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REVIEW ARTICLE

Neonicotinoids as emerging contaminants in China's environment: a review of current data

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Abstract

Neonicotinoids (NEOs), the most widely used class of insecticides, are pervasive in the environment, eliciting concerns due to their hydrophilicity, persistence, and potential ecological risks. As the leading pesticide consumer, China shows significant regional disparities in NEO contamination. This review explores NEO distribution, sources, and toxic risks across China. The primary NEO pollutants identified in environmental samples include imidacloprid, thiamethoxam, and acetamiprid. In the north, corn cultivation represents the principal source of NEOs during wet seasons, while rice dominates in the south year-round. The high concentration levels of NEOs have been detected in the aquatic environment in the southern regions (130.25 ng/L), the urban river Sects. (157.66 ng/L), and the downstream sections of the Yangtze River (58.9 ng/L), indicating that climate conditions and urban pollution emissions are important drivers of water pollution. Neonicotinoids were detected at higher levels in agricultural soils compared to other soil types, with southern agricultural areas showing higher concentrations (average 27.21 ng/g) than northern regions (average 12.77 ng/g). Atmospheric NEO levels were lower, with the highest concentration at 1560 pg/m^3. The levels of total neonicotinoid pesticides in aquatic environments across China predominantly exceed the chronic toxicity ecological threshold of 35 ng/L, particularly in the regions of Beijing and the Qilu Lake Basin, where they likely exceed the acute toxicity ecological threshold of 200 ng/L. In the future, efforts should focus on neonicotinoid distribution in agriculturally developed regions of Southwest China, while also emphasizing their usage in urban greening and household settings.

Keywords Neonicotinoids · Sources · Occurrence · Regional difference · Ecotoxicity

Introduction

Neonicotinoids (NEOs), following organophosphates, pyrethroids, and carbamates, are widely used globally and control pests like aphids and whiteflies (Elbert et al. 2008). NEOs have been registered in more than 120 countries and already accounted for approximately 25% of the global pesticide market in 2014 (Bass et al. 2015). As the world's top user of pesticides, China had an annual cultivated area exceeding 150 million hectares and an annual demand for pesticides above 273.3 thousand tons (FAO 2023).

The first generation of neonicotinoid insecticide imidacloprid (IMI) was put on the market in 1991 (Jeschke et al. 2011). Subsequently, several other neonicotinoids such as nitenpyram (NIT), acetamiprid (ACE), thiamethoxam (THIM), clothianidin (CLO), thiacloprid (THID), and dinotefuran (DIN) were developed and released into the market between 1995 and 2002 (Bass et al. 2015). China has independently innovated and synthesized a new generation of neonicotinoids: Imidaclothiz (IMIZ), Cycloxaprid (CYC), Guadipyr (GUA), Paichongding (IPP), and Cycolxylidin (CYCN) (Tan, 2023). Currently, the new generation of neonicotinoids was only used in China and has not been registered in the USA or the European Union (Thompson et al. 2020).

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According to the current publications, neonicotinoids could be harmful to non-target beneficials (e.g., pollinators and insectivorous birds) and inhabitants (e.g., earthworms and fish) (Hallmann et al. 2014; Hano et al. 2019; Rundlöf et al. 2015; Wang et al. 2015). Mounting studies showed that neonicotinoids can lead to the decline of bee populations (Rundlöf et al. 2015; Wang et al. 2020; Woodcock et al. 2016), which subsequently resulted in the reduction of food production (Klein et al. 2007) and losses of bee biodiversity (Woodcock et al. 2016). Especially, the new generation of neonicotinoids may indicate increased toxicity. For instance, GUA is highly toxic to silkworms and honeybees (Li et al. 2016), whereas CYC, IPP, and IMIZ exhibit lower LC_{50} values in zebrafish compared to traditional neonicotinoids (Wang et al. 2023b). Notably, neonicotinoids can enter the human body through diets, causing potential chronic risks (e.g., hepatotoxicity, neurotoxicity, genotoxicity, and endocrine-disrupting effect) (Han et al. 2018; Zhang and Lu 2022).

Neonicotinoids are widely used in agriculture including foliar sprays, seed treatment, and soil drenches (Alford and Krupke 2019), and also used as household pesticides and veterinary drugs (Simon-Delso et al. 2015). However, the majority of neonicotinoids are released into the environments with a small amount left being absorbed by the targeted plants or animals (Sur and Stork 2003). Previous studies found that only 1.6–4.9% of IMI was absorbed by cotton, eggplant, potato, and rice during seed dressing or particle seeding (Canadian Council of Ministers of the Environment, 2007; Wood and Goulson 2017), and the majority of IMI was released into soils (He et al. 2021; Naumann et al. 2022). Due to its high hydrophilia, neonicotinoids in the soil and the atmosphere can enter the aquatic environment through precipitation. Although some neonicotinoids are restricted in some countries (CCME 2007; Pietrzak et al. 2019; EU 2013), they are widely detected and exist in the environment (Bradford et al. 2018; Hladik and Kolpin 2016; Starner and Goh 2012). For example, concentrations of neonicotinoids were 343 ± 210 ng/L along the east coast of China (Chen et al. 2019b), which is significantly higher than the acute and chronic toxicity levels (200 and 8.3 ng/L) of the aquatic environment in Europe (Borsuah et al. 2020). The new generation neonicotinoid insecticide, IMIZ, has even been detected in the surface waters of the Yangtze River basin and Beijing (Chen et al. 2019a, 2023; Li et al. 2022), with an average concentration reaching up to 27.49 ng/L (Chen et al. 2023), approaching the residue levels of earlier generations of neonicotinoids. It is important to identify the concentration, biotoxicity, and ecological risks of neonicotinoids in the ecosystems.

There have been some works in the literature on neonicotinoids in aquatic ecosystems or other environmental metrics in China. However, there are diverse climate types across the country, especially the northern regions and the southern regions, which lead to diverse planting cycles, crop types, and neonicotinoid applications. The neonicotinoids sources and distribution caused by the regional differences have little been systematically summarized. This study aims to (1) summarize the dominant sources of neonicotinoid insecticides, from the aspects of the agricultural and urban activities in China's environment; (2) clarify the spatial distribution of neonicotinoid insecticides; and (3) elucidate the effects of neonicotinoid insecticides on organisms and the ecological risks.

Methodology

This article employs the keywords neonicotinoids, insecticides, soil, surface water, atmosphere, agriculture, urban, ecological risk, and biological toxicity to conduct a literature search on the presence of neonicotinoids in China's environment from 2016 to 2023. The trend in the number of publications retrieved from the search is shown in Fig. 1. The search encompasses databases such as Web of Science, Google Scholar, PubMed, ScienceDirect, and other online resources. Utilizing the data obtained from these searches, the article analyzes the origins of neonicotinoids in China's agricultural and urban settings and their distribution across

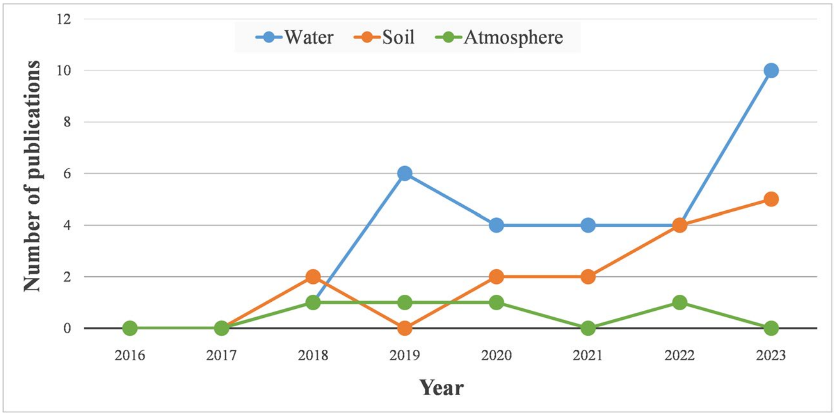

Fig. 1 Number of studies on the detection of neonicotinoids in various media in China from 2016 to 2023

soil, water, and atmospheric media, as well as their toxicological impacts on living organisms and the associated ecological risks.

Sources of neonicotinoids in China's environment

Agricultural sources

In China, abundant resources allow for the cultivation of a variety of crops, with corn leading in the cultivation area, followed by rice, accounting for 25.33% and 17.32% of the total cultivated area, respectively (National Bureau of Statistics of China 2023). Neonicotinoids are applied to corn mainly through seed coating or mixing with seed, while rice is primarily treated with pesticide sprays. The pollution characteristics of neonicotinoids in the soil environment are affected by the different periods and types of pesticide application for these main crops.

Corn is typically planted once a year, with sowing times ranging from March to May in northern regions of China. Thus, this is also an explanation for the high NEO value in summer in northern regions (Huang et al. 2022). In the southern tropical regions, it can be planted twice a year, with the second planting in October and November. The total neonicotinoid concentration in cornfields tends to increase in the first 5 weeks after planting, especially after rainfall (Schaafsma et al. 2015). THIM and CLO are commonly used as seed treatments for corn (Ding et al. 2018). As reported in previous research, THIM can be spread to 30 cm deep on the eighth day after sowing through seed coating (Radolinski et al. 2018). Most of the THIM remains in the 0–30 cm soil layer by the 33rd day, although it could reach a larger depth of 30–45 cm (Radolinski et al. 2018).

In China, rice cultivation typically begins in spring, occurring once in northern regions and two to three times in southern regions. Neonicotinoids are heavily used at the beginning of rice planting to eliminate overwintering pests. Common pests are the rice stem borer, rice planthopper, and rice leaf folder, which account for 86.3% of the total area affected by rice pests and diseases. These pests are targets for neonicotinoid control, with the main pesticide used dinotefuran (Sun et al. 2016). Therefore, the levels of dinotefuran in the effluent from Poyang Lake rice fields reached up to 802 ± 139 ng/L (Wang et al. 2023a). Due to the predominance of coarse-stemmed, large-eared varieties, the fields are densely planted and could create a microclimate conducive to pest and disease occurrence. The application cycle of pesticides applied to rice is closely related to the growth cycle of rice. In the process of controlling rice pests, neonicotinoids contaminate non-target areas due to inefficient pesticide application and pesticide drift problems (Wang et al. 2022). China's manual spraying machinery accounts for 80% of the market (He 2019), and the pesticide utilization rate is less than 41% as of 2020 (Ministry of Agriculture 2015). The spraying drones used to improve work efficiency caused serious pesticide drift, and pesticide droplets were still detected 17 m downwind (Yan et al. 2021).

Urban sources

Urban greening activities are the second largest non-point source of neonicotinoids after agricultural activities. The usage of chemical pesticides during urban municipal pest control in lawn turf, gardens, and parks was 10 times higher than that in agriculture (Meftaul et al. 2020). In addition, neonicotinoids were used in municipal pest control, such as ant, cockroach, and fly bait products, and in the veterinary field, such as treating lice on pets (Shao et al. 2013).

According to data from the Chinese Statistical Yearbook, the urban green space area increased from 865,000 hectares in 2000 to 3.586 million hectares in 2022, appearing a 3.14-fold increase in the 20 years. The park area also grew from 82,000 hectares to 623,000 hectares. There are numerous types of pests and diseases in ornamental plants. Aphids and scale insects are the primary targets for neonicotinoid control. Due to different climatic conditions and natural environments, the manifestation of pests and diseases can vary in different seasons and regions. Aphids are widely distributed throughout the country and can reproduce to cause damage all year round under suitable conditions, affecting herbaceous flowers in summer and autumn and woody plants in April and May. However, scale insects mainly occur in southern China, parasitizing on woody plants. Ornamental plants may be an important pathway for the influx of neonicotinoids from outside urban areas, with mean neonicotinoid concentrations in the leaves of different ornamental plants ranging from 1.7 to 34 ng/g (Lentola et al. 2017). Spring overwintering pest control in parks also leads to neonicotinoid pollution, with an average concentration of 102 ng/g in park soil during spring, higher than 50.4 ng/g in autumn (Zhou et al. 2021). As a result, the increase in green spaces could lead to an increase in the use of neonicotinoid insecticides. However, there is currently no statistical data on the quantities of neonicotinoids used in urban greening (Zhang 2022).

Neonicotinoids in urban sewage typically originate from pet flea treatments, horticulture, and household pest control products (Sadaria et al. 2016). Urban sewage treatment plants (STPs) currently do not have specific and efficient methods for addressing the migration and transformation of neonicotinoids. Conventional sewage treatment processes such as the activated sludge process, A2/O process, and oxidation ditch are not effective in removing neonicotinoids (Campo et al. 2013). The treatment technologies commonly used in Chinese sewage treatment plants include biological wastewater treatment methods, especially the activated sludge process. Sludge adsorption is a major removal pathway for neonicotinoid insecticides in urban sewage treatment systems, with an average adsorption rate of 41% during the anaerobic phase. However, the overall removal rate was only 1% due to desorption that may occur during the anoxic and aerobic phases, resulting in a decrease in the concentration of neonicotinoid insecticides in the sludge (Sun et al. 2021). The low removal rate results in higher concentrations of neonicotinoids in the effluent. For example, IMI was detected at concentrations of 45–106 ng/L in the effluents of municipal STPs in Beijing (Qi et al. 2015). In addition, wastewater from food, beverage, and raw material processing facilities is also an important source of neonicotinoids in the environment (Hubbard et al. 2022).

Occurrence of neonicotinoids in China's environment

Neonicotinoids in the water

Regional occurrence

The water solubility of neonicotinoid pesticides allows them to be detected in diverse water environments throughout China, with concentrations ranging from not detected (ND) to 3543.85 ng/L (Table 1). However, the majority of detected levels are below 100 ng/L. Chinese researchers have focused their studies primarily on inland rivers, particularly in the southern, eastern, and central regions of the country, especially in the Yangtze River Basin and Pearl River Basin (Fig. 2). The detection in small watersheds is still relatively sparse, especially the research on surface water in the southwestern region, which has only involved sampling in the Yangtze River. Research on marine environments and groundwater regions is scarce. The author has created a bar graph depicting the detection of these pollutants in different regions of China, as shown in Fig. 3.

Spatial and seasonal distribution

According to the current data (Fig. 3), the detection of neonicotinoids in urban river Sects. (157.7 ng/L) was 3.73 times higher than in other river Sects. (42.3 ng/L). Among urban river sections, the highest average detection concentration was found in Beijing (446.67 ng/L), followed by Guangzhou (190.97 ng/L), and Changzhou Wujin District, northwest of Lake Taihu (88.86 ng/L) (Fig. 3). This confirms that the application of neonicotinoids in residential daily life and urban green space management also had a certain impact on urban aquatic ecosystems, especially in areas with high population density (Jia et al. 2023). Overall, neonicotinoid contamination in the surface waters of Eastern China was severely significant (Li et al 2023). However, in some southwestern areas, such as the Qilu Lake basin in Yunnan, the average concentration during summer can reach 2593.04 ng/L (Luo et al. 2023). The Southwest, one of China's six major rice-growing regions, accounted for 41.22% of the total grain output in 2014. Yet, due to a lack of scholarly focus, research on neonicotinoids in this area remains sparse, potentially not accurately representing the actual conditions in each province.

The concentration of neonicotinoids in rivers typically increases as they flow downstream. For example, downstream concentrations can be 1000 times higher than upstream in the Yangtze River, which may be related to the special distribution pattern of cities in China. Most river downstream areas are often located in many developed cities, such as the Yangtze Delta and Pearl River Delta, where various pollutants continuously converge. Whereas, the concentration of NEOs decreases during the migration process due to adsorption, transformation, degradation, and sedimentation. For example, the pollution levels of Dongting Lake and Poyang Lake, with the water inlet connected to the Yangtze River, are relatively lower compared to the Yangtze River (990 ± 490 ng/L), with concentrations of 144.07 and 79.37 ng/L, respectively (Chen et al. 2019a). The concentration ratio of the parent compound to the transformation products decreases during the transfer of neonicotinoids from paddy fields to receiving lakes, indicating that degradation affects the residue of pollutants during the migration process (Xiong et al. 2021). For river basins, tributaries showed higher pollution levels than the mainstream. In the Hangzhou water system and Songhua River basin, tributaries have higher pollution levels than the mainstream (Liu et al. 2021; Ying et al. 2022), possibly due to their direct connection with agricultural emission sources and the dilution effect during the converging into the mainstream. Neonicotinoids entering the sea also show a significant decrease in concentration, for example, with low detection levels in the seawater of Jiaozhou Bay (1.22 ng/L) and the Bohai Sea (0.56 ng/L). Groundwater detection levels are also lower than surface water, with an average concentration of 13.61 ng/L (Mahai et al. 2021).

Seasonal distribution shows that detection levels are much higher during the rainy season compared to the dry season. For example, the concentrations of $\sum$NEOs were 2.51 and 3.09 times higher in wet seasons than in dry seasons in the central Yangtze River, and in the Bohai Sea respectively (Mahai et al. 2019; Naumann et al. 2022). Additionally, due to the high water solubility of neonicotinoids and their transport through the xylem of plants to various parts, dry weather conditions can make it difficult for plants to translocate neonicotinoids, thereby reducing the effectiveness of the pesticides and potentially leading to increased pesticide use (Khodaverdi et al. 2016).

Table 1 The detected concentrations of neonicotinoids in China's aquatic environment

Sampling site	Year	Regions	Nine detected NNIs									Reference
			ACE	IMI	CLO	THIM	THID	DIN	IMIZ	NIT	FLO	
Danjiangkou Reservoir	2021	Hubei	0.46–93.10 (0.82) 100%	0.46–71.56 (1.33) 100%	ND–11.99 (0.27) 92.86%	ND–22.27 (0.14) 78.57%	ND–2.63 (0.12) 96.43%	ND	ND–10.75 (ND) 46.43%	ND	ND–1.87 (0.71) 96.43%	Chen et al. 2022b
The Harbin section of the Songhua River	2019	Heilongjiang	0.20–10.8 (1.94) 100%	10.9–83.5 (22.4) 100%	1.66–13.1 (3.42) 100%	16.3–83.5 (30.7) 100%	ND–1.21 (0.80) 15.4%	ND–5.91 (2.89) 23.1%	ND–0.04 (0.03) 15.4%	-	-	Liu et al. 2021
Surface water of Qinghai	2021	Qinghai	ND–7.23 (0.96) 84.2%	0.13–102 (8.06) 100%	ND–6.69 (0.55) 76.3%	ND–8.72 (0.98) 71.1	ND–0.42 (0.05) 65.8%	ND–4.49 (0.56) 81.6%	ND–1.45 (0.32) 76.3%	ND–0.06 (0.01) 50%	ND–0.2 (0.01) 39.5%	Yang et al. 2023a
Surface waters of Beijing	2020	Beijing	ND–179.1 (12.21) 95.80%	ND–1094.3 (112.28) 96.65%	ND–39.3 (4.32) 97.50%	ND–45.1 (4.42) 97.50%	ND–23.1 (0.48) 48.35%	ND–2628.4 (311.36) 92.50%	ND–374.9 (27.49) 78.35%	ND–42.7 (1.60) 70.00%	ND78.9 (7.49) 93.30%	Chen et al. 2023
Surface water in the northwest of Taihu Lake	2019	Jiangsu	0.3–368 (17.78) 100%	ND–907 (41.18) 97%	ND–391 (3.95) 48%	ND–952 (25.63) 83%	ND–15 (0.32) 13%	ND–228 (6.42) 62%	-	-	-	Wang et al. 2021
Surface water of Wujin District	2019	Jiangsu	0.3–65 (7.4) 100%	ND–452 (16) 98%	ND–39 (1.2) 71%	ND–503 (21) 90%	ND–2.1 (ND) 7.7%	ND–39 (1.6) 58%	-	-	-	Zhou et al. 2020a
The Pearl River and its tributaries	2016	Guangdong	18.8–157 (51.2) 100%	32.9–249 (81.1) 100%	14.8–47.6 (25.6) 100%	ND–52.4 (10.9) 68.2%	ND	-	-	-	-	Xiong et al. 2019
The Guangzhou section of the Pearl River	2017	Guangdong	6.24–77.1 (36.0) 100%	40.1–154 (78.3) 100%	13.1–38.0 (25.3) 100%	16.3–70.2 (50.2) 100%	0.44–2.97 (1.17) 92.9%	-	-	-	-	Yi et al. 2019
Wuchong Stream of Guangzhou	2020	Guangdong	0.61–308.96 (71.63) 100.00%	0.13–29.44 (7.88) 100%	0–12.78 (1.37) 46.15%	0–9.69 (2.11) 65.38%	0–0.93 (0.11) 19.23%	0–6.21 (0.82) 23.08%	-	0–5.31 (0.86) 42.31%	-	Jia et al. 2023
Huangpu River	2018	Shanghai	6.40–44.30 (20.80) 93.75%	4–102.80 (30.30) 93.75%	-	1.40–37.70 (3.75) 100%	-	-	-	-	-	Xu et al. 2020
Huai River	2022	Henan, Anhui, Jiangsu	0.09–10.11 (2.85) 100%	0.28–23.38 (6.64) 100%	0.65–25.91 (9.88) 100%	ND–112.62 (32.06) 95%	ND–0.67 (0.27) 45%	ND–46.75 (12.12) 95%	ND–0.76 (0.32) 60%	ND	-	Zhang et al. 2023
Surface water of the Jiaodong peninsula	2020	Shandong	ND–287.73 (9.76) 27.33%	-	-	ND–645.31 (39.53) 38.67%	-	-	-	-	-	Li et al. 2023
Water sources of Hainan	2021	Hainan	ND–23.78 (7.23) 38%	ND–86.41 (18.9) 94%	ND–164.08 (22.27) 88%	ND–183.22 (29.92) 78%	ND ND 0%	ND–68.19 (17.68) 25%	ND ND 0%	ND ND ND	-	Xiong et al. 2023

Table 1 (continued)

Sampling site	Year	Regions	Nine detected NNIs									Reference
			ACE	IMI	CLO	THIM	THID	DIN	IMIZ	NIT	FLO	
Qilu lake Basin	2020	Yunnan	-	1.39–3543.85 (698.77) 100%	8.78–2392.53 (610.61) 100%	0.65–2516.56 (552.99) 100%	-	-	-	-	-	Luo et al. 2023
Poyang Lake	2019	Jiangxi	ND–8.82 (1.63) 94.30%	2.14–42.68 (19.48) 100%	ND–8.85 (1.84) 97.10%	0.65–18.30 (6.35) 100%	0.49–21.03 (3.67) 100%	0.21–9.39 (2.16) 100%	ND–1.08 (0.24) 51.40%	ND–0.58 (0.28) 97.10%	ND–1.78 (0.17) 48.60%	Wang et al. 2023a
Rivers flowing into Jiaozhou Bay	2018	Shandong	ND–12.29 (1.69) 50%	ND–51.36 (5.74) 85.71%	ND–2.80 (0.10) 11.11%	ND–125.28 (5.01) 21.43%	ND–3.98 (0.44) 50%	ND–6.77 (-) 14.28%	ND	ND	-	He et al. 2021
Jiaozhou Bay, surface seawater	2018	Shandong	ND–1.26 (0.54) 81.82%	ND–2.83 (0.43) 36.36%	ND	ND	ND–1.43 (0.25) 50%	ND	ND	ND	-	He et al. 2021
In the Bohai Sea	2018		0.13–1.8 (0.43) 100%	`ND–0.75 (0.04) 6%	ND–0.30 - 2%	ND–0.55 (0.05) 30%	ND–0.14 (0.04) 85%	`ND ND	ND ND -	`ND ND	-	Naumann et al. 2022
Along the Yangtze River Basin	2016	Sichuan, Chongqing, Hubei, Hunan, Jiangxi, Jiangsu	4.74–22.9 (8.12) 100%	4.18–46.7 (18.85) 100%	ND–46.3 (8.01) 58%	ND–87.7 (12.5) 92%	ND–3.85 (1.28) 67%	ND–921 (20.2) 92%	4.71–83.4 (16.7) 100%	ND–800 (42.9) 92%	ND	Chen et al. 2019a
The entire Yangtze River	2020	Yunnan, Sichuan, Chongqing, Hubei, Anhui, Jiangsu, Shanghai	ND–28,1 (2.97) 98.6%	ND–97.9 (6.20) 98.6%	ND–24.8 (2.75) 95.8%	0.09–84.8 (4.68) 100%	ND–1.52 (0.09) 85.4%	ND–19.5 (3.64) 86.1%	-		ND–5.90 (0.31) 86.8%	Wang et al. 2023c
The central Yangtze River	2015	Hubei, Hunan	2.32–11.98 (3.52) 100%	2.42–44.36 (10.16) 100%	ND–6.7 (0.46) 64%	0.46–14.26 (2.66) 95%	0.02–0.26 (0.04) 87%	-	-	ND–0.94 (0.38) 73%	-	Mahai et al. 2019
The Yangtze River Delta	2016	Jiangsu	2.21–58.49 (18.64)	10.92–1886.89 (41.44)	-	2.97–90.85 (9.30)	-	-	-	-	-	Peng et al. 2018
The lower reaches of the Yangtze River	2021	Jiangsu	ND–1.63 (0.52) 97.72	1.69–20.57 (5.60) 100%	0.32–3.90 (1.12) 100%	0.29–48.15 (13.69) 100%	-	0.98–25.32 (3.50) 100%	0.28–3.62 (1.45) 100%	0.42–8.00 (2.19) 100%	0.89–2.53 (1.32) 100%	Li et al. 2022
The Yangtze River estuary	2017	Shanghai	ND–1.35 (0.15) 20%	ND–7.2 (1.58) 35%	ND	ND–1.84 (0.54) 65%	ND–0.4 (0.05) 15%	ND–2.68 (0.54) 55%	ND	ND–2.4 (0.60) 30%		Pan et al. 2020
Groundwater throughout China	2019		ND–3.38 (0.22) 86%	ND–20.0 (1.88) 73%	ND–137 (2.11) 54%	ND–807 (9.09) 44%	ND–1.46 (0.03) 26%	ND–5.64 (0.23) 11%	ND–0.18 (0.002) 1.1%	ND–0.10 (0.03) 2.1%	ND	Mahai et al. 2021

[a] The format of concentration expression: range, (mean), detection rate%

[b] *ND*, not detected; *ACE*, acetamiprid; *IMI*, imidacloprid; *CLO*, clothianidin; *THIM*, thiamethoxam; *THID*, thiacloprid; *DIN*, dinotefuran; *IMIZ*, imidaclothiz; *NIT*, nitenpyram; *FLO*, flonicamid

Neonicotinoids in the soil

Neonicotinoids can persist in soil for extended periods, sometimes exceeding several years. In citrus orchard soil that has been planted for 1 year, neonicotinoids can only be detected at a depth of 0–50 cm, while in soil that has been planted for 20 years, neonicotinoids can reach a depth of 80–100 cm (Zheng et al. 2022). Compared to aquatic environments, neonicotinoids have limited mobility in soil but longer retention time, necessitating attention to the risks posed by accumulation effects.

Regional occurrence

The levels of neonicotinoids in the soil vary greatly, with the concentration ranging from ND to 9643.9 ng/g, and the highest detection in Hainan's farmland (Tan et al. 2023). Overall, areas with high concentrations of neonicotinoids were concentrated in the tropical regions of southern China. Given the varied detection methods across the current studies, the comparison between northern and southern regions' data could lead to significant inaccuracies. It can be concluded from the soil neonicotinoid pollution map in China that the concentration of neonicotinoids in the soil of agricultural areas in the south (mean 27.21 ng/g) was higher than in the northern regions (mean 12.77 ng/g), and the provinces with the highest median concentrations were Fujian (109 ng/g), Yunnan (53.7 ng/g), and Guangdong (45.6 ng/g), possibly due to the humid climate that easily triggers pests and diseases, necessitating the use of large amounts of pesticides (Hou et al. 2023).

Dominant congers

In most soils, IMI was the most widely detected neonicotinoid, due to its relatively low water solubility of 610 mg/L and strong adsorption potential in soil (Kurwadkar et al. 2013). However, the concentration of IMI detected varies significantly across the country. In major grain-producing areas, the IMI detection rate in Jiangsu, Zhejiang, Guangdong, and Jiangxi exceeds 96% (Gu et al. 2023). The average total residual concentration of nine types of neonicotinoid insecticides in Zhejiang Province was 75.8 ng/g, with an IMI of 49.6 ng/g, accounting for 60.4% of the total neonicotinoids (Chen et al. 2022a). IMI residues detected in Tianjin (101 ng/g) are higher than those in Shandong's agricultural soils (1.90 ng/g) (Wu et al. 2020; Zhou et al. 2021). The IMI contribution rate exceeds 50% in orchards and rural areas, and 80% in parks and residential areas, indicating a prominent role in pest and disease control (Zhou et al. 2021).

The impact of land use and soil types

Neonicotinoid pollution levels in soils vary by land use types, influenced by crop types and the extent of arable land areas. Generally, the pollution level in farmland soil is the highest. In a soil survey in Tianjin, the average concentration of neonicotinoids in greenhouses was 4 to 11.48 times higher than in orchards, parks, and residential areas (Zhou et al. 2021). The concentration in Guangzhou farmland (1.69 ng/g) was also higher than those in urban land use types (0.13–0.70 ng/g) (Ying et al. 2022; Zhang et al. 2020a). Further division of farmland showed that the median concentration of neonicotinoids in the Pearl River Delta was highest in vegetable fields, followed by rice paddies and orchards (Yu et al. 2021). In soil samples from vegetable cultivation areas, the residue levels of neonicotinoids were relatively high, with an average total concentration ranging from 27.55 to 157.64 ng/g, peaking at 1816.67 ng/g in tomato and pepper cultivation areas (Cui et al. 2023; Wu et al. 2020). This may be due to the high frequency of vegetable cultivation leading to higher pesticide use and resulting in higher pollution. Especially, the longer vegetable cultivation time in greenhouse environments and the enclosed environment are conducive to the retention of neonicotinoids. Furthermore, studies have shown that at a spatial resolution of 1×1 km^2, neonicotinoid concentrations are significantly positively correlated with the coverage of arable land (Chen et al. 2022a).

In terms of soil properties, clay and organic particles can increase the persistence of pesticides in the soil (Morrison et al. 2022). The adsorption strength follows the order of black soils, fluvo-aquic soils, paddy soils, and red soils in China (Zhang et al. 2018). Soil types exhibit distinct geographic distribution patterns across regions. Black soil predominates in the Northeast region, and fluvo-aquic soil is the main soil type in the North China Plain, while paddy soils and red soil are primarily distributed in Southern China (Based on the Soil Science Database n.d.). A study by Hu et al. (2023) confirmed that red soil has a higher leaching potential than other soils, with the mass percentage range of neonicotinoids in the 20–30 cm leaching layer and leachate being 73.8 to 87.4%, indicating that red soils in the southern regions of the Yangtze River are more prone to neonicotinoid migration.

Neonicotinoids in the atmosphere

The vapor pressure of neonicotinoid insecticides generally ranges from 1.3×10^{-10} to 4.5×10^{-4} Pa (Raina-Fulton 2015). The low volatility means that they are primarily present in the atmosphere in the form of atmospheric particulate matter.

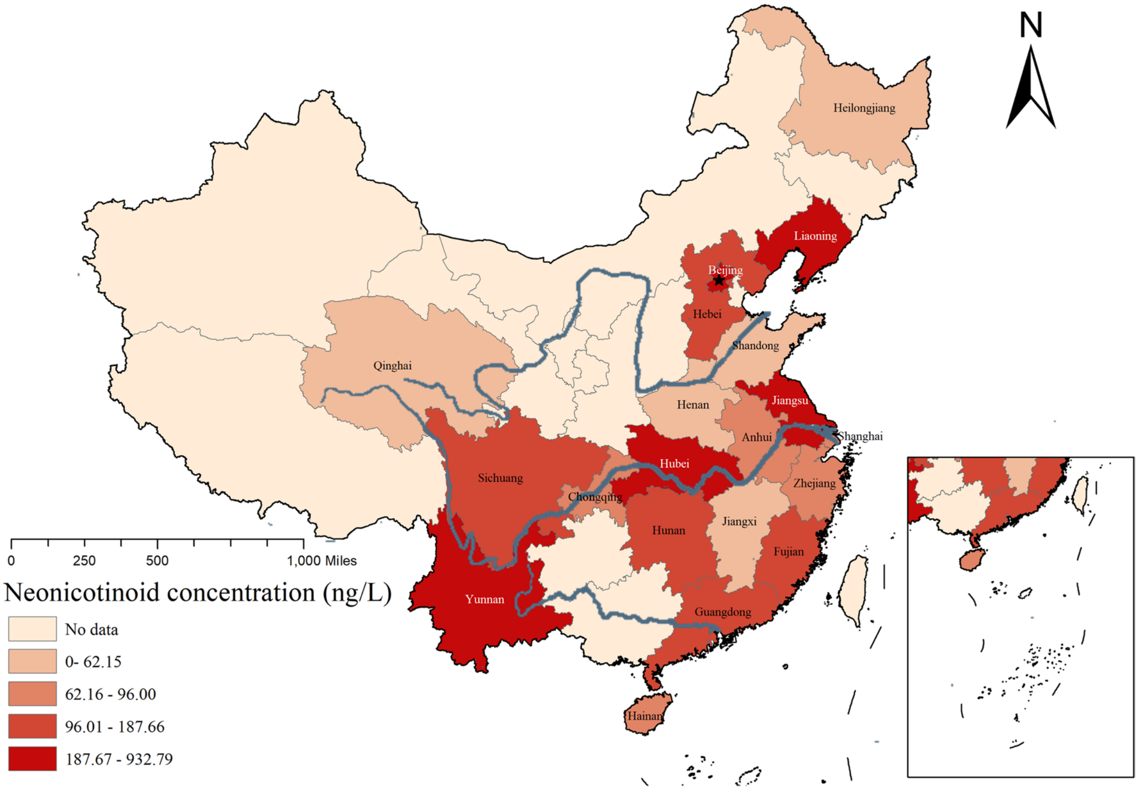

Fig. 2 The total concentrations of nine neonicotinoids (ΣNEOs, average value) in China's aquatic environment

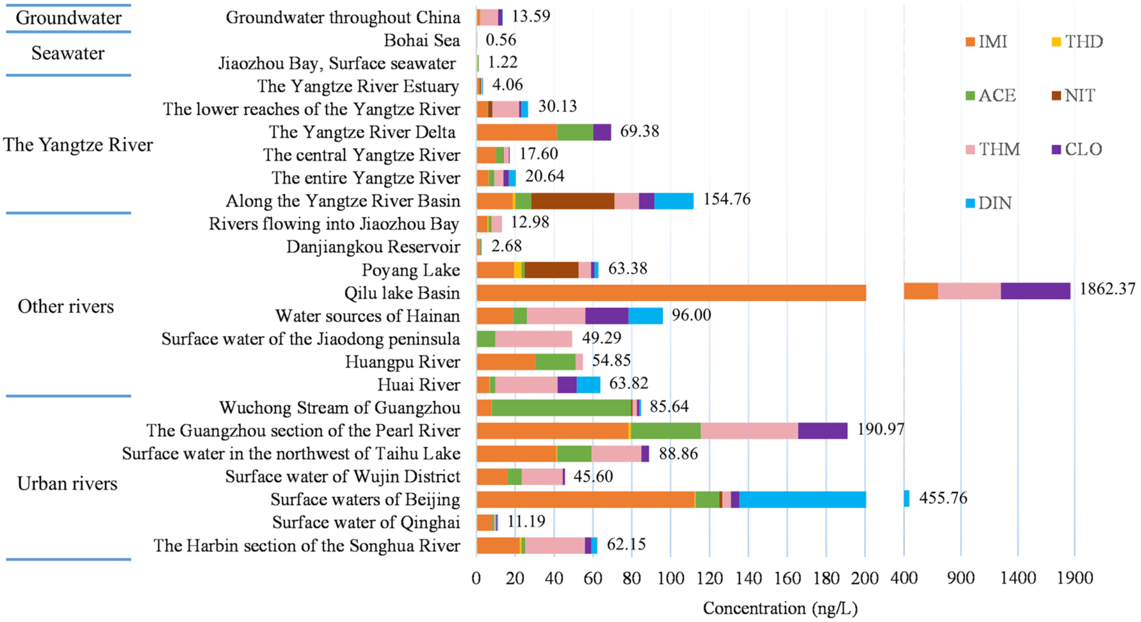

Fig. 3 Average concentrations of neonicotinoids in different types of water bodies in China

In the agricultural area, the air concentration level reached 80.9 pg/m^3, and 13.1×10^6 pg/m^3 at a distance of 10 m from the exhaust of pneumatic seeders, which is more severe than in the nearby urban areas (Zhou et al. 2020b). Urban air neonicotinoid surveys in China have been conducted in Beijing, Taiyuan, Zhengzhou, Nanjing, Wuhan, and Shenzhen, which are representative of North China, Middle China, East China, and South China. According to the existing research data, Nanjing has the highest degree of urban air pollution, and IMI has the highest median concentration (45.2 ng/g), followed by ACE of 4.09 ng/g, far exceeding other regions (Chen et al. 2022c). IMI and ACE are registered for use in lawn greening and indoor pest control, indicating their widespread application in cities. With the increase in the usage of neonicotinoids, the concentration in the air also exhibits an upward trend. For example, the concentration of neonicotinoids in indoor dust in 2018 (geometric mean 86.1 ng/g) had significantly increased compared to 2016 (geometric mean 17.3 ng/g) in the Wuhan area (Wang et al. 2019), which may be due to the increase in the number of neonicotinoid registrations for household sanitation pesticides in China, from 87 types in 2016 to 139 types in 2018.

Effects of neonicotinoids on organisms and the ecological risks

Neonicotinoids have been widely detected in organisms, including aquatic invertebrates, insects, and fish (Barmentlo et al. 2021; Hano et al. 2019; Lima-Fernandes et al. 2019). Previous studies showed that neonicotinoids had detrimental effects on aquatic organisms from the individual level to the community level, finally resulting in ecological risks (Sánchez-Bayo et al. 2016). In general, IMI shows the highest toxicity to non-target organisms, with the half-lethal concentration (LC$_{50}$) progressively rising from insects to crustaceans, fish, birds, and mammals (Zhang et al. 2020b). Table 2 lists the toxicity data of non-target species to neonicotinoids in China.

Toxic effects of neonicotinoids on fish

Research on the toxicity of neonicotinoids to fish in China usually uses zebrafish as test subjects. According to the results of seven local studies on the toxicity of neonicotinoids to fish in China, the sublethal toxicity of neonicotinoids to fish was specifically manifested in inducing oxidative stress effects, DNA damage, and changes in metabolite levels within the fish body. Studies by Yan et al. (2016) and Ge et al. (2015) respectively found that short-term exposure to 0.3 mg/L THIM and IMI can induce oxidative stress and DNA damage in zebrafish, and DNA damage has an obvious dose–effect relationship. After 28 days, the antioxidant enzyme activity and the level of reactive oxygen species in the body were significantly different compared with the control group. THID and NIT exposure also affects oxidative stress, antioxidant enzyme activity, and DNA damage in the liver of zebrafish (Xie et al. 2022; Yan et al. 2015). Judging from the current studies, IMI caused the greatest damage to zebrafish DNA, with the Olive Tail Moment (OTM) > 20 exposed to a concentration of 1.25 mg/L on the 7th day. However, OTM only exceeded 20 on the 28th day after exposure to 5 mg/L of THIM, while exposure to a 5 mg/L concentration of NIT for 28 days resulted in an OTM below 8 (Ge et al. 2015; Yan et al. 2015; Yan et al. 2016). Zhang and Zhao (2017) found that ACE caused the metabolism of zebrafish head, serum, and liver (amino acid metabolism, TCA cycle, and neurotransmitter balance) interference, especially the liver was more sensitive to neonicotinoids. Ma et al. (2019) also showed that ACE affects the development of zebrafish and increases embryonic mortality and malformation rates.

Toxicity experiments under laboratory conditions have shown that neonicotinoids at high concentrations are subacutely toxic to zebrafish. However, the concentration of neonicotinoids in the environment was generally much lower than the mg/L level used in laboratory toxicity studies, and the toxicity damage to zebrafish at low concentrations still needs to be investigated. Yang et al. (2023b) found that zebrafish exposed to 0.0001 mg/L THIM are more at risk of bioaccumulation, while exposure to 0.01 mg/L THIM will make them hyperactive and restless, with enhanced social activities, short-term memory loss, and other abnormal behaviors, which may increase predation risk for adult zebrafish and affect community safety. THIM at a concentration of 0.05 mg/L can cause a significant increase in the embryonic mortality rate of the Chinese rare minnows, *Gobiocypris rarus*, and a significant increase in the deformity rate of hatchling larvae (Zhu et al. 2023). Even at a concentration of 0.005 mg/L, THIM can cause a downregulation of functional gene transcript expression in larval fish (Zhu et al. 2023). Neonicotinoids at 0.5 mg/L or 2 mg/L cause oxidative stress and DNA damage in *Gobiocypris rarus* (Tian et al. 2020). The diverse pollutants in the environment may cause more severe damage to zebrafish than single pollutants. For instance, the toxicity of IMI is significantly enhanced when mixed with other types of insecticides (Wang et al. 2017). Judging from a survey from 2017 to 2021, the existing fishery resources in China's Yangtze River are 124,800 tons, which is only equivalent to 58.7% of the 1980s (Yang et al. 2023c). Apart from human overfishing, water pollution of the neonicotinoid pesticides has contributed to the deterioration of fish habitats (Lin et al. 2023).

Table 2 Toxicity of neonicotinoids to non-target organisms

Organisms	Species	NNIs	Does	Exposure time	Effect	LC50/EC50	Reference
Zebrafish	*Danio rerio*	THID	1, 10, 100, 1000, and 10,000 µg/L	20 days	Developmental toxicity and oxidative stress; hypoactivity; behavioral alterations; neurotoxicity		Xie et al. 2022
Zebrafish	*Danio rerio*	IMI	0, 0.3, 1.25, and 5 mg/L	7, 14, 21, and 28 days	Oxidative stress and DNA damage		Ge et al. 2015
Zebrafish	*Danio rerio*	THIM	0.30, 1.25, and 5.00 mg/L	7, 14, 21, and 28 days	Oxidative stress and DNA damage		Yan et al. 2016
Zebrafish	*Danio rerio*	THIM	0.1, 10, and 1000 µg/L		Abnormal behavior; brain tissue lesions		Yang et al. 2023b
Zebrafish	*Brachydanio rerio*	ACE	2.4 mg/L	4 days	Impaired metabolism of head, serum, and liver		Zhang and Zhao 2017
Zebrafish	*Danio rerio*	NIT	0.6, 1.2, 2.5, and 5.0 mg/L	7, 14, 21, and 28 days	Oxidative stress and DNA damage		Yan et al. 2015
Minnows	*Gobiocypris rarus*	IMI, NIT, and DIN	0.1, 0.5, or 2.0 mg/L	60 days	Oxidative stress and DNA damage		Tian et al. 2020
Minnows	*Gobiocypris rarus*	THIM	0, 0.5, 5, 50 µg/L	28 days	Teratogenesis and death of larvae; expression levels of some functional genes are down-regulated		Zhu et al. 2023
Quails	*Coturnix japonica*	IMI	20–45.75 mg/kg body weight	7 days	Significant reduction in weight and food consumption	30.25 mg/kg	Deng et al. 2013
Quails	*Coturnix japonica*	THIM	5 mg/kg body weight	24 hours	THIM was rapidly absorbed, distributed, metabolized, and eliminated		Pan et al. 2022
Bee	*Apis mellifera*	ACE	0, 5, and 25 mg/L		Interference with birth weight and emergence rate of newly emerged bees; shortened lifespan		Shi et al. 2020
Bee	*Apis mellifera*	IMI, and CLO	IMI (6–14 ng/bee) CLO (1.6–2.4 ng/bee)	24 hours	Downregulation of activity of some detoxification enzymes; lethal effects	IMI: 8.6 ng/bee CLO: 2.0 ng/bee	Li et al. 2017

Table 2 (continued)

Organisms	Species	NNIs	Does	Exposure time	Effect	LC50/EC50	Reference
Bee	*Apis cerana*	IMI, and CLO	IMI (1–5 ng/bee) CLO (0.2–1 ng/bee)	24 hours	Increased activity of some detoxification enzymes; lethal effect	IMI: 2.7 ng/bee CLO: 0.5 ng/bee	Li et al. 2017
Bee	*Apis cerana*	IMI	10, 20, and 40 mg/L		Reduce predator avoidance behavior; inhibit worker bees from foraging		Tan et al. 2014
Bee	*Apis cerana*	THIM	0.2 ng/bee		Muscle agitation; impaired learning ability		Ma et al. 2019

[a] *ACE*, acetamiprid; *IMI*, imidacloprid; *CLO*, clothianidin; *THIM*, thiamethoxam; *THID*, thiacloprid; *DIN*, dinotefuran; *NIT*, nitenpyram

Toxic effects of neonicotinoids on birds

In the USA and the Netherlands, it has been reported that the decline in bird populations is closely related to the increased use of neonicotinoids (Hallmann et al. 2014; Li et al. 2020). However, there are no official statistics on the bird population in China (Hallmann et al. 2014). The main effects of neonicotinoids on birds are physiological and reproductive harm. Consuming invertebrates contaminated with neonicotinoids and eating seeds coated with neonicotinoids are the main ways of exposure (Eng et al. 2019). Neonicotinoids are less toxic to birds, and their effects can be eliminated quickly with less exposure over a short period. Pan et al. (2022) showed that even after oral administration of 5 mg/kg body weight of THIM to *Coturnix japonica*, it was rapidly metabolized or eliminated within 4 h so that the contaminant could not be detected in the plasma. It is worth noting that the metabolism of THIM is accompanied by the production of its metabolite CLO, whose rapid increase may result in comprehensive exposure risks (Pan et al. 2022). Under the same toxicity experiment, it was observed that neonicotinoids can have varying effects on different individuals, likely due to genetic differences, age, and other factors. For example, male *Coturnix japonica* exposed to IMI showed hyperactive and nervous states such as being easily frightened, while females showed reduced activity and dyskinesia (Deng et al. 2013). Neonicotinoids reduce the feeding and movement of birds and cause migration delays, which may affect their survival and reproduction and cause population declines (Eng et al. 2019). There are currently nine bird migration corridors in the world, four of which pass through China. Among them, Poyang Lake, the most important waterbird wintering ground on the "East Asia-Australasia" migratory bird migration route, has been contaminated by neonicotinoids (Wang et al. 2023a). Although endangered birds are concentrated in areas that have been less impacted by human activities, the threat to them after the widespread use of neonicotinoids cannot be ignored (Yang et al. 2021). Future studies should focus more on the effects of neonicotinoids on seed-feeding and migratory birds, as these populations are at high risk of toxicity and may provide critical insights into the broader ecological impacts.

Toxic effects of neonicotinoids on bees

The two main bee species in China are *Apis mellifera* Linnaeus and *Apis cerana* Fabricius (Yue et al. 2018). *Apis mellifera* may be exposed to more neonicotinoids than *A. cerana* because the detection rate and concentration of neonicotinoids in honey produced by *A. mellifera* are higher (Wang et al. 2020). Studies have compared the sensitivity of two bee species to neonicotinoids, but the results have been inconsistent. Li et al. (2017) found that IMI and CLO were more toxic to *A. cerana* than *A. mellifera*, with acute oral median lethal dose of 2.7 and 8.6 ng/bee (IMI) and 0.5 and 2.0 ng/bee (CLO) respectively. Research by Yue et al. (2018) shows that *A. mellifera* was more sensitive to IMI than *A. cerana*. The differences in study results may be due to various factors such as the genetic characteristics of the bees (Rinkevich et al. 2015), age (Rinkevich et al. 2015), or environmental temperature (Saleem et al. 2020). In general, the order of toxicity of neonicotinoids to bees was CLO > THIM > IMI > DIN > NIT > ACE (Yue et al. 2018). Orally administering 0.2 ng of THIM will increase the average return time, flight speed, flight distance, and flight duration for *A. cerana*, thereby impairing its homing ability (Ma et al. 2019). The cognitive ability of *A. cerana* to avoid predators was reduced when feeding on nectar containing 40 mg/L IMI (Tan et al. 2014). ACE affects the emergence and development of *A. mellifera* larvae and shortens the lifespan of adult bees (Shi et al. 2020). Multiple pressures such as environmental changes and pesticides have led to a decline in bee populations (Liu et al. 2018). China has enacted bans on 46 highly toxic pesticides and imposed usage restrictions on 22 other highly toxic pesticides, contributing to the protection of pollinating insects. However, it has not yet established targeted policies akin to those in place in the European Union and Canada.

Many studies have reviewed the ecological risks of aquatic invertebrates (Malhotra et al. 2021; Zhang et al. 2020b), and through the species sensitivity distribution method and joint probability distribution curve method, it was found that neonicotinoids pose the highest threat to aquatic insects, especially *Chironomus dilutus* (Fan et al. 2022; Wang et al. 2023b). A comprehensive analysis of species sensitivity distribution, based on 214 toxicity tests across 48 species, predicted ecological thresholds for neonicotinoid concentrations in the water environment of 2×10^{-4} mg/L for short-term acute exposure and 3.5×10^{-5} mg/L for long-term chronic exposure (Morrissey et al. 2015). The total neonicotinoid concentration in most of China's surface water exceeds the chronic toxicity ecological threshold. At 49 sampling points in the Pearl River, neonicotinoid concentrations exceeded 35 ng/L, with 15.4% of these points showing levels above 2×10^{-4} mg/L (Zhang et al. 2019). Near the Bohai Sea, 72.2% of the 36 rivers were under chronic toxicity, and 8.3% were under acute toxicity (Naumann et al. 2022). Among the water samples collected from 12 sites along the Yangtze River Basin in wet seasons, neonicotinoid concentrations in 58.3% of samples were above the chronic toxicity threshold, and 33.3% exceeded the acute toxicity threshold. In the surface water of Beijing and the Qilu Lake Basin, although concentration data for each sampling point was unavailable, their overall average value was significantly higher than 2×10^{-4} mg/L, indicating that most aquatic organisms in these waters were likely subjected to acute toxicity. Although the survey data were not sufficiently comprehensive, these studies indicated the potential for both short-term and long-term impacts of neonicotinoids on aquatic invertebrate species in China.

Conclusion

This article discusses the sources of neonicotinoids (mainly agricultural and urban non-point sources) and analyzes the factors affecting their distribution based on China's regional characteristics, as well as their toxicity and ecological risks to organisms. The presence of these compounds has been widely documented across various environmental compartments, including water, soil, and atmosphere, with detection no longer confined to agricultural areas, as urban contributions are increasingly recognized. The southern climate provides advantages for pest reproduction and multiple planting cycles, and rainfall plays a significant role in the detection rate of pesticides. Urban activities, such as park greening and household pesticide use, also contribute to their presence in cities. The distribution surveys of neonicotinoids in China's aquatic environments are predominantly concentrated in the eastern river basins (such as the Yangtze River Basin, the Pearl River Basin, the Huai River Basin, and the Yellow River Basin). The southwestern region of China (such as Guizhou and Guangxi) boasts rich agriculture, but currently lacks surveys on the distribution of neonicotinoids within the area. The latest surveys are continuously filling the gaps in pollution data, but there is still a lack of specific data on the usage of neonicotinoid pesticides in various applications, and further analysis of their sources. The regulated application of neonicotinoids will play a crucial role in elucidating the origins of neonicotinoid residues and control of pollution levels. Under laboratory conditions, neonicotinoids have shown chronic toxicity, and in densely populated areas of China, the detection of neonicotinoids exceeds the predicted ecological threshold, potentially causing significant ecological harm in the long term. It is worth noting that the combined toxicity of neonicotinoids and other pesticides may be greater than their individual effects. While some countries have restricted certain neonicotinoids, the existing compounds in the soil will continue to leach into the water environment, highlighting the need for continued risk assessment, particularly in China where restrictions have not been issued.

Author contribution Lingzhi Liao: investigation; resources; data curation; writing—review and editing. Ting Sun: conceptualization; methodology; writing—review and editing. Zhenhui Gao: writing—review and editing. Meng Gao: writing—review and editing. Ao Li: writing—review and editing. Teng Gao: writing—review and editing. Ziqin Gao: writing—review and editing. Jianing Lin: conceptualization, methodology, investigation, supervision, resources, data curation, funding acquisition.

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Declarations

Ethical approval Strictly abide by basic academic ethics, and use others' data and conclusions objectively and impartially.

Competing interests The authors declare no competing interests.

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