Frontiers of Environmental Science & Engineering
2025, 19(6): 80 https://doi.org/10.1007/s11783-025-2000-0

RESEARCH ARTICLE

Investigating contaminant distribution, health risk, and remediation of pesticide industrial sites in China

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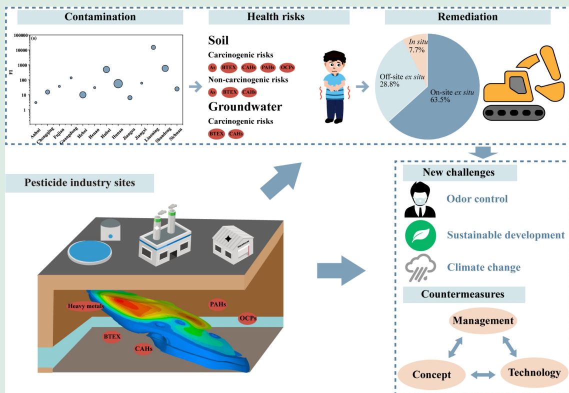
HIGHLIGHTS

- Multiple contaminants showed complex interactions affecting environmental risks.
- Heavily polluted sites clustered in industrial east coast and agricultural regions.
- Runtime, product type, and production scale jointly mediate site pollution levels.
- *Ex situ* remediation dominates high-risk soil treatment.
- Challenges and countermeasures for remediation projects in the new era explored.



ABSTRACT: The present study aimed to identify the major pollutants, contamination characteristics, spatial distributions, health risks, and remediation projects associated with pesticide sites and discuss challenges and countermeasures for remediation projects in the new era. Over 100 full-process environmental management reports were collected from 57 sites and analyzed. The results showed that heavy metals, BTEX, chlorinated hydrocarbons, and organochlorine pesticides were the main pollutants at pesticide industry sites in China, for instance, arsenic (PI_{mean} = 45.88), benzene (PI_{mean} = 3315.35), trichloroethylene (PI_{mean} = 7887.76), and hexachlorocyclohexane (PI_{mean} = 8087.04). Most (> 70%) sites contained soil and groundwater contaminated by a combination of multiple pollutants. Furthermore, heavily polluted sites were widely distributed in industrially developed eastern coastal areas and in the agriculturally developed Yellow River Basin, Yangtze River Basin, and North-east China. Arsenic, benzene, chloroform, and hexachlorocyclohexane were identified as the key pollutants contributing to health risks. For instance, the average carcinogenic risk of hexachlorocyclohexane can reach 2.00E-01, while the average non-carcinogenic risk of chloroform can reach 573.04. Notably, the use of off-site and

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Article history: Received 19 December 2024, Revised 20 March 2025, Accepted 24 March 2025, Available online 15 April 2025

one-site *ex situ* techniques is still common for soil remediation, whereas *in situ* remediation techniques are used for groundwater. However, restoration projects face challenges such as neighbor avoidance, sustainable development, and climate change in the new era, which can be addressed by optimizing management systems and improving technical systems. Overall, our findings provide a reference for pollution prevention and control of pesticide production enterprises, risk management of decommissioned enterprises, and research and development of targeted green and sustainable remediation technologies.

KEYWORDS: Pesticide-contaminated land, Spatial distribution, Clean up, Soil pollution, Groundwater pollution

1 Introduction

Pesticides are potentially hazardous chemical substances that remain in the environment. These chemicals are harmful to public health and seriously threaten soil, water, air, and human health, attracting extensive research attention and public concerns in both developed and developing countries (Tang et al., 2021; Tang et al., 2022; Bokade et al., 2023). China is a major global producer and consumer accounting for 63% of worldwide pesticide usage, and its pesticide manufacturing industry is clustered predominantly in the Yangtze River Delta, North China, and central-southern regions (Tang et al., 2022). The areas are characterized by abundant fertile farmlands, large industrial cities, and high population density (Zhang et al., 2022a). Based on chemical properties of pesticides, they typically include organochlorines (OCPs), organophosphates (OPPs), carbamates, amides, triazines, triazoles, pyrethroids, and neonicotinoids (Gu et al., 2023). A study has indicated that excessive levels of hexachlorocyclohexane (HCH) and DDT are commonly observed in both operational and abandoned pesticide factories in China (Ma et al., 2020). In several sites, the maximum concentrations of HCH and DDT have been found to be thousands of times higher than the standard limits. This challenge is not unique to China. The soils or groundwater of abandoned pesticide factories worldwide usually accumulate high concentrations/contents of pesticides, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and heavy metal pollutants (Vijgen et al., 2022; Boudh et al., 2024). Effective management of pesticide-contaminated sites poses a challenge in many countries (Tripathi et al., 2014; Villamizar et al., 2020).

Notably, a large number of enterprises that produce and use these chemicals have closed or relocated because of the implementation of the Stockholm Convention (Dvorská et al., 2012; Zhang et al., 2022b), accelerated urbanization, and industrial restructuring. This has resulted in large numbers of abandoned pesticide-contaminated sites (Ma et al., 2020; Bokade et al., 2023). These sites are of global concern because of their high concentrations of organic pollutants, foul odors, and complete loss of habitat conditions (Kan et al., 2021; Tang et al., 2022; Qu et al., 2023). Moreover, most of these enterprises have a lifelong cycle with historical problems, such as unstandardized production and storage measures, insufficient pollution prevention and control measures, and weak environmental awareness (Dvorská et al., 2012; Wang et al., 2023a). In addition, the pesticide production process is complex, involving many highly toxic substances that result in decommissioned pesticide plants that are often heavily contaminated (Li et al., 2023). Furthermore, large quantities of contaminants often remain in soil and groundwater for many years after a facility has closed (Huang et al., 2017). Notably, some organochlorine production and processing facilities have raw materials, intermediates, products, and degradation products that contain a wide range of persistent and highly toxic persistent organic pollutants (POPs). These pollutants have high persistence and bioaccumulation characteristics, leading to chronic toxic effects in ecosystems and carcinogenic and endocrine-disrupting risks to humans (Al-Shaalan et al., 2019; Basheer and Ali, 2018). They also have long-range transport properties (Fang et al., 2017; Fan et al., 2022), posing a major threat to the environment and human health (Ali and Aboul-Enein, 2001; 2002).

Furthermore, controlling and reducing environmental pollution and site remediation is possible when the characteristics of contaminated sites are understood (Li et al., 2023). Meanwhile, pesticide producers are numerous and dispersed geographically (Ma et al., 2020), and several studies have focused on investigating contamination at specific sites and regions and analyzing specific pollutants (Dvorská et al., 2012;

Fang et al., 2017; Fan et al., 2022; Ye et al., 2023). However, the number of pesticide-contaminated sites continues to increase as businesses are abandoned and relocated. Early studies have addressed only a minor part of the issue, and incidents of soil contamination continue to occur (Fang et al., 2017). Systematic evaluation of key information such as site contamination characteristics, health risks and remedial measures is essential for guiding future pollution prevention in production enterprises and survey and remediation of decommissioned sites (Li et al., 2023; Wei et al., 2023). Therefore, a more macro-level study of contaminated sites is essential to control the risk of the subsequent reuse of contaminated sites (Fang et al., 2017). To the best of our knowledge, no other study has conducted a more extensive investigation of pesticide industry pollutants and their characteristics in the Chinese environment. Furthermore, as the economy and society progress, there is increased demand for a higher quality of life. In the wake of climate change, the concept of sustainable restoration has emerged, posing new challenges for the development of pesticide site remediation projects. Hence, it is imperative to develop targeted strategies that align with the specific pollution characteristics of pesticide sites.

In the present study, a macro analysis of reports from 57 pesticide-contaminated sites in China was carried out, collecting data from soil and groundwater investigation, risk assessment, and remediation phases. The aim of the present study was to identify the main pollutants, pollution characteristics, spatial distribution, and health risks of pesticide sites, and to analyze the implementation of current remediation projects. Additionally, we propose emerging challenges and countermeasures for remediation projects and provide a basis for improving the management and technology systems of contaminated sites in the pesticide industry to ensure effective removal or control of risks.

2 Methods

2.1 Studied sites

In this study, we used pesticide-contaminated sites as keywords and collected information from databases, such as the soil environmental information publicity platform for construction sites, related enterprises, and relevant business units. The screened reports adhered to the following criteria: 1) The procedures for soil and groundwater sampling, layout, and analysis comply with the standards issued by the Ministry of Ecology and Environment of China or verified standard methods (MEE, 2020; 2004); 2) The risk assessment process aligns with the technical guidelines for risk assessment issued by the Ministry of Ecology and Environment of China (MEE, 2019) or employ models recommended by the USEPA; 3) All types of reports have undergone expert review; 4) The original enterprise was engaged in pesticide production and processing for more than three years.

Finally, we collected over 100 reports on site investigation, risk assessment, remediation, and risk control in the pesticide industry from 57 sites. The spatial distribution of the pesticide-contaminated sites is shown in Fig. 1(a), which focused on Hebei Province (7), Hubei Province (7), Henan Province (6), and Hunan Province (5). Most pesticide factories were established before 2000 and closed or relocated after the implementation of the policy supporting the second industry, the development of the third industry, and the fulfillment of the Stockholm Convention, as detailed in Fig. 1(b). Most of the sites generally covered an area of $\geqslant$ 10000 m^2, with multiple production halls (Fig. 1(c)). Furthermore, classification of pesticides based on chemical structure is illustrated in Fig. 1(d); most of the factories simultaneously produced several types of pesticides simultaneously, with organophosphorus and organochlorine pesticides being the most common types of pesticides. Moreover, pyrethroids, triazoles, carbamates, and other types of pesticides were produced.

2.2 Data analysis methods

2.2.1 Pollution level data

The pollution index (PI_i), which is the ratio of pollutant content/concentration to the standard value, is a key indicator that reflects the pollution level of a single pollutant at a site, and FI_j is the average pollution level of all factors at site j, calculated as follows:

$$PI_i = \frac{C_i}{SV_i}, \tag{1}$$

$$FI_i = \sqrt{\frac{P^2{}_{i-\mathrm{ave}} + P^2{}_{i-\max}}{2}}, \tag{2}$$

$$FI_j = \frac{1}{n}\sum_{i=1}^{n} F_i, \tag{3}$$

where C_i is the maximum or average concentration of compound i at site j, SV_i is the standard value of compound i. SV of soil is the screening value of GB 36600 Class I construction land (MEE, 2018), and the

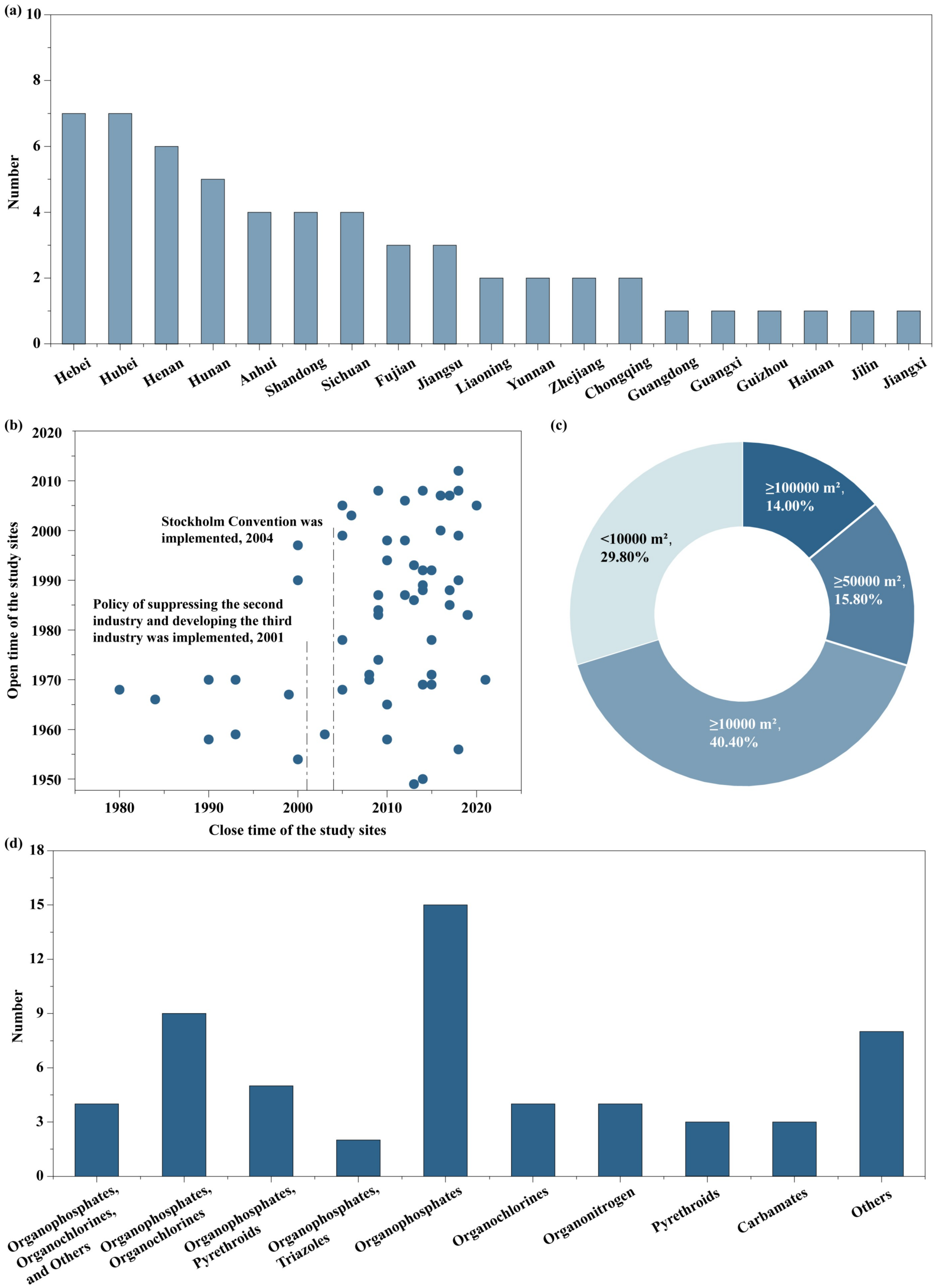

Fig. 1 Overview of the study site. (a) Distribution of the original production and processing enterprises, (b) time of opening and closing of the former production and processing enterprises, (c) floor space of the former production and processing enterprises, and (d) main products of the former production and processing enterprises.

SV of groundwater is the standard value of GB 14848 Class III water (MEE, 2017). Higher PI_i values indicate greater pollutant accumulation. FI_i rapidly assesses the comprehensive pollution level of a single pollutant on the basis of single factor evaluation. FI_j represents the site's overall pollution level, with higher values indicating more severe contamination. Typically, PI_i, FI_i, and $FI_j \geqslant 3$, are indicative of severe pollution, $2 < PI_i, FI_i$, and $FI_j \leqslant 3$ (moderate contamination), $1 < PI_i, FI_i$, and $FI_j \leqslant 2$ (slight contamination), $0.7 < PI_i, FI_i$, and $FI_j \leqslant 1$ (precaution), PI_i, FI_i, and $FI_j \leqslant 0.7$ (safe) (Brady et al., 2015; Hong et al., 2021; Hu et al., 2024).

2.2.2 Health risk assessment data

The health risk assessment data used in this study were obtained based on evaluation models recommended by the MEE (MEE, 2019) or USEPA. The exposure pathways include oral ingestion, dermal contact, inhalation of soil particulates, inhalation of gaseous pollutants from surface soil in outdoor air, inhalation of gaseous pollutants from subsurface soil in outdoor air, and inhalation of gaseous pollutants from subsurface soil in indoor air. Carcinogenic risk (CR) greater than 1E-06 is considered to indicate a potential carcinogenic risk, and CR greater than 1E-04 is considered to indicate a certain carcinogenic risk; non-carcinogenic risk (HI) greater than 1 is considered to indicate a non-carcinogenic risk. All site risk assessment data that met the health risk assessment criteria were calculated. Afterward, the average, median, and maximum values of the carcinogenic and non-carcinogenic risks for individual pollutants were calculated across all sites, in addition to the contribution of the six exposure pathways to health risks.

3 Results and discussion

3.1 Characterization of soil and groundwater contamination

3.1.1 Main pollutants

The top 20 contaminant types were ranked by the number of contaminant exceedances at different sites, and the highest number of exceedances in the soil were heavy metals, VOCs, SVOCs, and pesticides (Fig. 2(a)). The heavy metals were arsenic (As), with a population index mean (PI_{mean}) of 45.88. Furthermore, trichloroethylene (PI_{mean} = 7887.76), chloroform (PI_{mean} = 4564.64), and benzene (PI_{mean} = 3315.35) were the most common VOCs in the pesticide industry. Additionally, hexachlorobenzene (PI_{mean} = 472.90) and 1,4-dichlorobenzene (PI_{mean} = 173.75) were the most dominant SVOCs. Two organochlorine pesticides, hexachlorocyclohexane and DDT, exceeded the limits 8087.04 and 1840.87 times, respectively. The main types of groundwater contaminants were routine contaminants, heavy metals, VOCs, and pesticides (Fig. 2(b)). Notably, ammonium-nitrogen was the dominant conventional contaminant (PI_{mean} = 413.37), and all the other contaminants had average exceedances of < 30. The highest level of contamination among the five major heavy metals was that of nickel (Ni) (PI_{mean} = 235.53). Carbon tetrachloride, phenol, and chloroform exhibited average exceedances of 10346.88, 2461.93, and 1807.45, respectively, among the nine VOCs.

The main pollutants in the pesticide industry were raw and auxiliary materials, consistent with previous studies (Fang et al., 2017; Li et al., 2023; Wang et al., 2023b). Furthermore, intermediates, products, and their degradation products during the production process were also identified (Tao et al., 2022; Li et al., 2023). Chlorinated hydrocarbons (CHs) and BTEX (Benzene, Toluene, Ethylbenzene, and Xylene) are critical contaminants in soil and groundwater, mainly resulting from the use of CHs and benzene as solvents during the production process. In addition, CHs, such as carbon tetrachloride and chloroform, which are typical dense non-aqueous phase liquids (DNAPLs), are more likely to migrate under gravity and contaminate deep soil and groundwater. Furthermore, heavy metals and polycyclic aromatic hydrocarbons (PAHs) in soil and groundwater may have resulted from historical activities such as the use of coal and diesel as fuels and stockpiling. Moreover, chlorobenzenes, which are raw materials for pesticide production and the degradation products of hexachlorocyclohexane, are also contaminants that cannot be ignored in the pesticide industry (Vijgen et al., 2022). Hexachlorocyclohexane and DDT, which are typically persistent, are often detected at very high levels in soils many years after the pesticide manufacturing plants were abandoned (Ma et al., 2020). However, hexachlorocyclohexane and DDT are difficult to transport downward and usually accumulate in shallow soil layers because of their strong adsorption to the soil and hydrophobic nature (Liu et al., 2015; Zhu et al., 2023). In contrast, phenol, a polar substance, easily migrates vertically to pollute groundwater, which is an important reason it has become a major ground water pollutant (Zheng et al., 2024). The organophosphorus pesticide glyphosate is strongly adsorbed by the soil, and the high degree of water solubility allows a certain amount of glyphosate to enter groundwater (Kanissery et al., 2019; Soares et al., 2023).

In addition, the main contaminants in soil and groundwater include a number of typical odors, such as

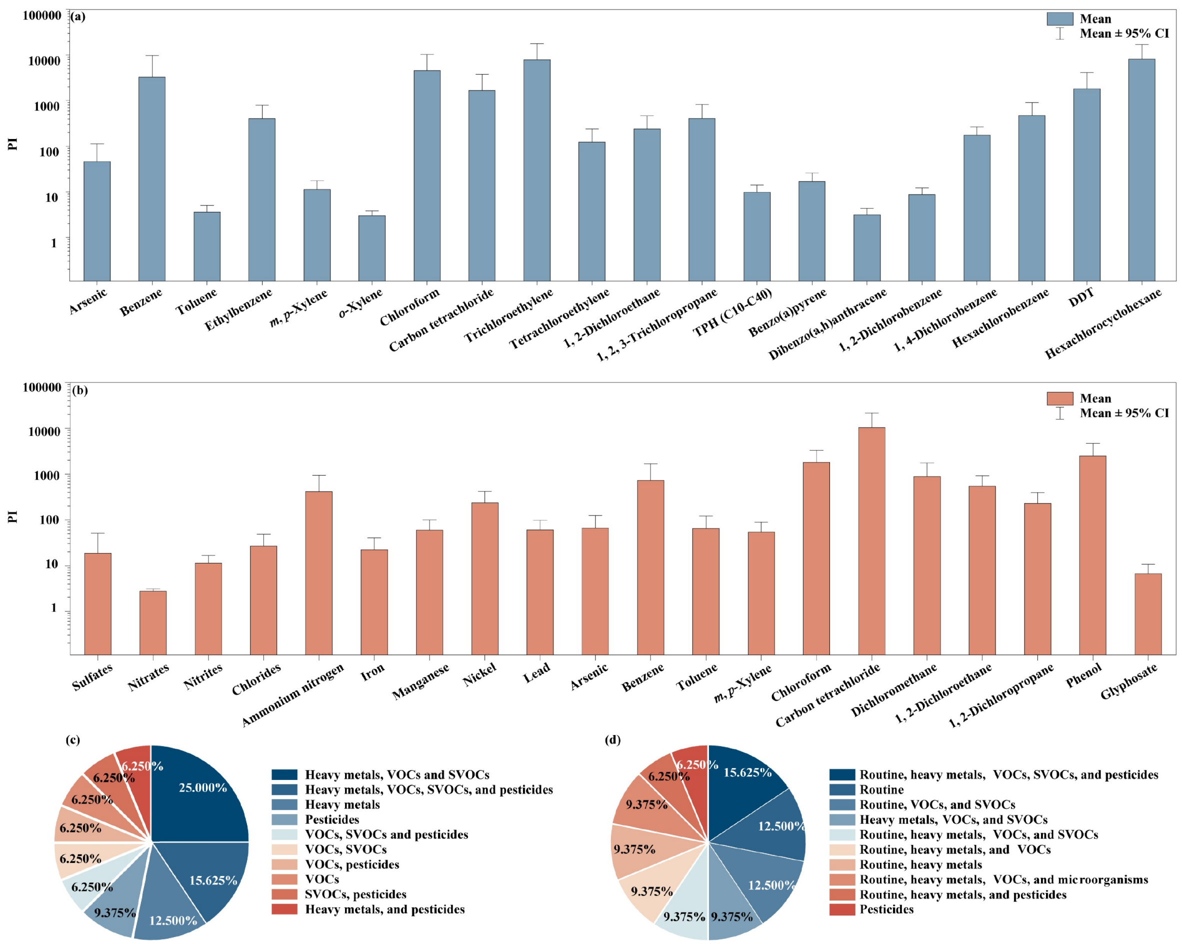

Fig. 2 Characteristics of soil and groundwater contamination at pesticide industry sites. (a) Major contaminants in soil, (b) major contaminants in groundwater, (c) types of soil composite contamination, and (d) types of groundwater composite contamination.

hexachlorocyclohexane, DDT, and phenol. Furthermore, a number of benzenes and CHs were detected at high levels at the pesticide site. These substances do not have an unpleasant odor profile; however, they may cause sensory irritation at high levels or may emit stronger odors when mixed with other malodorous substances (Zheng et al., 2024).

3.1.2 Composite pollution characteristics

Contaminated sites in the pesticide industry usually involve complex combined pollution caused by long production times and complex processes (Figs. 2(c) and 2(d)). Approximately 71.88% of the site's soil and 81.25% of the groundwater were contaminated with multiple pollutants. The main pollutants in the combined soil were heavy metals, VOCs and SVOCs (25.00%), and heavy metals, VOCs, SVOCs, and pesticides (15.63%). Additionally, the main pollutants in the combined groundwater were routine pollutants, heavy metals, VOCs, SVOCs, and pesticides (15.63%), and routine pollutants, VOCs, and SVOCs (12.50%).

Complex contamination is not only a simple combination of contaminants but also involves a complex interaction between contaminants, leading to more complex soil and groundwater contamination in decommissioned pesticide factories. These contaminations pose a challenge for remediation projects. Notably, various physical, chemical, and biological interactions occur between different contaminants that affect their environmental behavior and toxicity. For example, heavy metal-PAH complex contamination may affect the environmental behavior of both types of contaminants by mediating cation-π interactions and adsorption properties of organic matter and clay particles (Liang et al., 2016; Chen et al., 2020; Ashkanani et al., 2024). Simultaneously, the coexistence of heavy metals and organic pollutants increases ecological and health risks (Liu et al., 2019; Jin et al., 2023; Upadhyay et al., 2023). However, it has also been suggested that heavy metals contribute to the degradation of pesticides or PAHs by affecting microbial growth and reproduction and by enhancing bioavailability (Liu et al., 2007; Ashkanani et al., 2024). In addition, interactions exist between different heavy metals and organic matter, such as forming miscible phases between BTEX and CHs, which result in BTEX possibly contaminating deep soils and groundwater (Li et al., 2023). Additionally, site competition and toxicity enhancement exist between the different heavy metals. In summary, complex synergistic, additive, and antagonistic interactions exist between pollutants, and understanding their potential mechanisms of action is important for developing appropriate targeting strategies (Wang et al., 2015; Yu et al., 2019; Yang et al., 2023).

3.1.3 Spatial distribution characteristics

At the regional scale (Figs. 3(a) and 3(b)), most pesticide-contaminated sites were located in economically developed and conveniently located eastern coastal areas with a long history of pesticide production and in the agriculturally developed Yellow River Basin, Yangtze River Basin, and North-east China. Meanwhile, heavily contaminated soil and groundwater sites were located in Hebei, Hubei, Hunan, Jiangsu, Shandong, and Liaoning provinces, which usually have a long history of production and are large in size, and most are former producers of organochlorine pesticides. In the early years of pesticide production, the lack of standardized environmental management practices led to soil and groundwater contamination. Furthermore, organochlorine pesticides such as hexachlorocyclohexane and DDT are typical POPs in which a large number of solvents, intermediates, and by-products are used in the production process. In addition, the sites used in the production of these types of pesticides are usually highly polluted (Ma et al., 2020). The analysis of pollution conditions across different types of sites further corroborates the aforementioned conclusions (Figs. 3(c) and 3(d)). Specifically, former pesticide manufacturing enterprises with longer operational periods, primary product types of organochlorine pesticides, and larger production scales generally indicate a higher likelihood of elevated contamination levels in soil and groundwater. Moreover, climatic conditions and site hydrogeology are key factors influencing the level of contamination at decommissioned pesticide sites (Li et al., 2023).

At the site scale, the horizontal distribution is

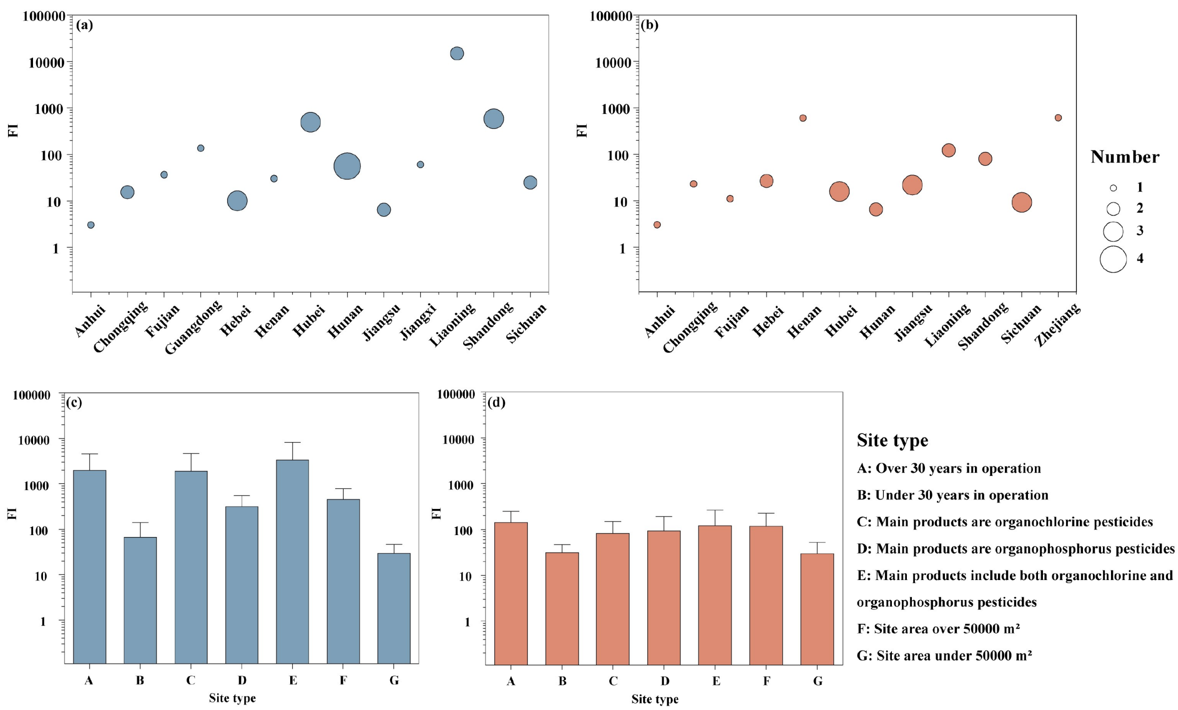

Fig. 3 The pollution characteristics of different areas ((a) soil, (b) groundwater) and types ((c) soil, (d) groundwater) of pesticide sites.

typically associated with the type of products, processes, layout, and environmental accidents at the original site. Most pollutants that were associated with raw and auxiliary materials, intermediates, products, and their degradation products usually accumulated in the soil and groundwater of production plants, warehouses, and wastewater treatment areas. The vertical distribution of contaminants is primarily influenced by the properties of the soil layers and the inherent characteristics of the contaminants. Generally, areas above 2 m are less polluted primarily because the soil at this depth is usually an uncontaminated backfill (Liu et al., 2015). In addition, the presence of more construction debris and loosely structured gravel in the soil at this depth provides a channel for contaminant transport. Notably, pollutants mainly accumulate in the clay layer, and soil adsorption and agglomerate formation could possibly be the primary reasons for their accumulation (Ma et al., 2017; Li et al., 2023). However, contaminant content generally decreased with an increase in depth below the clay layer. Furthermore, the vertical distribution of contaminants is inextricably linked to the properties of the pollutants. For instance, CHs and BTEX, characterized by lower soil-water partition coefficients and higher solubility, are more prone to migrate into deeper soil layers and groundwater. Heavy metal and PAHs contents were generally not observed at great depths. The conclusions are largely consistent with previous research findings on individual sites or limited areas (Liu et al., 2015; Li et al., 2023; Zheng et al., 2024).

Furthermore, most pesticide factories have a long production history, with 64.9% of the enterprises having over 20 years of production history and 21.1% having over 44 years (Fig. 1(b)). Most of the original factories had undergone several reconstructions, and more detailed data should be collected at the stage when the pollutions are identified to provide a basis for identifying key pollution areas. Additionally, long-term diffusion of pollutants in the soil may also affect non-key contaminated areas; hence, it is necessary to investigate these areas at the investigation stage. The vertical distribution of pollutants in the soil is also affected by climatic characteristics, such as rainfall, temperature, and the physical and chemical characteristics of each pollutant. For example, the leaching of pollutants from rainfall increases hydrodynamic migration, and indirect effects of water table fluctuations can significantly promote pollution of deep soil and groundwater (Xia et al., 2022; Li et al., 2023; Wei et al., 2023). Furthermore, temperature affects the volatility, solubility, and soil moisture content of pollutants, thus promoting or restricting the vertical migration of pollutants (Cavelan et al., 2022). Notably, the distribution coefficient of n-octanol–water, solubility, and volatility of pollutants are also key factors that affect their vertical distribution (Li et al., 2023).

3.2 Health risks of soil and groundwater

Table 1 summarizes the contaminants that posed health risks at more than three sites and their carcinogenic and non-carcinogenic risks. Arsenic, benzene, CHs, PAHs, and hexachlorocyclohexane were the key contaminants associated with soil cancer risk. Particularly, hexachlorocyclohexane had a cancer risk of 1.00E + 00 at one site. For non-carcinogenic risks, arsenic, BTEX, and CHs are key contaminants, notably benzene and chloroform, with an HI_{Max} 3620 times the acceptable value (HI = 1). In addition, oral ingestion and dermal exposure routes are usually not considered in the risk assessment process because the use of groundwater at pesticide-contaminated sites is usually restricted. The groundwater health risk was generally acceptable for both outdoor and indoor volatile gas inhalation exposure pathways, with only benzene, chloroform and 1,2-dichloroethane presenting a possible carcinogenic risk.

However, exposure pathways vary widely among pollutants and are influenced by pollutant depth and future land use planning. Overall, for arsenic and pesticides in the soil, oral ingestion was the main exposure pathway (contributing 76.51%–88.79% and 58.54%–78.13%, respectively), whereas the health risk mainly arises from the inhalation of gaseous pollutants from the subsoil in indoor air (average contribution 69.07%) and oral ingestion (average contribution 35.65%), for most VOCs in the soil. Oral ingestion (21.99%–70.50%) and dermal contact (29.25%–60.32%) were the key exposure pathways for SVOCs in the soil. Furthermore, inhaling indoor air from gaseous groundwater pollutants was identified for VOCs in groundwater, with an average contribution of 91.27%. In addition, pollutants pose different health risks to different age groups because of their different exposure pathways and times. Notably, children are more sensitive to pollutants because of their low bodyweight and underdeveloped enzyme metabolism (Kumar et al., 2017; Li et al., 2021a).

Generally, soils from decommissioned pesticide plants present unacceptable health risks, particularly in residential settings. Hence, there is a need to further restrict the future use of such sites by prohibiting residential use and possibly avoiding sites that may involve children (Li et al., 2023). Simultaneously, it is

Table 1 Descriptive statistics of the health risk of main soil and groundwater contaminants

Medium	Contaminant	Carcinogenic risk (CR)			Non-carcinogenic risk (HI)		
		Max	Mean	Median	Max	Mean	Median
Soil	Arsenic	2.14E-02	3.69E-03	2.40E-04	786.00	199.37	20.92
	Benzene	4.47E-02	3.47E-03	2.30E-05	3620.00	305.99	2.07
	Toluene	/	/	/	3.88	2.45	2.43
	Ethylbenzene	/	/	/	26.30	10.82	8.27
	m, *p*-Xylene				374.00	103.06	20.64
	o-Xylene	/	/	/	786.00	217.85	168.00
	Chloroform	2.84E-03	1.01E-03	1.48E-04	3620.00	573.04	10.90
	Carbon tetrachloride	1.40E-04	4.32E-05	1.53E-05	43.10	9.86	3.16
	Trichloroethylene	/	/	/	26.30	9.36	7.45
	Tetrachloroethylene	/	/	/	/	/	/
	1,2-Dichloroethane	7.44E-04	4.14E-04	4.44E-04	374.00	95.05	54.45
	1,2,3-Trichloropropane	2.94E-04	1.40E-04	1.21E-04	786.00	173.20	22.88
	1,2-Dichlorobenzene	/	/	/	/	/	/
	1,4-Dichlorobenzene	/	/	/	/	/	/
	Benzo(a)pyrene	4.69E-04	1.90E-04	1.44E-04	/	/	/
	Dibenzo(a,h)anthracene	6.13E-05	1.69E-05	2.55E-06	/	/	/
	α-Hexachlorocyclohexane	1.00E+00	2.00E-01	1.29E-04	/	/	/
	β-Hexachlorocyclohexane	9.56E-02	1.92E-02	1.45E-05	/	/	/
	γ-Hexachlorocyclohexane	3.85E-02	1.28E-02	2.33E-06	/	/	/
Groundwater	Benzene	9.32E-06	5.24E-06	5.25E-06	/	/	/
	Chloroform	3.74E-06	2.47E-06	1.83E-06	/	/	/
	1,2-Dichloroethane	3.21E-05	9.97E-06	2.67E-06	/	/	/

necessary to take measures to control the diffusion of VOCs, SVOCs, and pesticides from the soil to the air, particularly in some disturbed situations with rapid diffusion. Furthermore, workers' occupational health should be protected by taking specialized protective measures when carrying out remediation work (Bari and Kindzierski, 2018; Li and Yan, 2022). Notably, groundwater use restrictions reduce the risk of groundwater exposure. However, pressurized water, surrounding area groundwater, surface water, and soil due to fluctuations in the water table, contaminant transport and dispersion may increase the risk (Li et al., 2021b; Wang et al., 2023c). Furthermore, the risk level of contaminants in a site and the main contaminants' contribution to the risk change over time should be considered. Additionally, making timely adjustments to critical areas and high-risk contaminants in complex contaminated sites through dynamic risk assessment to develop effective remediation plans is essential (Li et al., 2020; Wang et al., 2023b). Meanwhile, a single risk assessment is insufficient to accurately reflect the risk of a composite-contaminated site (Wang et al., 2023b). Complex interactions between contaminants are not considered when assessing the health risk of a single contaminant following the Technical Guidelines for Risk Assessment of Contaminated Sites issued by the Chinese Ministry of Ecology and Environment. Therefore, scientific assessment of the health risks of soil and groundwater at complex sites, such as in the pesticide industry, requires further consideration.

3.3 Overview of rehabilitation works carried out

The high health risk of pesticide sites has always been the focus of control; however, high cost and technical difficulty have caused remediation projects in China to address fewer cases. However, with increasing awareness of environmental protection in recent years, especially since the release of the Soil Pollution Prevention and Control Action Plan in 2016, several pesticide sites have been remediated and their risk-control work performed (Fig. 4(a)). However, China is still generally dominated by off-site *ex situ* cement kiln co-processing, on-site *ex situ* thermal treatment, chemical treatment, and solidification/stabilization, accounting for 92.3% of all soil remediation technologies (Fig. 4(b)). Notably, groundwater is dominated by chemical treatment, monitored natural attenuation, vertically engineered barriers, and other *in situ* remediation techniques (Table 2). One-site *ex situ* pump-and-treat techniques are conventionally used only in areas with heavy groundwater contamination.

The average remediation depth, area, and volume of these pesticide sites reached 8 m, 20892 m^2 and 62218 m^3, respectively as shown in Figs. 4(c)–4(e). Specifically, 68.0% of the pesticide sites had remediation depths > 6 m, and three sites had remediation volumes of approximately 20 m. The remediation area of 61% of the sites was 8000 m^2, and the area exceeded 70000 m^2 at three sites. The remediation volume of 60% of the sites reached 20000 m^3, and the volume exceeded 200000 m^3 at three sites. The area of groundwater remediation was generally > 20000 m^2 because of high migration and diffusion levels of groundwater contaminants. Additionally, the volume of remediation at the three sites was > 120000 m^3 (Table 2).

Moreover, *ex situ* remediation is less time-consuming than *in situ* remediation. In addition, it is capable of homogenizing, screening, and continuously mixing the soil and has a higher degree of certainty regarding the homogeneity of the treatment process for more contaminated soils. Thus, it has become the mainstream technology for soil remediation (Amponsah et al., 2018; Beames et al., 2014; Chu and Zhu, 2024). However, high and large remediation depth and volume, respectively, render the remediation cost of pesticide sites extremely high. In addition, the possibility of secondary contamination during the remediation process (odorous nuisance, acute poisoning of workers, or neighboring residents) is a major challenge to remediation projects (Cadotte et al., 2007). Furthermore, the use of groundwater pathways is restricted, and exposure risks are relatively low. In contrast, *in situ* remediation technology has the advantages of low treatment cost, ability to address deep contamination, and low environmental perturbation, making it a promising groundwater pollution remediation technology (Amponsah et al.,

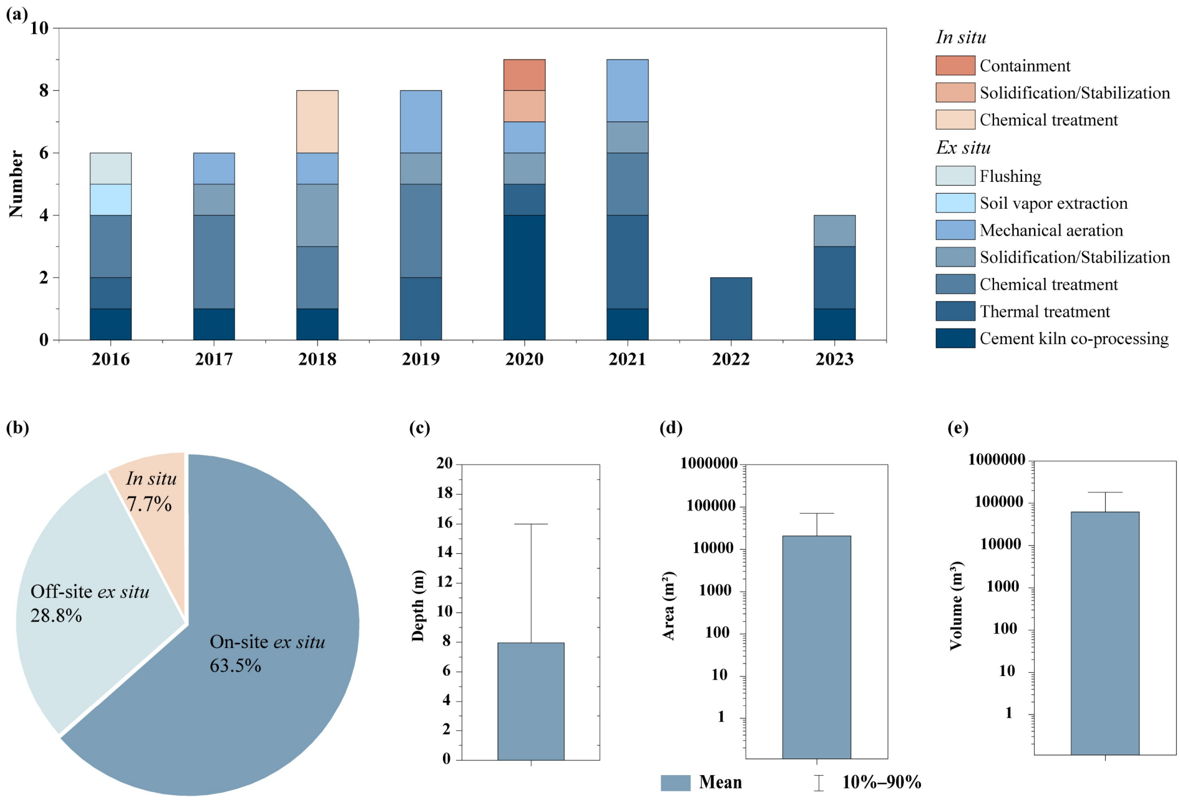

Fig. 4 Overview of soil remediation works performed at sites in the pesticide industry. (a) Application of technology, (b) type of technology applied, (c) depth of remediation, and (d) volume of remediation.

Table 2 Examples of groundwater remediation projects at pesticide sites

ID	Remedy	Area (m^2)	Volume (m^3)	Contaminant	Year
1	Pump and treat (*ex situ*) Chemical treatment (*in situ*)	20600.51	/	VOCs and Pesticides	2017
2	Chemical treatment (*in situ*)	39044.51	338906.33	VOCs	2018
3	Chemical treatment (*in situ*)	20300.00	/	Heavy Metals, VOCs and Pesticides	2018
4	Monitored natural attenuation (*in situ*) Vertical engineered barrier (*in situ*)	16000.00	/	VOCs, and TPH	2019
5	Vertical engineered barrier (*in situ*) Solidification/stabilization (*in situ*)	93000.00	/	Routine Pollutants, Heavy Metals, VOCs, SVOCs,	2020
6	Pump and treat (*ex situ*)	71372.20	124089.97	Routine Pollutants, VOCs, and SVOCs	2020
7	Pump and treat (*ex situ*) Vertical engineered barrier (*in situ*)	30900.00	14100.00	VOCs	2021
8	Pump and treat (*ex situ*)	/	193467.00	Heavy Metals and VOCs	2021
9	Monitored natural attenuation (*in situ*)	35328.00	/	VOCs	2021
10	Pump and treat (*ex situ*)	3440.00	3219.00	VOCs	2023
11	Vertical engineered barrier (*in situ*)	51439.00	/	Pesticides	2023

2018). However, a long remediation time, unstable remediation effect, and limited applicability limit its use.

3.4 New challenges and countermeasures for restoration works

3.4.1 Challenges and responses to odor

A wide range of odorous substances are the main pollutants in the pesticide industry, particularly strong odors, which have been highlighted in several reports. Odors are the second most important environmental problem in China after noise, complicating the development of pesticide site remediation. Furthermore, a number of contaminated sites have received numerous complaints regarding unpleasant odors, leading to suspension or delays in remediation works, which has resulted in considerable losses to stakeholders. At the same time, bad odors may also affect the reuse value of the site, leading to public dissatisfaction and even mass incidents. Practical experience has shown that conventional methods for preventing and controlling secondary pollution are inadequate, making it difficult to manage malodors that escape from the soil during remediation. Consequently, odor control throughout the site remediation process has become the focus of public complaints. Additionally, difficulties in remediation and management evaluation of have affected project completion.

Studies have shown that both the types and spatial distributions of malodor pollutants differ from those of other environmental pollutants (Zheng et al., 2023; 2024). Separate identification, assessment, and treatment of malodorous pollutants are necessary to prevent malodorous nuisance during remediation and reuse. Hence, it is necessary to standardize the methodology for site malodor assessment and clarify the objectives and scope of malodor control. Simultaneously, targeted measures regarding the site of the malodorous substances, such as the formation of “source removal-interface blocking and control-air reduction” all-round control technology system, effectively reduce the nuisance of malodors to achieve the safe use of the site. In addition, malodor is simultaneously a social issue (Zheng et al., 2024), and the remediation party needs to closely consider the public's needs, which requires frequent field visits to the surrounding residential areas to gain a deeper understanding of the public’s concerns and communicate with resident representatives about the progress of remediation in a timely manner. Furthermore, strengthening public opinion guidance is an important task that needs to be conducted. Moreover, the education level of the surrounding residents should be duly considered, and science popularization activities, widely carried out around the site to inform residents of the actual impacts of malodor and the control measures to be taken and to clarify misunderstandings and one-sided perceptions such as “malodor is equal to the existence of health risks.”

3.4.2 Challenges and responses to sustainable development

The remediation depth and volume of a pesticide industry site, which are heavily contaminated sites, are much greater than those of a typical site, which implies an extremely high remediation cost. Recently, the green and sustainable remediation (GSR) movement has emerged, and the economic, environmental, and social benefits of the whole process of remediation projects have received increasing attention (Xiao et al., 2024). Additionally, a series of secondary contamination events and sustainable *in situ* and risk management technologies are increasingly favored (Hou et al., 2023). However, remediation efficiency and market maturity limit the application of GSR technology in the remediation of heavily contaminated sites, such as those with pesticides. Furthermore, more efficient traditional *ex situ* remediation technologies are still preferred in most remediation projects in China, driven by profit and stringent remediation schedules, despite their socioeconomic impacts and secondary environmental burdens (Hou et al., 2023).

The development of efficient GSR technologies and engineering demonstrations of these technologies to form a marketable GSR technology system that can be scaled up and applied may be an important project that is needed. Simultaneously, while recognizing the advantages of GSR, identifying its limitations is also important. Most GSR technologies usually leave a certain amount of pollutants remaining in the target area (Song et al., 2019). Hence, there is a need to establish a more comprehensive site risk management system, incorporate long-term management based on the GSR, and achieve effective risk control through risk management, institutional control, and other measures (Song et al., 2019; Shi et al., 2024).

3.4.3 Challenges and responses to climate change

Many pesticide sites have been in production for a long time and still have high levels of deep soil and groundwater contamination, along with complex contamination. This also indicates that the remediation of pesticide sites usually requires a longer remediation period and is more likely to face the challenges of climate change. Furthermore, strong fluctuations in groundwater levels and higher temperatures alter the environmental behavior of contaminants, particularly NAPLs and heavy metals, which are important contaminant types for pesticide sites (Wei et al., 2021; Cavelan et al., 2022). Furthermore, changes in hydrological conditions make restoration programs less effective, and restoration facilities can be damaged by climate change, which also increases risks to worker safety (Hou et al., 2023).

In summary, these findings could increase the involvement level of restoration programs and require the incorporation of climate change resilience. Furthermore, the potential impact of climate change remediation projects on the full lifecycle should be assessed before the commencement of work, and targeted strategies should be designed in advance. The targeted strategies should also be adjusted in a timely manner as restoration progresses and climate change occurs rather than being set from the outset (Kumar and Reddy, 2020). The development of universal restoration techniques is also a viable option. In addition, protective measures for restoration work against extreme weather conditions may be included in the scope of regulation.

4 Conclusions and perspectives

The present study broke through the mold of previous studies that have been limited to a single area or specific pollutants, and it integrated multi-source data of 57 pesticide-contaminated sites in China to reveal the distribution characteristics, pollution characteristics, and health risks of pesticide-contaminated sites. Overall, the main conclusions are as follows: 1) Heavy metals (As), VOCs (CHs, BTEX), SVOCs (PAHs), and pesticides (BHC, DDT) are major soil pollutants. Furthermore, routine pollutants (ammonium-nitrogen), heavy metals (Ni, Pb, As), VOCs (CHs, BTEX), and pesticides (glyphosate) are the main pollutants in groundwater. 2) Soil and groundwater are generally polluted by various pollutants. 3) Heavily polluted sites were mainly concentrated in Hebei, Hubei, Hunan, Jiangsu, Shandong, and Liaoning provinces, which have been engaged in pesticide production for a long time, especially at sites used to produce organochlorine pesticides. 4) Soils generally present unacceptable health risks due to key pollutants such as arsenic, benzene, CHs, PAHs, and hexachlorocyclohexane, which are associated with carcinogenic risk. However, non-carcinogenic risks are primarily associated with arsenic, BTEX, and CHs. 5) More comprehensive and efficient restoration technologies, such as on-site *ex situ* or off-site *ex situ* technologies, remain the first choices for restoration projects owing to the high soil health risks. Meanwhile, higher costs and lower health risks promote the use of *in situ* remediation and risk management techniques in groundwater remediation projects. 6) Pesticide site restoration projects in the new era face challenges such as odor nuisance, sustainable development, and climate change. Therefore, it is necessary to improve the corresponding management and remediation technology systems to meet these challenges, realize effective control of soil and groundwater risks at pesticide sites, maintain public health, guarantee the quality of public life, and improve public satisfaction.

The current study explored overall pollution and remediation technology development status. However, in-depth data analysis is still lacking. Factors such as soil properties, climate conditions, and production processes that contribute to the degree of pollution still need to be explored. Machine learning may be a reliable tool in future research.

Credit Authorship Contribution Statement
Hongguang Zheng: Formal analysis, Methodology, Data Curation, and writing original draft; **Ying Hou:** Formal analysis, writing original draft; **Yi Shi:** Methodology, Data Curation; **Hongxia Hu:** Visualization; **Weiguang Zhao:** Data Curation; **Nuchao Xu:** Visualization; **Juejun Yao:** Conceptualization, Supervision; **Aizhong Ding:** Writing-review and editing, Funding acquisition.

Conflict of Interests 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.

Acknowledgements We are grateful to the grants from This research was supported by the National Natural Science Foundation of China (No. 42472323), the Beijing Municipal Natural Science Foundation (No. 8232037).

References

Al-Shaalan N H, Ali I, Alothman Z A, Al-Wahaibi L H, Alabdulmonem H (2019). High performance removal and simulation studies of diuron pesticide in water on MWCNTs. Journal of Molecular Liquids, 289: 111039

Ali I, Aboul-Enein H Y (2001). Leaching of triazine pesticides in loamy soil and their determination by reversed phase HPLC. International Journal of Environmental Analytical Chemistry, 81(4): 315–322

Ali I, Aboul-Enein H Y (2002). Determination of chiral ratio of *o,p*-DDT and *o,p*-DDD pesticides on polysaccharides chiral stationary phases by HPLC under reversed-phase mode. Environmental Toxicology, 17(4): 329–333

Amponsah N Y, Wang J, Zhao L (2018). A review of life cycle greenhouse gas (GHG) emissions of commonly used *ex-situ* soil treatment technologies. Journal of Cleaner Production, 186: 514–525

Ashkanani Z, Mohtar R, Al-Enezi S, Smith P K, Calabrese S, Ma X, Abdullah M (2024). AI-assisted systematic review on remediation of contaminated soils with PAHs and heavy metals. Journal of Hazardous Materials, 468: 133813

Bari M A, Kindzierski W B (2018). Ambient volatile organic compounds (VOCs) in Calgary, Alberta: sources and screening health risk assessment. Science of the Total Environment, 631–632: 627–640

Basheer A A, Ali I (2018). Stereoselective uptake and degradation of (±)-*o,p*-DDD pesticide stereomers in water-sediment system. Chirality, 30(9): 1088–1095

Beames A, Broekx S, Lookman R, Touchant K, Seuntjens P (2014). Sustainability appraisal tools for soil and groundwater remediation: how is the choice of remediation alternative influenced by different sets of sustainability indicators and tool structures? Science of the Total Environment, 470–471: 954–966

Bokade P, Gaur V K, Tripathi V, Bobate S, Manickam N, Bajaj A (2023). Bacterial remediation of pesticide polluted soils: exploring the feasibility of site restoration. Journal of Hazardous Materials, 441: 129906

Boudh S, Tiwari S, Singh C, Singh J S (2024). Lindane degradation potential of methanotrophs and soil microbial biomass from HCH contaminated sites. Environmental Advances, 17: 100581

Brady J P, Ayoko G A, Martens W N, Goonetilleke A (2015). Development of a hybrid pollution index for heavy metals in marine and estuarine sediments. Environmental Monitoring and Assessment, 187(5): 306

Cadotte M, Deschênes L, Samson R (2007). Selection of a remediation scenario for a diesel-contaminated site using LCA. International Journal of Life Cycle Assessment, 12(4): 239–251

Cavelan A, Golfier F, Colombano S, Davarzani H, Deparis J, Faure P (2022). A critical review of the influence of groundwater level fluctuations and temperature on LNAPL contaminations in the context of climate change. Science of the Total Environment, 806(1): 150412

Chen J, Xia X, Chu S, Wang H, Zhang Z, Xi N, Gan J (2020). Cation-pi interactions with coexisting heavy metals enhanced the uptake and accumulation of polycyclic aromatic hydrocarbons in spinach. Environmental Science & Technology, 54(12): 7261–7270

Chu C, Zhu L (2024). Paving the way toward soil safety and health: current status, challenges, and potential solutions. Frontiers of Environmental Science & Engineering, 18(6): 74

Dvorská A, Sír M, Honzajková Z, Komprda J, Cupr P, Petrlík J, Anakhasyan E, Simonyan L, Kubal M (2012). Obsolete pesticide storage sites and their POP release into the environment: an Armenian case study. Environmental Science and Pollution Research International, 19(6): 1944–1952

Fan T, Yang M, Li Q, Zhou Y, Xia F, Chen Y, Yang L, Ding D, Zhang S, Zhang X, et al. (2022). A new insight into the influencing factors of natural attenuation of chlorinated hydrocarbons contaminated groundwater: a long-term field study of a retired pesticide site. Journal of Hazardous Materials, 439: 129595

Fang Y, Nie Z, Die Q, Tian Y, Liu F, He J, Huang Q (2017). Organochlorine pesticides in soil, air, and vegetation at and around a contaminated site in southwestern China: concentration, transmission, and risk evaluation. Chemosphere, 178: 340–349

Gu W, Xing W, Liang M, Wang Z, Zhang B, Sun S, Fan D, Wang L (2023). Occurrence, distribution, and risk assessment of pesticides in surface water and sediment in Jiangsu Province, China. Environmental Science and Pollution Research International, 30(56): 118418–118429

Hong H, Wu S, Wang Q, Qian L, Lu H, Liu J, Lin H J, Zhang J, Xu W B, Yan C (2021). Trace metal pollution risk assessment in urban mangrove patches: potential linkage with the spectral characteristics of chromophoric dissolved organic matter. Environmental Pollution, 272: 115996

Hou D, Al-Tabbaa A, O'Connor D, Hu Q, Zhu Y G, Wang L, Kirkwood N, Ok Y S, Tsang D C W, Bolan N S, et al. (2023). Sustainable remediation and redevelopment of brownfield sites. Nature Reviews. Earth & Environment, 4(4): 271–286

Hu H, Zheng H, Liu F, Ding Z, Wang Z, Peng Y, Zhang D, Zhang Y, Zheng Y, Ding A (2024). Heavy metal contamination assessment and source attribution in the Vicinity of an iron slag pile in Hechi, China: Integrating multi-medium analysis. Environmental Research, 263(3): 120206

Huang S, Zhao X, Sun Y, Ma J, Gao X, Xie T, Xu D, Yu Y, Zhao Y (2017). Pollution of hazardous substances in industrial construction and demolition wastes and their multi-path risk within an abandoned pesticide manufacturing plant. Frontiers of Environmental Science & Engineering, 11(1): 12

Jin N, Yang K, Li J, Song Y, Ding A, Sun Y, Li G, Zhang D (2023). Toxicity characterization of environment-related pollutants using a biospectroscopy-bioreporter-coupling approach: potential for real-world toxicity determination and source apportionment of multiple pollutants. Analytical Chemistry, 95(9): 4291–4300

Kan H, Wang T, Yu J, Qu G, Zhang P, Jia H, Sun H (2021). Remediation of organophosphorus pesticide polluted soil using persulfate oxidation activated by microwave. Journal of Hazardous Materials, 401: 123361

Kanissery R, Gairhe B, Kadyampakeni D, Batuman O, Alferez F (2019). Glyphosate: its environmental persistence and impact on crop health and nutrition. Plants, 8(11): 499

Kumar G, Reddy K R (2020). Addressing climate change impacts and resiliency in contaminated site remediation. Journal of Hazardous, Toxic and Radioactive Waste, 24(4): 04020026

Kumar S M, Sivasankar V, Gopalakrishna G V T (2017). Quantification of benzene in groundwater sources and risk analysis in a popular south Indian Pilgrimage City: a GIS based approach. Arabian Journal of Chemistry, 10(S2): 2523–2533

Li C, Sanchez G M, Wu Z, Cheng J, Zhang S, Wang Q, Li F, Sun G, Meentemeyer R K (2020). Spatiotemporal patterns and drivers of soil contamination with heavy metals during an intensive urbanization period (1989–2018) in Southern China. Environmental Pollution, 260: 114075

Li M, Chen Q, Yang L, Zhang Y, Jiang J, Deng S, Wan J, Fan T, Long T, Zhang S, et al. (2023). Contaminant characterization at pesticide production sites in the Yangtze River Delta: residue, distribution, and environmental risk. Science of the Total Environment, 860: 160156

Li P, Karunanidhi D, Subramani T, Srinivasamoorthy K (2021b). Sources and consequences of groundwater contamination. Archives of Environmental Contamination and Toxicology, 80(1): 1–10

Li X, Huang X, Zhang Y (2021a). Spatio-temporal analysis of groundwater chemistry, quality and potential human health risks in the Pinggu Basin of North China Plain: evidence from high-resolution monitoring dataset of 2015–2017. Science of the Total Environment, 800: 149568

Li Y, Yan B (2022). Human health risk assessment and distribution of VOCs in a chemical site, Weinan, China. Open Chemistry, 20(1): 192–203

Liang X, Zhu L, Zhuang S (2016). Sorption of polycyclic aromatic hydrocarbons to soils enhanced by heavy metals: perspective of molecular interactions. Journal of Soils and Sediments, 16(5): 1509–1518

Liu L, Bai L, Man C, Liang W, Li F, Meng X (2015). DDT vertical migration and formation of accumulation layer in pesticide-producing sites. Environmental Science & Technology, 49(15): 9084–9091

Liu N, Zhong G, Zhou J, Liu Y, Pang Y, Cai H, Wu Z (2019). Separate and combined effects of glyphosate and copper on growth and antioxidative enzymes in *Salvinia natans* (L.) All. Science of the Total Environment, 655: 1448–1456

Liu T F, Sun C, Ta N, Hong J, Yang S G, Chen C X (2007). Effect of copper on the degradation of pesticides cypermethrin and cyhalothrin. Journal of Environmental Sciences, 19(10): 1235–1238

Ma Y, Shi Y, Hou D, Zhang X, Chen J, Wang Z, Xu Z, Li F, Du X (2017). Treatability of volatile chlorinated hydrocarbon-contaminated soils of different textures along a vertical profile by mechanical soil aeration: a laboratory test. Journal of Environmental Sciences, 54: 328–335

Ma Y, Yun X, Ruan Z, Lu C, Shi Y, Qin Q, Men Z, Zou D, Du X, Xing B, et al. (2020). Review of hexachlorocyclohexane (HCH) and dichlorodiphenyltrichloroethane (DDT) contamination in Chinese soils. Science of the Total Environment, 749: 141212

MEE (2004). The Technical Specification for Soil Environmental monitoring (HJ/T 166–2004). Beijing: Ministry of Ecology and Environment of The People's Republic of China (in Chinese)

MEE (2017). Standard for Groundwater Quality (GB 14848–2017). Beijing: Ministry of Ecology and Environment of The People's Republic of China (in Chinese)

MEE (2018). Soil Environmental Quality Risk Control Standard for Soil Contamination of Development Land (GB 36600–2018). Beijing: Ministry of Ecology and Environment of The People's Republic of China (in Chinese)

MEE (2019). Technical Guidelines for Risk Assessment of Soil Contamination of Land for Construction (HJ 25.3–2019).

Beijing: Ministry of Ecology and Environment of The People's Republic of China (in Chinese)

MEE (2020). Technical Specifications for Environmental Monitoring of Groundwater (HJ 164–2020). Beijing: Ministry of Ecology and Environment of The People's Republic of China (in Chinese)

Qu J, Liu R, Bi X, Li Z, Li K, Hu Q, Zhang X, Zhang G, Ma S, Zhang Y (2023). Remediation of atrazine contaminated soil by microwave activated persulfate system: performance, mechanism and DFT calculation. Journal of Cleaner Production, 399: 136546

Shi P, Ma Y, Peng Z, Wei G, Kang R, Wang L, Liu Z, Fan Y, Li F (2024). Developing an institutional control framework for contaminated sites in China: an analytical case study. Science of the Total Environment, 951: 175563

Soares C, Fernandes B, Paiva C, Nogueira V, Cachada A, Fidalgo F, Pereira R (2023). Ecotoxicological relevance of glyphosate and flazasulfuron to soil habitat and retention functions: single vs combined exposures. Journal of Hazardous Materials, 442: 130128

Song Y, Kirkwood N, Maksimović Č, Zheng X, O'Connor D, Jin Y, Hou D (2019). Nature based solutions for contaminated land remediation and brownfield redevelopment in cities: a review. Science of the Total Environment, 663: 568–579

Tang F H M, Lenzen M, Mcbratney A, Maggi F (2021). Risk of pesticide pollution at the global scale. Nature Geoscience, 14(4): 206–210

Tang F H M, Malik A, Li M, Lenzen M, Maggi F (2022). International demand for food and services drives environmental footprints of pesticide use. Communications Earth & Environment, 3(1): 272

Tao Y, Liu J, Xu Y, Liu H, Yang G, He Y, Xu J, Lu Z (2022). Suspecting screening "known unknown" pesticides and transformation products in soil at pesticide manufacturing sites. Science of the Total Environment, 808: 152074

Tripathi V, Dubey R K, Edrisi S A, Narain K, Singh H B, Singh N, Abhilash P C (2014). Towards the ecological profiling of a pesticide contaminated soil site for remediation and management. Ecological Engineering, 71: 318–325

Upadhyay S K, Rani N, Kumar V, Mythili R, Jain D (2023). A review on simultaneous heavy metal removal and organo-contaminants degradation by potential microbes: current findings and future outlook. Microbiological Research, 273: 127419

Vijgen J, Fokke B, van de Coterlet G, Amstaetter K, Sancho J, Bensaïah C, Weber R (2022). European cooperation to tackle the legacies of hexachlorocyclohexane (HCH) and lindane. Emerging Contaminants, 8: 97–112

Villamizar M L, Stoate C, Biggs J, Morris C, Szczur J, Brown C D (2020). Comparison of technical and systems-based approaches to managing pesticide contamination in surface water catchments. Journal of Environmental Management, 260: 110027

Wang H, Yan Z, Zhang Z, Jiang K, Yu J, Yang Y, Yang B, Shu J, Yu Z, Wei Z (2023a). Real-time emission characteristics, health risks, and olfactory effects of VOCs released from soil disturbance during the remediation of an abandoned chemical pesticide industrial site. Environmental Science and Pollution Research International, 30(41): 93617–93628

Wang M, Jiang D, Ding D, Deng S, Kong L, Wei J, Xia F, Li M, Long T (2023b). Spatiotemporal characteristics and dynamic risk assessment of a multi-solvents abandoned pesticide-contaminated site with a long history, in China. Journal of Environmental Management, 336: 117633

Wang Y, Chen C, Qian Y, Zhao X, Wang Q (2015). Ternary toxicological interactions of insecticides, herbicides, and a heavy metal on the earthworm *Eisenia fetida*. Journal of Hazardous Materials, 284: 233–240

Wang Y, Yuan S, Shi J, Ma T, Xie X, Deng Y, Du Y, Gan Y, Guo Z, Dong Y, et al. (2023c). Groundwater quality and health: making the invisible visible. Environmental Science & Technology, 57(13): 5125–5136

Wei J, Shi P, Cui G, Li X, Xu M, Xu D, Xie Y (2023). Analysis of soil pollution characteristics and influencing factors based on ten electroplating enterprises. Environmental Pollution, 337: 122562

Wei Y, Xu X, Zhao L, Chen X, Qiu H, Gao B, Cao X (2021). Migration and transformation of chromium in unsaturated soil during groundwater table fluctuations induced by rainfall. Journal of Hazardous Materials, 416: 126229

Xia X, Stewart D I, Cheng L, Liu Y, Wang Y, Ding A (2022). Variation of bacterial community and alkane monooxygenase gene abundance in diesel *n*-alkane contaminated subsurface environment under seasonal water table fluctuation. Journal of Contaminant Hydrology, 248: 104017

Xiao M, Li X, Zhang H, Meng H, Dong J (2024). Environmental impact assessment and remediation decision-making of a contaminated megasite: combining LCA and IO-LCA. Journal of Cleaner Production, 462: 142586

Yang Q, Li G, Jin N, Zhang D (2023). Synergistic/antagonistic toxicity characterization and source-apportionment of heavy metals and organophosphorus pesticides by the biospectroscopy-bioreporter-coupling approach. Science of the Total Environment, 905: 167057

Ye T, Wang Z, Liu G, Teng J, Xu C, Liu L, He C, Chen J (2023). Contaminant characterization of odor in soil of typical pesticide-contaminated site with shallow groundwater. Environmental Science and Pollution Research International, 30(57): 121182–121195

Yu Y, Li X, Yang G, Wang Y, Wang X, Cai L, Liu X (2019). Joint toxic effects of cadmium and four pesticides on the earthworm (*Eisenia fetida*). Chemosphere, 227: 489–495

Zhang Y, Peng Z, Dong Z, Wang M, Jiang C (2022b). Twenty years of achievements in China's implementation of the Stockholm Convention. Frontiers of Environmental Science & Engineering, 16(12): 152

Zhang Z, Yan X, Jones KC, Jiao C, Sun C, Liu Y, Zhu Y, Zhang Q, Zhai L, Shen Z, et al. (2022a). Pesticide risk constraints to achieving Sustainable Development Goals in China based on national modeling. npj Clean Water, 5(1): 59

Zheng H, Du X, Ma Y, Zhao W, Zhang H, Yao J, Shi Y, Zhao C (2023). Combined assessment of health hazard and odour impact of soils at a contaminated site: a case study on a defunct pharmaceuticals factory in China. Environmental Geochemistry and Health, 45(11): 7679–7692

Zheng H, Zhao W, Du X, Hua J, Ma Y, Zhao C, Lu H, Shi Y, Yao J (2024). Determining the soil odor control area: a case study of an abandoned organophosphorus pesticide factory in China. Science of the Total Environment, 906: 167436

Zhu X, Yang F, Li Z, Fang M, Ma S, Zhang T, Li C, Guo Q, Wang X, Zhang G, et al. (2023). Substantial halogenated organic chemicals stored in permafrost soils on the Tibetan Plateau. Nature Geoscience, 16(11): 989–996