases where two ingredients were used together, nearly half of grain crop growers applied proper doses of pesticide mixtures, with correct use rates 9 % and 23 % higher than vegetable farmers and orchard owners, respectively (Fig. S1). Similarly, compared with vegetable farmers, more grain crop growers could spray appropriate doses when using three ingredients simultaneously.

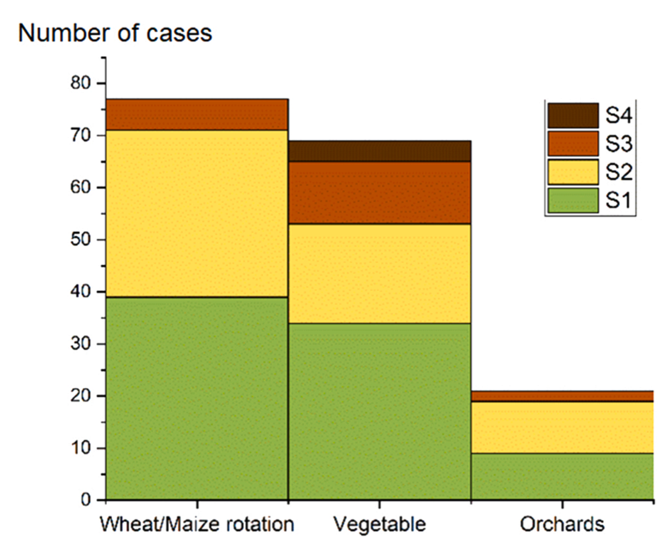

Fig. 2. Number of pesticide usage scenario cases in different cropping systems Note: S1, correct use; S2, one pesticide ingredient was misused; S3, more than one pesticide ingredients were misused; S4, using forbidden/ restricted pesticides.

Omethoate, dimethoate, chlorpyrifos and fipronil were found to be used in grain crop fields, vegetable fields and orchards, although these chemicals have been banned by the government for certain cropping systems (MOARA, 2019) Farmers' pesticide usage strategies for different crop protection purposes were evaluated and summarized (Table S2 and S3). Cases for eliminating aphids and red spiders accounted for 55.7 % and 28.7 % of pest control cases, thus aphids and red spiders were recognized as major pests in this study. In the meantime, *Pieris rapae, Helicoverpa armigera* and *Spodoptera exigua* were recognized as secondary pests. As a most handled insect in the study area, aphid was found to be eliminated by farmers via occasionally spraying restricted/forbidden or overdosed pesticides.

3.2.2. Potential driving factors of pesticide misuse

The Bee-REX model were used to assess the exposure risk of pesticides to bees, addressing a significant higher level of exposure risk when pesticides were misused. To explore the potential driving factors of pesticide misuse, principal component analysis (PCA) was performed to extract the correlations between pesticide misuse and farmers' socio-economic indicators (Table S1). The results shows that 79.9 % of the total variance could be explained by the four extracted principal components (PCs). Pesticide usage (misuse) was found highly correlated with farmers' pesticide specialized training experience due to the similar loading patterns of PC1, 2 and 3 on these two variables (Fig. 3 and Fig. S2). Female farmers were prone to using pesticides correctly during agricultural practices, which may need to be further studied due to the limited samples from female respondents.

3.3. Exposure risks of pesticides to pollinators

3.3.1. Calculated risk quotients (RQs) based on Bee-REX model

To address the exposure risks by pesticides through acute contact and dietary routes, the Tier I assessment based on collected cases was examined using the Bee-REX model. Because toxicity data could be obtained for only a limited range of pesticides, and to cover more cases and provide a more general assessment, the ETEs for pesticides lacking solid toxicity data were simplified to 0 in further analysis.

The RQs for each pesticide being used in more than three cases were extracted and examined (Fig. 3(a)). The results showed that extreme high RQs were found for abamectin with the median value over 300 and 3900 for acute contact and dietary routes (Table 2), followed by

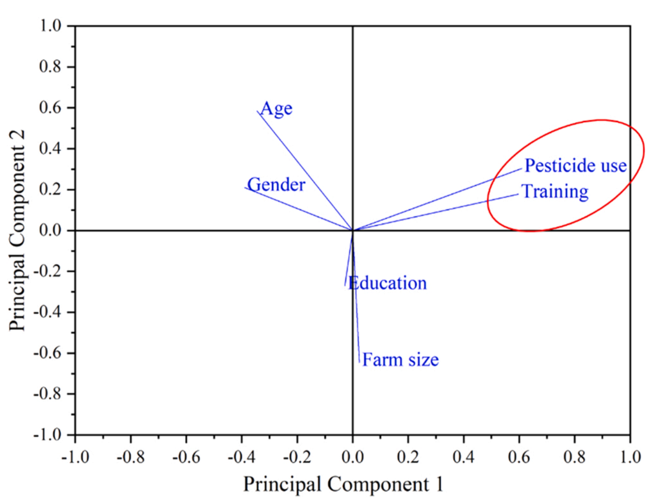

Fig. 3. Biplot of Principal component analysis (PCA) referring pesticide use and the sociological determinants Notes: Age: 1, under 50 years old; 2, 31 - 45 years old; 3, 46 - 60 years old; 61 - 70 years old; 5, older than 70 years old. Education: 1, illiterate; 2, primary school; 3, middle school; 4, high school; 5, higher educated experience. Farm size: 1, less than 2 mu; 2, 2.1 - 3 mu; 3, 3.1 - 5 mu; 4, 5.1 - 8 mu; 5, larger than 8 mu. Gender: 0, female; 1, male. Training: 0, never has been received pesticide related specialized training; 1, has received specialized training. Pesticide use: 0, misuse; 1, correct use.
15 mu = 1 ha.

cypermethrin and thiamethoxam. The RQs for herbicides and fungicides were relatively low, with mean value of RQs all below the LOC. For imidacloprid and omethoate that also being widely used by local farmers, high RQs were also frequently found especially refers to the acute dietary route with the median RQs all exceeds 2000.

Generally, pesticide applications in orchards have caused highest exposure risks to bees whereas the least risk was found for grain producing cases for both acute dietary exposure and direct contact routes (Fig. 4(a) and Table S6). The mean of RQs in vegetable fields were found from 1.2 to 1.5 times than those of grain crop and vegetable cases. There was no significant difference in the RQs for grain and vegetable crop cases when looking at acute contact route. The acute risk posed by dietary exposure was found to be much higher than for direct contact exposure (Table S7). It should also be noted that all calculated RQs through acute dietary route exceed the LOC, while roughly 3 out of 4 RQs in contact route exceed the LOC (Table S7). For different pest control purposes, such as dealing with secondary insects in the vegetable fields, the exposure risk was much lower than in other scenarios (Fig. S3). For both acute dietary and dietary routes, red spider related cases exhibited highest RQs with the mean RQ 1.5–17.6 times than those for other PPPs.

Meanwhile, the assessment results indicate that pesticide misuse caused the higher exposure risks to bees compared to the scenarios that pesticides were correctly used (Fig. 5(b)). The ratio of mean RQs from misuse and correct use of pesticide was 5.8. It is worth noting that most of the RQs calculated based on the recommended doses of each pesticide were exceeded the LOC, with extreme high values detected for insecticides such as abamectin, imidacloprid, dimethoate and thiamethoxam (Table 2).

3.3.2. Contributions of pesticides to the exposure risk

For both acute contact and dietary exposure routes, abamectin was the biggest contributor to the exposure risk, followed by fipronil and neonicotinoids (Fig. 6). As a broad-spectrum insecticide, abamectin has been widely used by local farmers to handle multiple pests such as red spiders and aphids. Similarly, fipronil and imidacloprid were also play an important role in pest control in the case study area.

4. Discussion

This study investigated the pesticide application patterns in Quzhou, the NCP based on field survey and farmer interview. To what extent pesticides were misused by farmers growing different crops and the resulting exposure risk to bees were further examined. The risk assessment results from Bee-REX model revealed that high level of exposure risks posed by insecticides such as abamectin, fipronil and neonicotinoids, furthermore, pesticide misuse has caused elevated exposure risk to bees.

4.1. Pesticides misuse in different cropping systems

Despite studies examined pesticide misuse in certain area are limited, unfortunately, the misuse of pesticides occurs in major crop production systems in China and other countries (Panuwet et al., 2012; Strid et al., 2021; Zhang et al., 2015a, 2015b). In one study, the misuse rates of pesticide cocktails on pests in grain crop fields in south and north China were found to over 52 %, with the misuse rate reaching 90 % when against wheat aphid (Zhang et al., 2015a, 2015b). Same trends were also exhibited by another field survey study that only 54.4 % of observed pesticide application cases can be recognized as correct use. Specifically, when dealing with aphid in tea, cucumber, tomato and apple orchard fields, the misuse rates were all exceeded 75 % (Sun et al., 2019). Much lower misuse frequencies were found in American in terms of red bug control, and the professional pesticide sprayers showed better performance in pesticide correct use (Strid et al., 2021), which is coherent with the positive correlations between pesticide correct use and training

Table 2
Calculated RQs for commonly used pesticides based on the realistic pesticide application data and recommended doses.

Pesticides	Acute contact		Acute dietary		Acute contact	Acute dietary
	RQ (mean)	RQ (median)	RQ (mean)	RQ (median)	RQ range (recommended doses)	
Abamectin	601.52	327.27	7174.11	3902.73	8.73–54.55	104.07–650.45
Imidacloprid	9.76	8.89	2547.95	2320.54	0.30–4.44	77.35–1160.27
Thiamethoxam	37.5	30	2146.4	1717.2	1–72	57.24–4121.28
Omethoate	11.96	9.9	142.59	118.06	NA	357.75–804.94
Dimethoate	11.03	9.45	131.5925	112.69	10.8–43.2	128.79–515.16
Chlorfenapyr	4.5	5.4	53.67	64.4	1.32–4.32	15.74–51.52
Indoxacarb	8.28	6.75	34.05	27.76	2.1–3.6	8.64–14.8
Acetamiprid	0.13	0.13	69.33	62.4	0.006–0.03	0.04–0.22
Cypermethrin	43.47	39.13	0.89	0.89	2.09–42.78	3.33–68.22
Tebuconazole	0.04	0.03	1.16	0.91	0.001–0.014	0.03–0.39
Nicosulfuron	0.06	0.05	9.88	9.2	0.0016–0.0019	0.27–0.33
Atrazine	0.07	0.07	0.87	0.87	0.05–0.07	0.64–0.86

Notation:
NA, data not applicable.

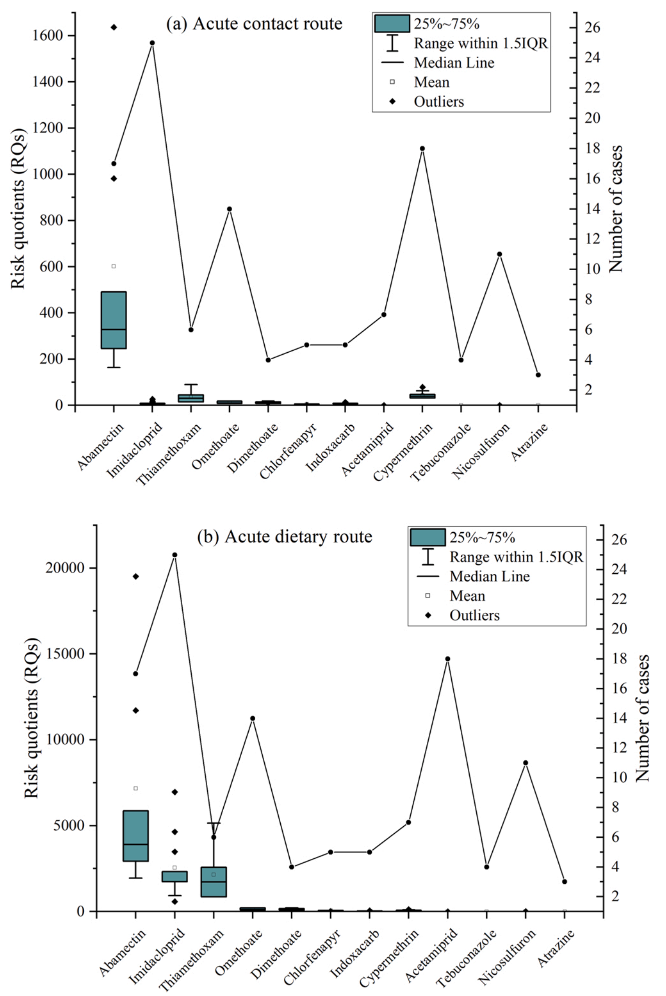

Fig. 4. Calculated risk quotients (RQs) of pesticides based on the Bee-REX model Notes: Only pesticides with usage cases more than three were included in the graph. IQR, interquartile range.

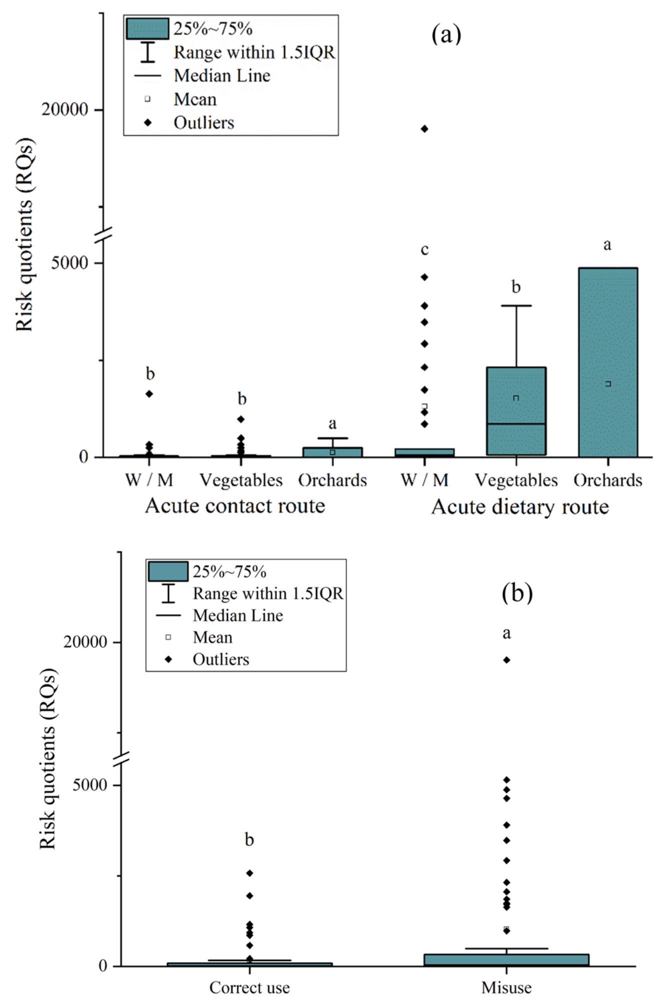

Fig. 5. Risk quotients (RQs) of cases (a) in different cropping systems and (b) under correct use and misuse scenarios Notes: Correct use refers to S1; misuse includes S2, 3 and 4.W/M, wheat/maize rotation; IQR, interquartile range.

experience in our study. Except training experience, farmers' education levels were found negatively associated with their pesticide application performance (Fig. 3). The reason could be explained that farmers with lower educational levels were well connected with the scientific and technology backyards (STBs) in the village and more willing to receive new crop management technologies and sustainable farming perceptions. STBs are non-profit demonstration farming stations focusing on transforming knowledge from the laboratory to the field that could provide farmer educating programs or field sessions related to pesticide use (Zhang et al., 2016). In this case, training and educating sessions from agriculture extension services or other farmer supporting agencies are highly needed to improve the pest management performance and reduce the load of agrochemicals to the environment.

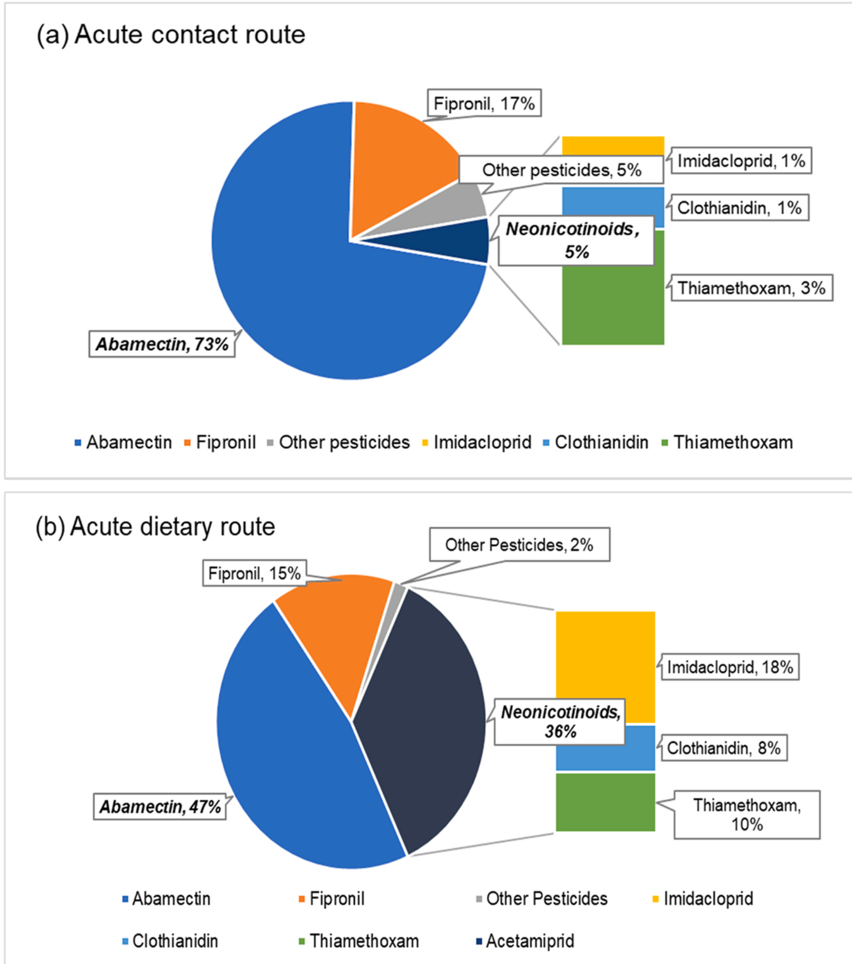

Fig. 6. Contributions (%) of each pesticide to the exposure risk to bees by (a) acute contact route and (b) acute dietary route.

4.2. Implications for systemic risk assessment to bees

Exposure levels for pollinators in actual field conditions were determined in this study despite the fact that the assessment was performed in a most conservative way. The lack of toxicity data on pesticides, especially insecticides, limited the study and may have attributed to uncertainties in the assessment. Field measurements can be carried out to determine residual levels of pesticides in the matrix, such as pollen and nectar, which can reflect the exposure level of bees (Gierer et al., 2019; Jiang et al., 2018). In this case, Tier II assessment based on field sampling and lab measurements was highly needed. With completed assessments, further risk remediation measures can be determined based on local agricultural characteristics.

In field conditions, bees are exposed to multiple pesticides. Except for addictive effects, synergistic effects have been found among commonly used pesticides such as combinations of insecticides and fungicides (Brigante et al., 2021; Christen et al., 2017; Wang et al., 2020). The existence of synergistic effects among field sprayed pesticides could cause greater exposure effects on bees, which should be considered in the development of further risk assessment methods. Bee-REX model takes honey bee A. mellifera as a model for other pollinator species, yet the sensitivities to pesticides differ among different species (Del Sarto et al., 2014; Sgolastra et al., 2020). For instance, non-Apis bees are more susceptible to neonicotinoids, one of the major risk contributors in the present study, than honey bees (Arena and Sgolastra, 2014), which potentially increases uncertainties of risk assessment results. It is reported that bumblebees suffered higher dose of pesticide exposure through diet and contact route, indicating that the risk assessment results taking honeybees as a model of bee species might not protective enough for bumblebees (Gradish et al., 2019). Thus, more systematic risk assessment models that provide most conservative results covering more bee species are required (Gradish et al., 2019).

This study assesses the acute exposure risks of pesticides to bees, while the assessment for chronic exposure scenarios should also be performed once the test data is available to present more comprehensive first Tier assessment results (Thompson and Pamminger, 2019). Given that some pesticides can potentially cause sublethal effects such as impaired performance in learning, orientation and reproduction, multi-dimensional criteria integrating essential sublethal consequences should also be considered in the future risk assessment (Sgolastra et al., 2020). To develop more holistic risk assessment methods, ecotoxicology tests for sublethal effects among commonly used pesticide combinations for different bee species are highly needed.

4.3. Implications for more sustainable management of pests and bees

The findings of this study indicated that the toxicity of pesticides to bees is the dominant factor to the exposures, while the pesticide misuse could significantly elevate the exposure level. Broad spectrum insecticides such as abamectin and neonicotinoids have been commonly used by local farmers, yet extreme high level of exposure risks was caused even if the applied doses were complied with the label instructions (Fig. 5 and Table 2). As the biggest risk contributor in the present study, abamectin was recognized as highly hazardous to bee populations with high mortalities via oral route exposure (G. Li et al., 2022). As major risk contributors, neonicotinoids were known that capable to hinder colony growth and queen production, causing reduction of bees population (Gill et al., 2012), for which the outdoor spray of these chemicals were banned by the EFSA (EFSA, 2018). In field condition, the co-existence of neonicotinoids and fungicides might pose synergistic effects enlarging the hazard to bees. In another study, imidacloprid and thiamethoxam were also assessed to impair honeybees based on measured concentrations in pollen, nectar and leaves (Jiang et al., 2018). In the present study, these high toxic pesticides were also frequently misused by farmers causing significantly higher RQs compared with RQs under correct use scenarios. Due to the high toxicity to bees, the use of these compounds in field spray should be banned and replaced by alternatives such as low-toxic insecticides or biopesticides.

Other than the moratorium of the high-risk insecticides in the outdoor spray, field measures should also be implemented to maintain the growing and diversity of bee population. Additional habitats along with a diverse planting of flowers or pollinator attractive crops should better be provided around the edge of orchards or farms in order to effectively facilitate the abundance of bee species (Biddinger and Rajotte, 2015). Meanwhile, comprehensive approaches such as the application of plant defense inducers and natural enemies of insect pests can efficiently protect the crop and ensure the ecological safety (X. Li et al., 2022).

5. Conclusions

This study investigated pesticide usage patterns and evaluated pesticides status by farmers in three cropping systems (i.e., wheat/maize, vegetable and apple) via farmer interviews in Quzhou county, the North China Plain. Based on the collected data, the exposure risk to bees from pesticide mixtures was further assessed based on the Bee-REX model. The main findings and conclusions are as following:

- Over 50 % of the farmers misused pesticides in Quzhou, NCP. Pesticides were more frequently misused by orchard owners.
- Farmers' pesticide usage performance is positively associated with the specialized training experience.
- Pesticides applied in orchards have caused higher exposure risks to bees with the mean of RQs exceed 120 and 1880 via acute contact and dietary routes, respectively. Pesticide misuse significantly elevates the exposure risk to bees that the mean RQ under misuse scenarios was 5.8 times than that of correct use. Abamectin, fipronil and neonicotinoids contributed most to the pesticide exposure risk to bees.

Based on the findings, we suggest that more sustainable pest and pollinator management strategies should be developed through moratorium high-risk insecticides and providing diverse habitats and flowers for bees along the fields. Specialized training and field school sessions are highly needed from both the government and agricultural extension services especially to orchard owners. Additionally, more systemic risk assessment methods integrating the synergistic effects of pesticides, sublethal effects and susceptibilities of different groups of bees are highly needed to address the realistic pesticide co-exposure risks to bees under field conditions.

CRediT authorship contribution statement

Hongyu Mu: Investigation, Formal analysis, Visualization, Writing – original draft. **Kai Wang:** Supervision, Writing – review & editing. **Xiaomei Yang:** Supervision, Writing – review & editing. **Wen Xu:** Project administration. **Xuejun Liu:** Supervision, Writing – review & editing. **Coen J. Ritsema:** Supervision, Writing – review & editing. **Violette Geissen:** Supervision, Writing – review & editing.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2022.113713.

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