ACS OMEGA
Open Access

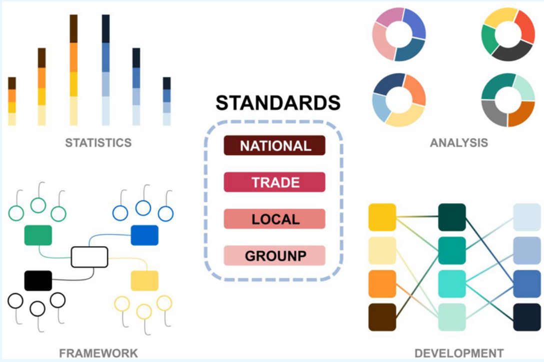
http://pubs.acs.org/journal/acsodf
Review

Development of a Multifaceted Perspective for Systematic Analysis, Assessment, and Performance for Environmental Standards of Contaminated Sites

Hao Zhang,* Yang Yang, Shaobing Ma, Wenchao Yuan, Mingjun Gao, Tongtong Li, Yuquan Wei, Yanwei Wang,* Yanna Xiong,* Aiyang Li, and Bin Zhao*

Cite This: *ACS Omega* 2024, 9, 3078−3091
Read Online

ABSTRACT: Contaminated soil and groundwater can pose significant risks to human health and ecological environments, making the remediation of contaminated sites a pressing and sustained challenge. It is significant to identify key performance indicators and advance environmental management standards of contaminated sites. The traditional study currently focuses on the inflexible collection of related files and displays configurable limitations regarding integrated assessment and in-depth analysis of published standards. In addition, there is a relative lack of research focusing on the analysis of different types of standard documents. Herein, we introduce a cross-systematic retrospective and review for the development of standards of the contaminated sites, including the comprehensive framework, multifaceted analysis, and improved suggestion of soil and groundwater standards related to the environment. The classification and structural characteristics of different types of files are systematically analyzed of over 300 national, trade, local, and group standards for the contaminated sites. It exhibits that trade standards are the main types and testing methods are the important format within numerical considerations of soil standards. The guide standard serves as a crucial component in environmental management for investigating, assessing, and remediating of contaminated sites. Future improvement plans and development directions are proposed for advancing robust technical support for effective soil contamination prevention and control. This multidimensional analysis and the accompanying suggestions can provide improved guidance for Chinese environmental management of contaminated sites and sparkle the application of standards in a wide range of countries.



1. INTRODUCTION

1.1. The Generation of the Contaminated Sites. With the continuous demand for urban development and the demolition of buildings, a large number of contaminated sites have been created causing serious environmental problems in China, due to the waste gas, wastewater, and waste residue emitted from the activities of industrial and mining production and also high regional background level.[1−3] These sites would pose a potential risk to human health and the ecological environment through the contamination of soil, sediment, surface water, groundwater, and air migration by hazardous chemicals,[4−6] such as heavy metals (e.g., Pb,[7] Cd,[8] Cr,[9] Hg[10]), metalloid (e.g., As[11]), volatile organic compounds (VOCs),[12,13] semivolatile organic compounds (SVOCs),[14] and pesticides.[15,16] It resulted in different exposure routes such as soil inhalation, surface and groundwater drinking, plant uptake, and accumulation in the food chain for different harmful contaminants.[17,18] Additionally, some chemicals in the contaminated soil can leach or enter the groundwater with seepage water, resulting in deterioration of groundwater quality over time and eventually leading to pollution.[19−21]

Effective environmental management necessitates the targeted risk control and remediation of contaminated sites, guided by robust scientific principles and efficient governance mechanisms, including laws, regulations, and standards.[22−24] However, the risks of soil and groundwater contamination are remaining in key industrial sites with in-depth characteristics such as concealment, complexity, and durability.[25,26] Consequently, the standardization of management practices and the scientific development of relevant documents have emerged as crucial research areas and focal points for ensuring effective environmental management.[27−29]

1.2. Environmental Management of the Contaminated Sites. In the past decade, it has consistently issued

Received: July 18, 2023
Revised: December 5, 2023
Accepted: December 15, 2023
Published: January 11, 2024

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

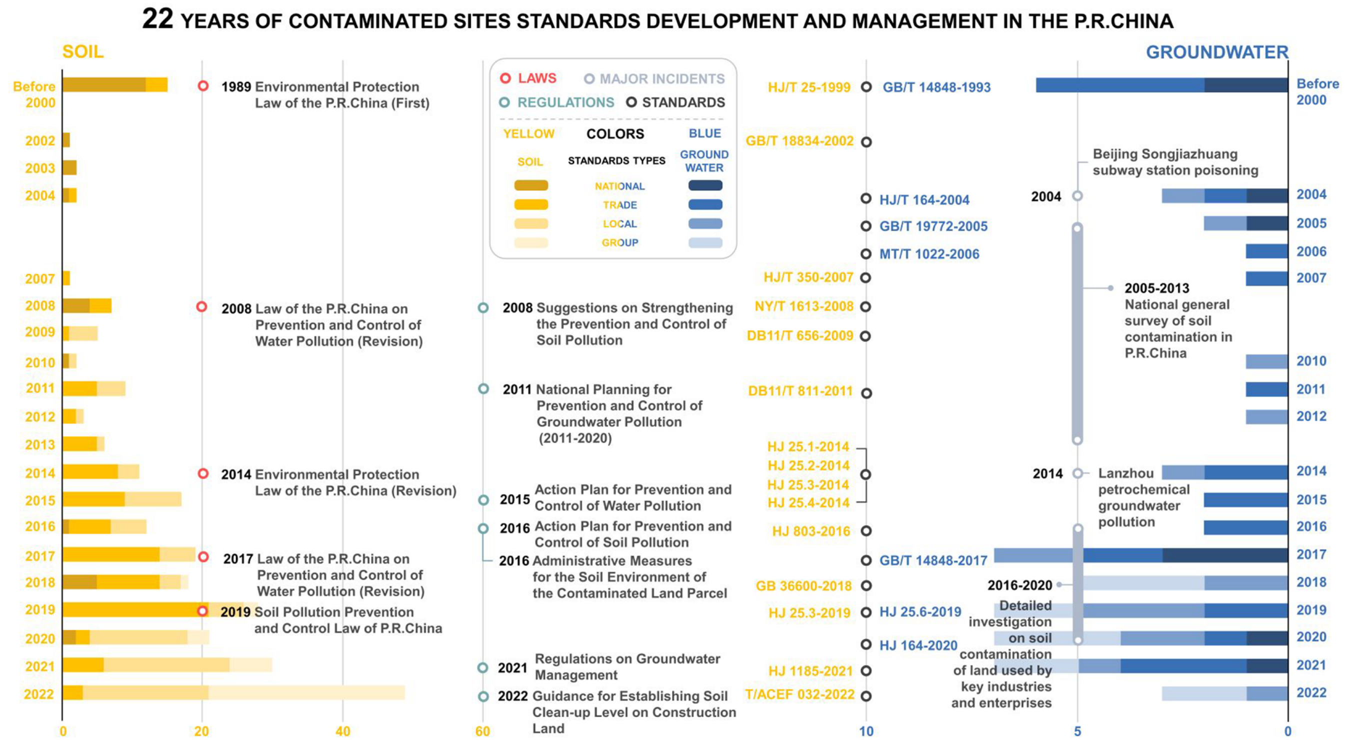


Figure 1. Important environmental management and statistics of different typed standards of contaminated sites in China about two decades. The colored histograms meant the counts of the different types of standards (yellow for soil and blue for groundwater). The historical developments of important laws, regulations, standards, and major accidents were also illustrated.

many policy documents and significant planning proposals to address the prevention and control of contaminated sites (Figure 1). These documents have established a comprehensive system of laws and regulations for soil and groundwater environmental management enhancing the legal framework for ecological environmental protection.[30,31] For example, it provided for the management of groundwater in terms of investigation and planning, conservation and protection, management of overexploitation, pollution prevention and control, and supervision and management (Regulations on Groundwater Management, 2021), and it has achieved certain results in the prevention and control of soil contamination with a sound system of policies and regulations for soil environmental protection (the Soil Pollution Prevention and Control Action Plan, 2016; Administrative Measures for the Soil Environment of the Contaminated Land Parcel, 2016; and the Soil Pollution Prevention and Control Law of the People's Republic of China, 2019).[32−34]

Among the various documents categorizing management practices, environmental standards play a fundamental role as indispensable devices for supervising contaminated sites.[35−37] These standards can be classified into different types including national, trade, local, group standards, and other relevant aspects. A national standard is a standard that has been adopted by a state agency and publicly released. Trade standards are complementary to national standards and are harmonized across the country within a particular industry. Local standards are those adopted and publicly released in a region of the country. Group standards are standards independently formulated and released by groups in accordance with the standard-setting procedures established by the groups and voluntarily adopted by society to fill the gaps in existing standards.[3,17,35]

Most studies have been reported regarding the environmental influence of contaminated sites, such as detailed investigation,[38] risk assessment,[17,39−41] and remediation technologies,[42−44] both domestically and internationally,[45−48] drawing proposed improvements to relevant policies and standard systems.[49,50] However, many previous studies have primarily concentrated on elaborating macroscopic data within the standard documents, such as quantitative profiling, surface type classification, and information description, often without establishing effective interaction between statistical information and content characterization.[44,51] There is also a considerable demand for an in-depth policy analysis of the standard system, including multifaceted discussions on the historical development differences, key standards assessment, and structural frameworks.[52] Furthermore, with the detailed introduction of previous findings, regular updates and systematic studies of the latest policies and standards documents are necessary to meet the future demands of environmental management.[53−55]

Hence, we introduced a multidimensional perspective to review the current development of environmental standards for contaminated sites in China. This assessment involved a comprehensive review of soil and groundwater environmental standards developed and published in China, primarily between 2001 and 2022. The historical development, systematical frameworks, key standards, related environmental influence, and content analysis were in-depth discussed. Additionally, the study provided a suggested supplement on the future direction and plan for potential standards development. Furthermore, advanced applications and multifaceted assessment can highlight environmental management with scientific methodologies in China and internationally.

2. DATA COLLECTION DETAILS

All standard information was systematically gathered from publicly available Web sites in China, ensuring comprehensive coverage. Detailed data sets corresponding to each standard were provided in Tables S1 and S2 (see Supporting Information). Related abbreviations were shown in Table 1.

Table 1. Detailed Information of Related Standards

Web sites for the environmental standards					
1	https://www.nssi.org.cn	National Library of Standards			
2	https://www.mee.gov.cn	Ministry of Ecology and Environment of the People's Republic of China			
3	https://std.samr.gov.cn/	National Public Service Platform for Standards Information			
Abbreviations of provincial regions					
1	Beijing	BJ	18	Hunan	HN
2	Tianjin	TJ	19	Guangdong	GD
3	Hebei	HE	20	Guangxi	GX
4	Shanxi	SX	21	Hainan	HI
5	Inner Mongolia	IM	22	Chongqing	CQ
6	Liaoning	LN	23	Sichuan	SC
7	Jilin	JL	24	Guizhou	GZ
8	Heilongjiang	HL	25	Yunnan	YN
9	Shanghai	SH	26	Tibet	TB
10	Jiangsu	JS	27	Shan'xi	SN
11	Zhejiang	ZJ	28	Gansu	GS
12	Anhui	AH	29	Qinghai	QH
13	Fujian	FJ	30	Ningxia	NX
14	Jiangxi	JX	31	Xinjiang	XJ
15	Shandong	SD	32	Hong Kong	HK
16	Henan	HA	33	Macao	MO
17	Hubei	HB	34	Taiwan	TW
National organizations and government					
1	Ministry of Ecology and Environment	MEE	4	Ministry of Natural Resources	MNR
2	Ministry of Industry and Information Technology	MIIT	5	Ministry of Agriculture and Rural Affairs	MARA
3	Ministry of Water Resources	MWR			
Analytical methods					
1	Inductively coupled plasma mass spectrometry	ICP-MS	4	High performance liquid chromatography	HPLC
2	Gaschromatography	GC	5	Elemental analysis	EA
3	Gaschromatography–mass spectrometry	GC-MS	6	Liquid chromatography mass spectrometry	LC-MS
Detection chemicals					
1	Volatile organic compounds	VOCs	3	Polychlorinated biphenyls	PCBs
2	Semivolatile organic compounds	SVOCs	4	Polycyclic aromatic hydrocarbons	PAHs

3. HISTORICAL DEVELOPMENT OF THE STANDARDS

Figure 1 exhibited the historical development of environmental standards and related management for the contaminated sites with distinct periodic characteristics in China. It mainly focused on the health standards for soil contaminants, particularly toxic chemicals, with emphasis on advanced instrumental testing methods employed during the 1990s. The initial regulatory document aimed to safeguard the health of individuals working or residing near industrial production activities. This pivotal reference document, titled "Environmental Quality Risk Assessment Criteria for Soil at Manufacturing Facilities" (HJ/T 25-1999), provided crucial guidance. It outlined two distinct categories for soil environmental quality criteria, encompassing direct contact and migration to groundwater, while also establishing threshold values for 89 commonly found chemicals in soil and groundwater.[56,57]

In the 21st century, driven by the relocation of manufacturing facilities and urban expansion, there has been a notable increase in the introduction of influential standards, particularly following major incidents such as the BJ Songjiazhuang subway station poisoning (2004) and the commencement of the SH World Expo (2010).[58−60] One such milestone standard was "Soil Quality Assessment for Exhibition Sites" (HJ/T 350-2007), which played a crucial role in managing soil contamination on construction land utilized for various purposes. Since 2009, BJ has consistently introduced a comprehensive suite of standards that not only possessed a strong theoretical foundation but also provided valuable technical expertise for managing contaminated sites.[61,62] Examples of these standards included "Environmental Site Assessment Guideline" (DB11/T 656-2009), "Technical Guideline for Contaminated Sites Remediation Validation" (DB11/T 783-2011), and "Screening Levels for Soil Environmental Risk Assessment of Sites" (DB11/T 811-2011). Notably, the local standard DB11/T 811-2011 represented the first set of screening values for soil contamination risks in China with three land utilization types: residential land, parks and green areas, and industrial/commercial land.

To regulate and supervise environmental management at contaminated sites, four prominent technical guide standards for soil contamination were issued in 2014, encompassing investigation, monitoring, risk assessment, and remediation technology requirements. Subsequently, these standards underwent updates and revisions, with additional standards introduced in 2018 and 2019, focusing on enrichment in risk control and remediation effect assessment, groundwater remediation, and risk control measures.[63] A significant standard, titled "Soil Environmental Quality Risk Control Standard for Soil Contamination of Development Land" (GB 36600-2018), was published by the Ministry of Ecology and Environment (MEE) in 2018.[64] This standard aimed to protect the soil environment of construction land, mitigate soil contamination risks, and ensure the safety of the human living environment. It provided specific screening and control values for soil contamination risks on construction land, encompassing 45 basic indicators and 40 other indicators along with additional requirements for monitoring, implementation, and supervision. The current sustainable management approach effectively addressed prevention, control, and supervision aspects in contaminated sites through the implementation of necessary laws, regulations, and standards. This approach emphasized the improvement of ecological environment quality and signified significant progress in integrated risk-based management performance.

Compared with soil management, groundwater contamination exhibited many serious challenges in terms of table depth, migration of contaminants, and structural complexity. The development of groundwater contamination management

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

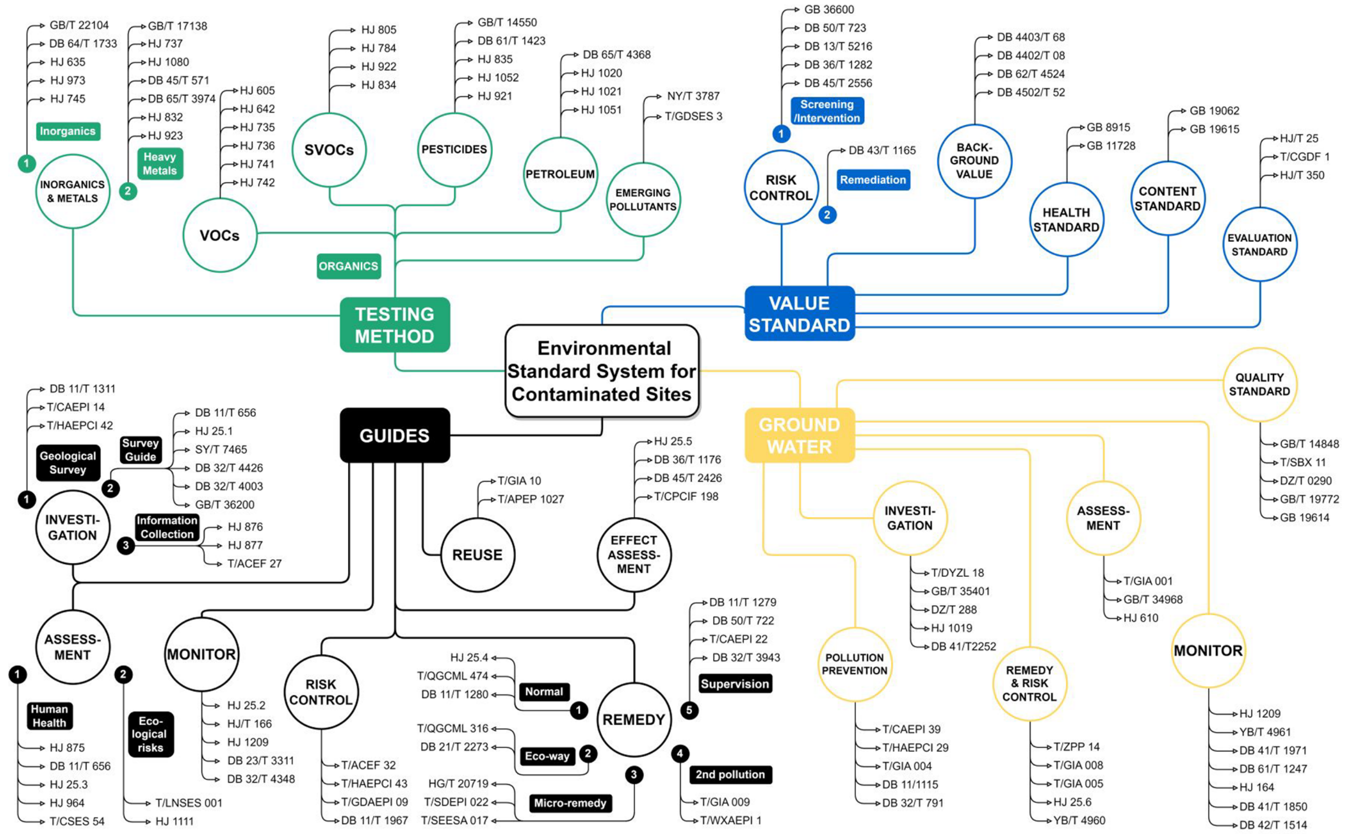


Figure 2. Detailed frameworks of the environmental standards system for contaminated sites. Guide standards for soil environmental management mainly encompassed technical guidelines for investigation (geological survey, survey guide, and information collection), monitoring, risk assessment (for the protection of human health and ecology), risk control, remediation (normal plan, eco-way, microremedy, and supervision), effect assessment, and redevelopment. Investigation and remediation related standards were the main categories and classification within guides. Testing methods primarily consisted of laboratory testing method standard requirements that covered the conventional contaminants (inorganics, heavy metals, VOCs, SVOCs, petroleum, and pesticides), as well as specific chemicals (antibiotics and emerging pollutants). Environmental standards for groundwater at contaminated sites primarily include types of pollution prevention, investigation, assessment, quality standards (GB/T 14848), monitoring, remediation, and risk control. It was worth noting that while groundwater and soil guides shared similar types, differently groundwater focused on toxicological quality standards conformation, whereas soil performed a risk-based management approach.[65,66]

started relatively later at the site scale, with a focus on issuing documents and regulations rather than published standards. Diverse standards both prompted significant performance with increasing attention to groundwater environmental management. Additionally, it also showed the sustainable risk control concept of soil and groundwater comanagement throughout the designed guidelines.

Furthermore, it was worth noting that group standards have emerged as a commendable strategy to effectively tackle specific challenges and intricate circumstances encountered at contaminated sites, given their adaptable and viable characteristics. Notably, there was a remarkable advancement in both the quantity and quality of group standards in recent years (2021−2022), providing essential technical assistance and scientific direction for comprehensive environmental management of contaminated sites.

4. SYSTEMATIC ANALYSIS AND FRAMEWORKS OF STANDARDS

4.1. Standards System Framework. Based on the current state of environmental management on contaminated sites, a comprehensive environmental standards framework has been established (Figure 2). This framework architecture was organized into a series of standards based on their content,

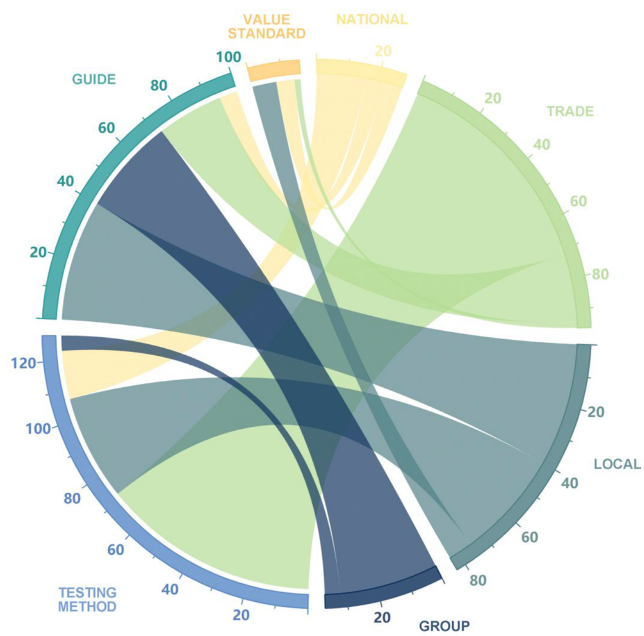


Figure 3. Related relationships between types and formats of different standards files.

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

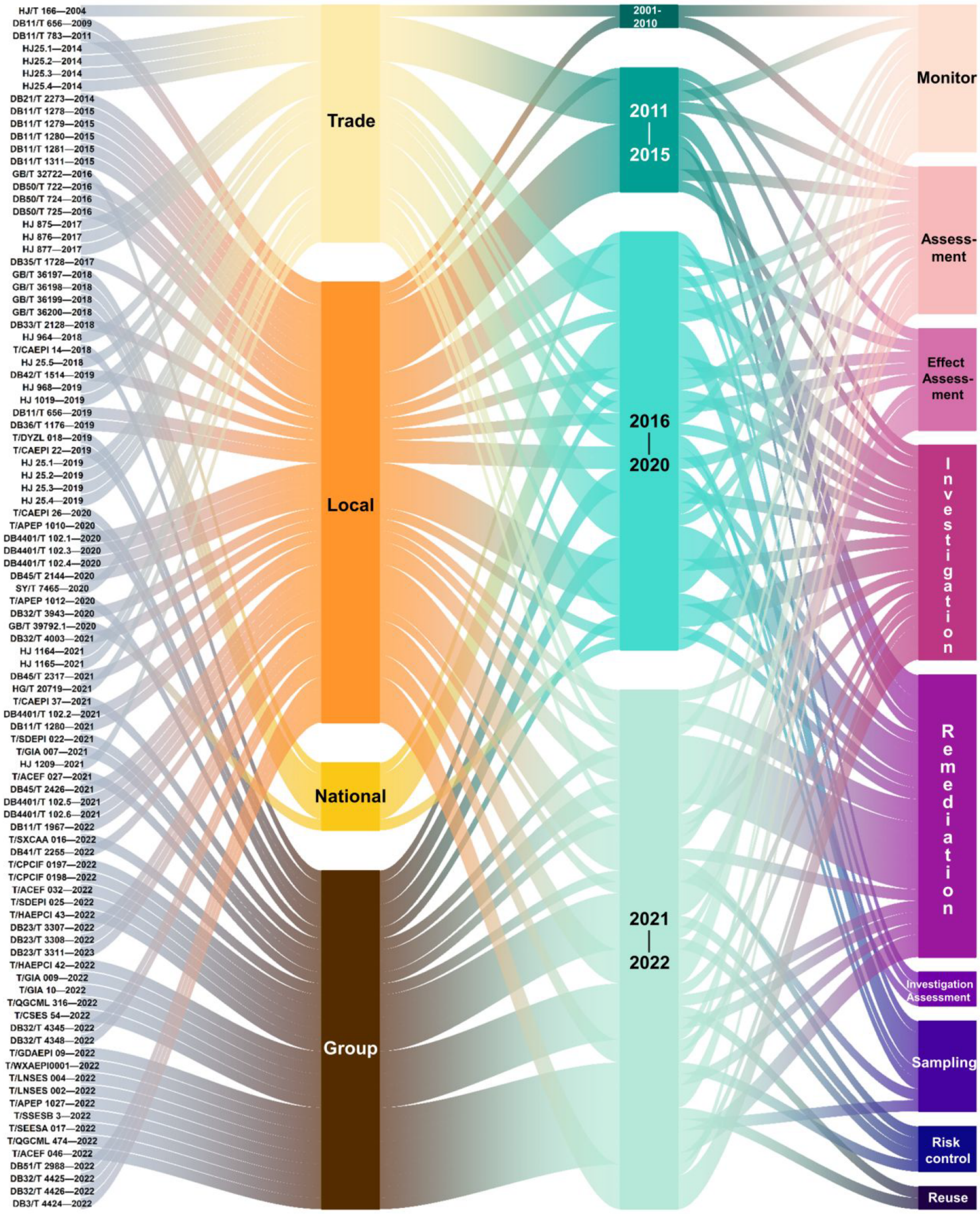


Figure 4. Development and analysis of different typed standards of guides.

including value limits, technical guidelines, test methods, and groundwater-related standards.[47,51,56] It demonstrated that the current framework had undergone initial establishment and essential development with the functional areas of regulatory management for each environmental factor. The value standards encompassed various types: the background value standards and national risk control screening standards (GB 36600), along with local screening standards with regional characteristics such as HB (DB 13/T 5216), JX (DB 36/T 1282), and GX (DB 45/T 2556). Some published value standards, such as health standards, content standards, and evaluation standards, have been replaced by risk-based standards, which showed remarkable performance throughout history and exploration periods.

Normative documents serve as guidelines to guide the management process, while trade standards provided technical guidelines and methods to regulate work procedures and requirements (Figure 3). Among the different types of standards, national standards possessed low quantitative proportions and primarily focused on value standards and testing methods. Trade standards played a crucial role in establishing testing standards, whereas local standards mainly covered both testing methods and guide standards. Different regions, characterized by diverse natural conditions, hydrogeology, and economic development, exhibited the distinct

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

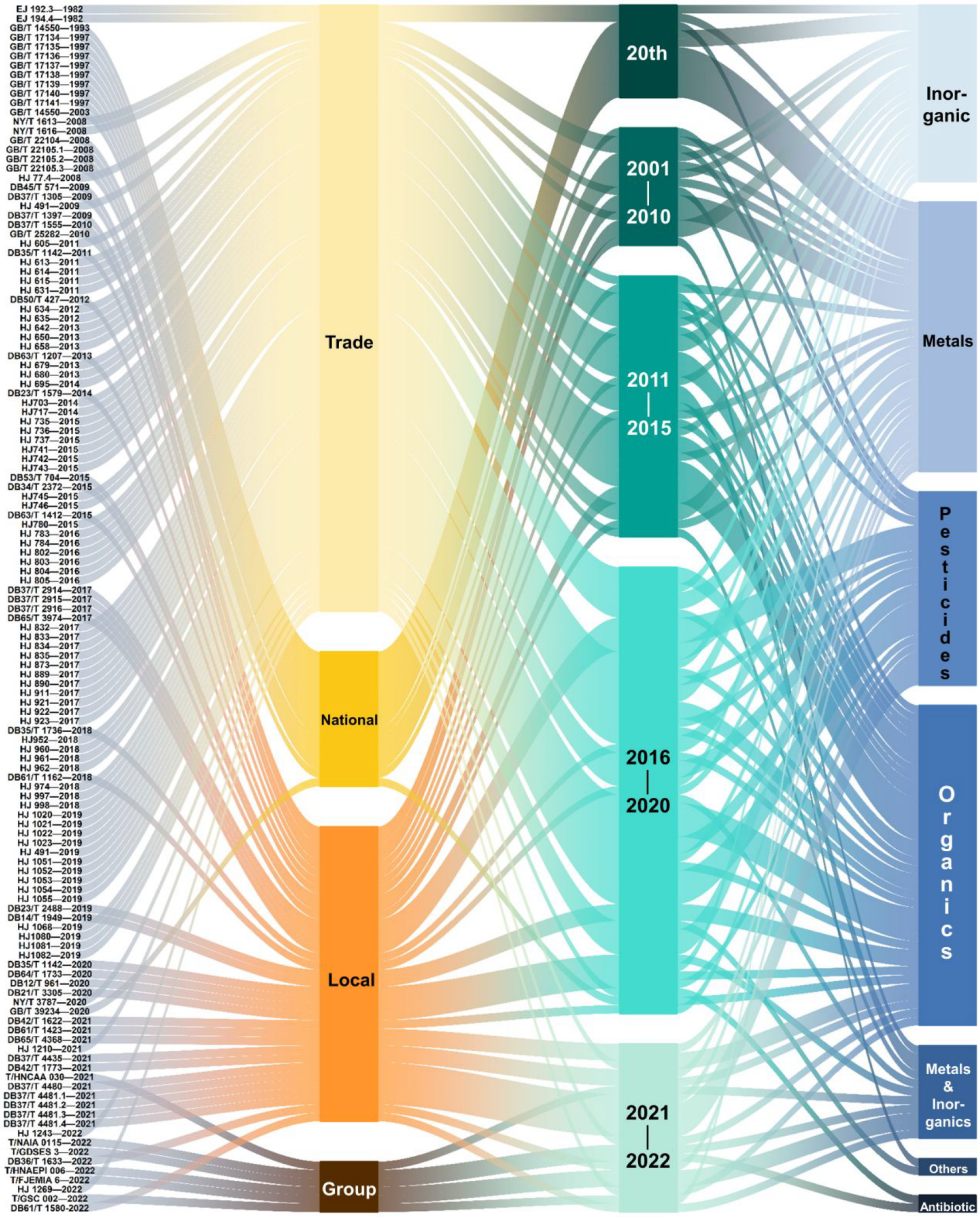


Figure 5. Development of different typed standards of testing method.

leadership in promoting the development and publication of local standards due to their regional environments and other characteristics. Group standards primarily focused on providing guide standards with obvious limitations of value standards.

4.2. The Progression of Guide and Testing Method Standards. Most guide standards were local and group types with a concentration of releases from 2016 to 2022 (Figure 4). During the early 21st century period (2001−2010), the focus primarily revolved around assessment and monitoring standards, subsequently transitioning to encompass remediation and investigation standards in the intermediate phase spanning 2016 to 2020. Notably, it witnessed a substantial increase in the development of group standards from the years 2021 to 2022. In recent years, there was a shift toward the standards of site reuse and redevelopment, sample collection, and other aspects, aiming to enhance the integrity and hierarchical structure of the whole guide standards process.

In terms of testing method standards, trade standards exhibited a distinct advantage in both quantity and coverage in comparison with that the guide standards (Figure 5). The testing method standards has a long historical development before the 21st century, initially attributed to the national and trade standards that predominantly addressed heavy metals measurements. Over the past decade (2011−2022), there was a continuous expansion and update of detection instruments and techniques, particularly in the organic and pesticide

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

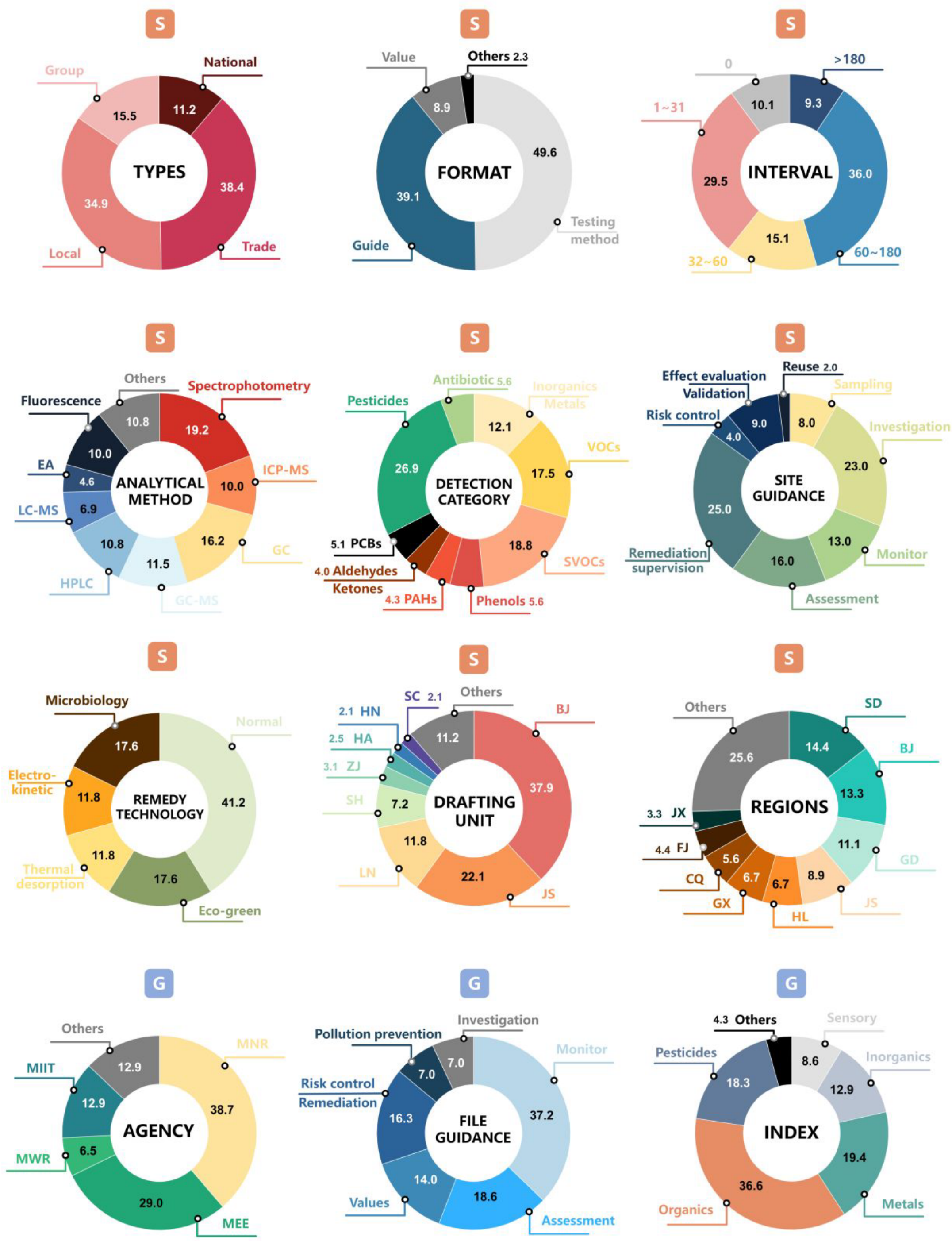


Figure 6. Analysis of different standards files according to classification methods.

categories, resulting in an advancing number of testing method standards. Nevertheless, the current repertoire of group standards and testing methods for emerging pollutants remained related to limitations with low proportions. The ongoing enrichment of comprehensive soil contaminants, testing methods, and associated standards has significantly improved the accuracy of chemicals detection outcomes. This progress sustained remarkable importance for the formulation of highly effective and scientifically informed measures to address soil contamination.[67]

4.3. Categorization and Analysis of Documents. Based on more than 300 standards, as national, trade, local, and group types related to the soil and groundwater environment of contaminated sites, a comparative analysis was assessed across 12 classifications with multifaceted scopes and applications (Figure 6). The statistics indicated that trade standards had the highest proportion, accounting for 38.4% of the total standards, followed by local standards (34.9%), group standards (15.5%), and national standards (11.2%) on soil environment standards. Among the various format of standards, the testing method exhibited the best level (49.6%), followed by guide format (39.1%), and value standards (8.9%). The time interval between the release and implementation dates of soil environmental standards is primarily concentrated

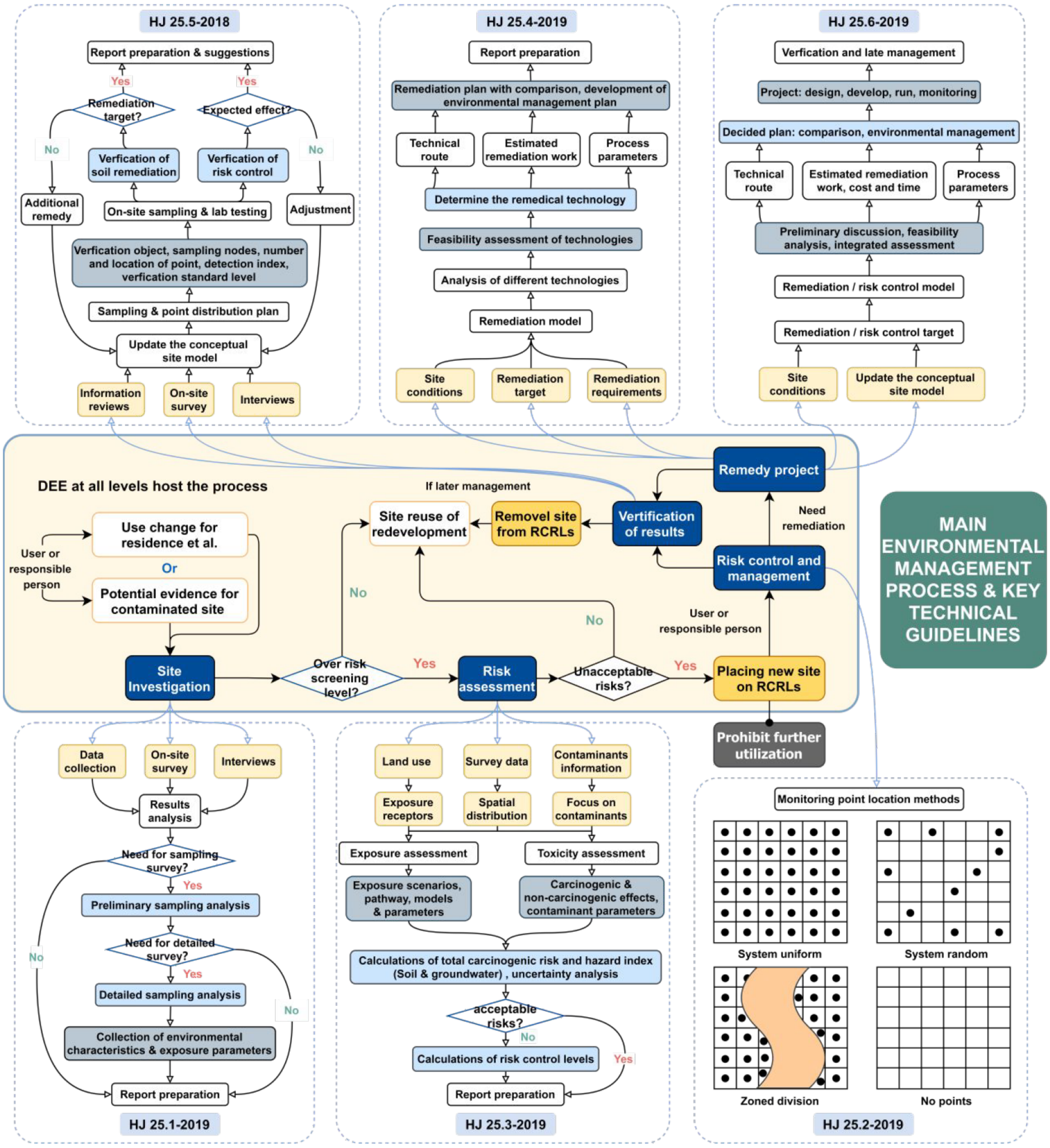


Figure 7. Main environmental management process with key technical guidelines. Third, for contaminated sites requiring risk control, specific programs were developed and targeted to control the identified risks and prevent the spread of contaminants in the soil or groundwater reducing potential harm. The key standard for risk control and monitoring was "Technical guidelines for monitoring during risk control and remediation of soil contamination of land for construction" (HJ 25.2-2019).[74]

in two time periods: within one month (29.5%) or between 60 and 180 days (36.0%). Spectrophotometry analytical methods constitute the largest proportion (19.2%) among soil contamination testing standards, with gas chromatography (GC)-related standards also being prominent (16.2%). Pesticide chemicals, characterized by high toxicity and a wide variety of species, represented a significant proportion (26.9%) of organics, followed by VOCs (18.8%), SVOCs (17.5%), and inorganics and metals (12.1%).[68,69]

Among the site guidance standards, remediation and investigation categories comprised a significant proportion, representing 23.0% and 25.0%, respectively. The most significant guide standard within the general remediation technology category accounted for 41.2%, followed by eco-green (17.6%) and microbial (17.6%) remediation, also hold substantial proportions. Research institutes, universities, and enterprises in BJ emerged as the primary drafting units (37.9%) of national and trade standards, and the development of local standards was particularly notable in SD (14.4%), BJ (13.3%), GD (11.1%), and JS (8.9%). Regarding site-scale groundwater, it showed that MNR and MEE ranked first and second at 38.7% and 29.0%, respectively. Monitoring standards took different precedence in the guide format (37.2%) of groundwater compared to soil environmental standards. It mainly exhibited that the value standard attributed to the quality assessment of the groundwater (GB/T 14848-2017), including 39 regular indicators and 54 nonregular indicators with organic compounds (36.6%) and metals (19.4%) being the predominant chemical constituents.

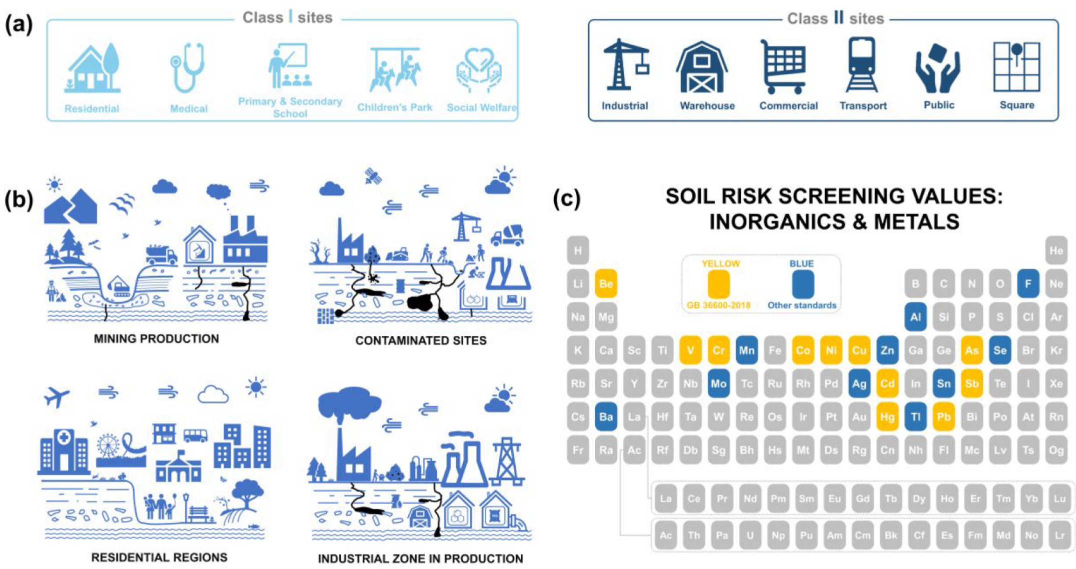


Figure 8. Fundamental information of the soil contamination and environmental management: (a) classical types of the construction land; (b) typed contaminated sites according to the different management; and (c) characteristic elements mentioned according to the different standards of screening risk level.

5. KEY STANDARDS AND ENVIRONMENTAL MANAGEMENT

5.1. Key Standards of the Guides. Risk management-based technical guidance a crucial tool conducted principles and Figure 7 provided an illustrative depiction of the core process and key standards involving the environmental management of contaminated sites. The system prompted risk control standards, such as soil screening values, with the purpose of the management process around the protection of human health. This approach assumed a central role across the entire life cycle of site management, encompassing activities, such as investigation, risk assessment, risk control or treatment, remediation, and evaluation of efficacy.[70,71]

The specific management advancements can be categorized into the following five dimensions. First, the environmental investigation was conducted to assess the contamination condition of soil and groundwater on potentially contaminated sites by employing the key standard like "Technical guidelines for investigation on soil contamination of land for construction" (HJ 25.1-2019).[72] A preliminary survey was performed to determine the presence of soil and groundwater contamination. A detailed survey was carried out on contaminated land to identify the categories of contaminants with the assessment of the range, dimension, and depth of contamination.

Second, following the identification of high-risk levels during the investigation, the next assessment should be conducted with the structural characterization for determining the level of soil contamination due to the detailed survey results and specific land use. Key standards involved "Technical guidelines for risk assessment of soil contamination of land for construction" (HJ 25.3-2019).[73]

Fourthly, remediation activities can be employed for the removal and degradation of harmful chemicals. It should be closely supervised to ensure that secondary pollution was effectively controlled during the remedial project process. The key standards were different for soil "Technical guidelines for soil remediation of land for construction" (HJ 25.4-2019)[75] and for groundwater "Technical guideline for groundwater remediation and risk control of contaminated sites" (HJ 25.6-2019).[76]

Lastly, the effectiveness of risk control treatment and remediation efforts was verified after the finished works. Users or responsible persons would be required to engage a third-party institution to assess the effectiveness of the verification of risk control and soil remediation of contaminated sites. The relevant standard for this assessment was "Technical guideline for verification of risk control and soil remediation of the contaminated site" (HJ 25.5-2018).[77]

5.2. Key Standards of the Values. It can be classified into two primary categories of construction land due to exposure scenarios for protecting individuals (GB 36600-2018),[64] where both children and adults may face long-term exposure hazards (class I sites), such as residence, and primarily associated with adult exposure assessment (class II sites) such as industrial land (Figure 8a).

The conceptual scenario models can be classified into mining production, normal contaminated sites, residential regions, and in-production zones exhibiting variations in contaminated groundwater and soil, according to the different management as well as sensitive receptors (Figure 8b). Current environmental management and scientific guidelines focused on the investigation and remediation of normal contaminated sites and source control and impermeability treatment for industrial in-production zone. Various 9-typed exposure pathways can enable contaminants from soil and groundwater at contaminated sites to reach and impact humans for routes such as oral ingestion, inhalation, contact with skin, inhalation, drink (groundwater), and vapor inhalations throughout different routes: outdoor (topsoil), indoor (below soil), outdoor (below soil), outdoor (groundwater), and indoor (groundwater).[73] Additionally, existing soil environmental standards predominantly emphasized transition heavy metals and certain toxic metalloids in terms of element coverage according to the different standards of screening risk level, including 21 categories, such as Be, F, Al, V, Cr, Mn, Co, Ni,

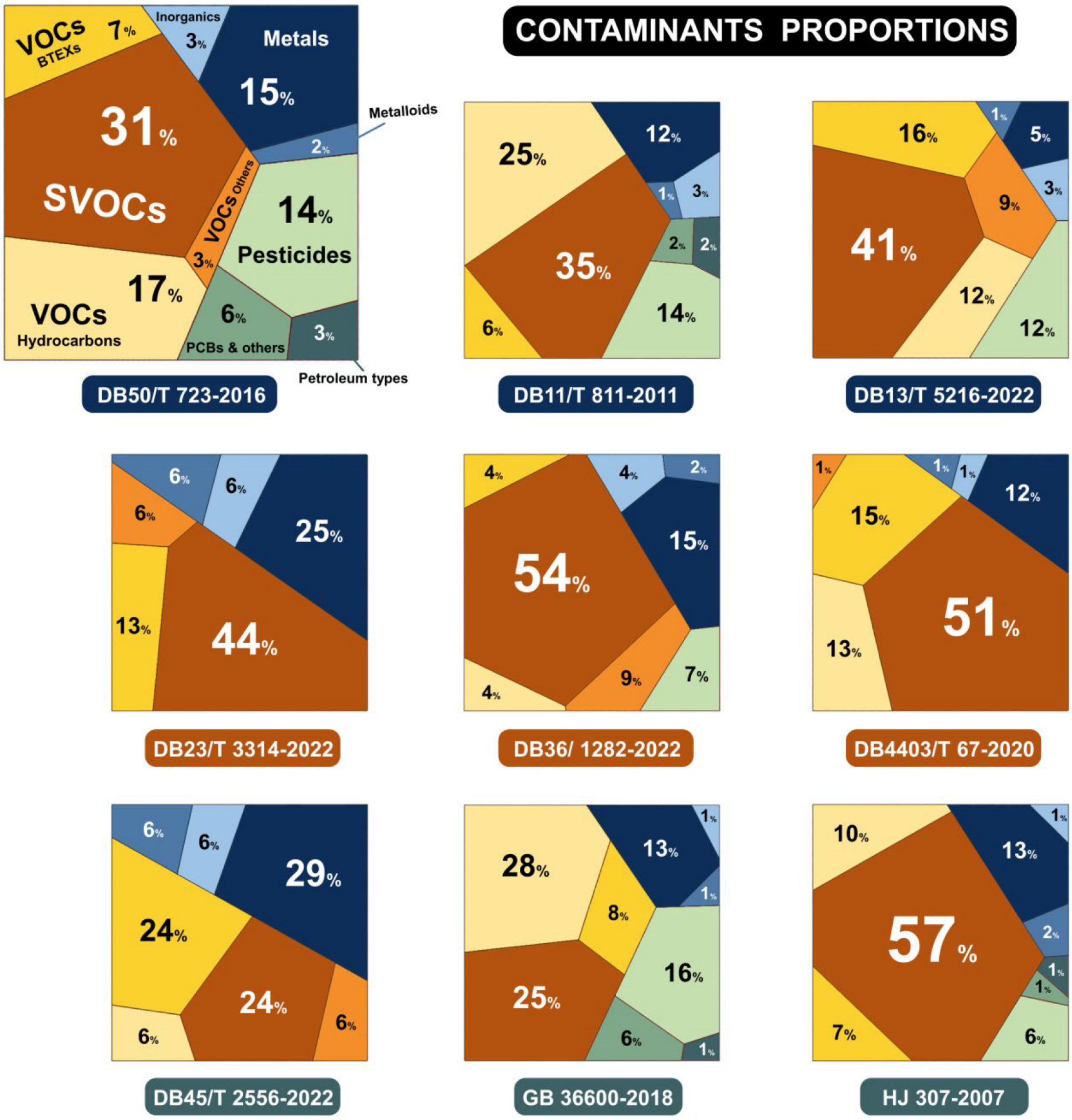


Figure 9. Contaminants proportions for the different value standards with screening risk levels.

Cu, Zn, As, Se, Mo, Ag, Cd, Sn, Sb, Ba, Hg, Tl, and Pb (Figure 8c).

To clarify the perspective and strategies of risk management in different regions by employing various screening value standards through the comparison and calculation of the ratio percentage of chemicals types in different standards (Figure 9). It showed that some contaminant types were relative majorities of different standards, such as SVOCs, VOCs, and metals, nevertheless, metalloid and petroleum types exhibited relatively low proportions. It mainly emphasized a balanced representation of different chemicals, covering 85 types of the national standard (GB36600-2018), 88 indicators of the BJ local standard (DB11/T 811-2011), and CQ local standard (DB50/T 723-2016) encompassed a more comprehensive range, involving 107 types. The local standards that were born after 2018, such as DB 23/T 3314-2022, largely derived from or referenced the national screening standard with regional characteristics, focused on the effective development of specific chemicals, such as Zn, Ag, Mo, acetone, formaldehyde, and phenanthrene. These supporting chemicals can promise the potential to facilitate advanced hazard identification and scientifically expand the coverage of certain contaminants catalogs.

6. CONCLUSIONS AND PERSPECTIVE

6.1. Conclusions and Outlook. Over the past two decades, significant progress and rapid growth have been witnessed in the development of environmental standards for contaminated sites, supported by robust scientific foundations and extensive practical experience. To date, over 300 types of national (11.2%), trade (38.4%), local (34.9%), and group (15.5%) standards had been published with different ratio proportions, focusing on the abundant number of testing methods (49.6%) and technical guide (39.1%). Centered on risk-based management, the systematic framework of standards China has established for construction land to protect human health and the ecological environment with four categories for testing method, guide, value, and groundwater related standards. Different types displayed remarkable behaviors, such as the national and trade standards maintained the top-level design and authoritative performance, local standards showed the obvious characteristics of environmental manage-

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

Table 2. Potential Fabricated Documents: Suggested Types, Features, and Production

Potential documents	Standard	Files	Necessity	Urgency	Difficulty	Duration
Screening risk level (Protect ecology)	•		★★★	♥♥♥	⚡⚡⚡	☾☾☾
Screening risk level (Protect groundwater)	•		★★	♥♥	⚡⚡⚡	☾☾
Testing method (Emerging pollutants)	•		★★★	♥♥	⚡⚡	☾☾
Testing method (Available contents)	•		★★	♥♥	⚡⚡⚡	☾☾☾
Testing method (Isotopes)	•		★	♥	⚡⚡	☾☾
Testing method (Unconventional elements)	•		★	♥	⚡⚡	☾
Technical guideline (Sampling, point & preservation)	•	•	★★★	♥♥♥	⚡⚡	☾☾
Fast on-site testing		•	★★	♥♥	⚡	☾
Technical guideline (Quality control)	•	•	★★★	♥♥♥	⚡⚡	☾
Bioavailability analysis		•	★★	♥♥	⚡⚡⚡	☾☾☾
Ecological risk assessment	•	•	★★	♥	⚡⚡⚡	☾☾☾
Exposure parameter selection	•	•	★	♥	⚡⚡	☾☾
Uncertainty analysis	•	•	★★	♥	⚡⚡	☾☾
Barrier risk control guideline		•	★★	♥♥	⚡⚡	☾
Site post management		•	★★★	♥♥	⚡⚡⚡	☾☾
Risk control guideline (Monitoring natural attenuation)	•		★★	♥♥♥	⚡	☾☾
Remediation guideline (Chemical oxidation-reduction)	•		★	♥♥♥	⚡	☾
Remediation guideline (Solidification & stabilization)	•		★★	♥♥♥	⚡⚡	☾
Remediation guideline (Electrochemistry)	•		★	♥♥♥	⚡⚡	☾☾
Remediation guideline (Extraction)	•		★	♥♥♥	⚡	☾
Reuse & redevelopment		•	★	♥♥	⚡⚡⚡	☾☾
Verification of risk control (Groundwater)	•		★★	♥♥♥	⚡⚡	☾☾
In-production management (Classical industries)		•	★★	♥♥♥	⚡⚡	☾
In-production management (Monitoring & prevention)	•	•	★★★	♥♥♥	⚡⚡	☾
Toxicological database		•	★★	♥	⚡⚡⚡	☾☾☾

ment, and group standards primarily focused on providing guides with excellent technical guidelines and scientific support.

Most guides can be attributed to local and group standards types which were published during the periods of 2016–2022 and testing method standards explored a continuous growth in the organic and pesticide chemicals particularly. Spectrophotometry was the main analytical method (19.2%) among soil contamination testing standards and investigation led to a relatively high proportion (25%) among the contaminated site guide standards. Different screening values of chemicals can improve hazard identification and enlarge the categories of certain contaminants.

6.2. Suggestions and Perspectives. The current standard system still possessed some limitations, including the diversity in risk management for protected eco-receptors, the inflexible utilization of exposure parameters in risk assessment models, insufficient guidance on remediation technologies, and covering the shortage of comprehensive test methods of chemicals. Table 2 outlined the proposed and potential development task of improving the enrichment of current environmental standards for contaminated sites, supplying the designed optimization and favorable suggestion for the standard system.[3,56,78] The following key areas are outlined: (a) Advancing the system of identification and risk-based standards for contaminated sites by developing technical guidelines for ecological soil contamination and expanding the assessment of various receptors (screening risk levels to protect ecology and groundwater). (b) Expanding the range of standards for emerging pollutants and nonconventional chemicals with soil contaminant testing methods and appropriate indicators.[27] Quantitative and qualitative measurements should be enriched to accurately measure classical harmful substances, toxic pesticides, and odorous compounds, utilizing highly sensitive equipment and refined testing protocols. (c) Improving the effectiveness and comprehensiveness of environmental management for contaminated sites through the design and implementation of detailed technical guides. This includes on-site testing, quality control, bioavailability analysis, ecological risk assessment, uncertainty

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

analysis, and selection of exposure parameters. (d) Development of technical guidelines for risk control and remediation technologies based on sustainable approaches and progressive strategies. This encompasses monitoring natural attenuation, chemical oxidation/reduction, solidification and stabilization, and electrochemistry. (e) Enhancing in-production management and prevention of contamination sources by implementing targeted standards that focus on content-based regions and key industries. Effective control and monitoring of soil and groundwater risks should be prioritized.

These proposed tasks aim to improve the enrichment and effectiveness of environmental standards for contaminated sites, providing a robust framework for managing and remediating such sites while mitigating potential risks. Hence, the current and supplementary standards can present a sustainable concept while promoting the protection progress of contaminated sites for the advanced environmental management of soil and groundwater and highlight scientific guidance for global experience.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.3c05187.

List of soil and groundwater related standards about their names and numbers (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Hao Zhang − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China;* orcid.org/0000-0003-2697-7103; Phone: 86-010-84757935; Email: zhanghao@tcare-mee.cn

Yanwei Wang − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China;* Email: wangyanwei@tcare-mee.cn

Yanna Xiong − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China;* Email: xiongyanna@tcare-mee.cn

Bin Zhao − *Institute of Eco-environmental and Soil Sciences, Guangdong Academy of Sciences, Guangzhou 510650, PR China; Norwegian University of Life Sciences, Department of Environmental Sciences, 5003 Ås, Norway;* Email: zhaobinbeikeda@163.com

Authors

Yang Yang − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China*

Shaobing Ma − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China*

Wenchao Yuan − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China*

Mingjun Gao − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China*

Tongtong Li − *Technical Centre for Soil, Agriculture and Rural Ecology and Environment, Ministry of Ecology and Environment, Beijing 100012, PR China*

Yuquan Wei − *China Agricultural University, Beijing 100193, PR China;* orcid.org/0000-0002-1309-5139

Aiyang Li − *Chinese Research Academy of Environmental Sciences, Beijing 100012, PR China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c05187

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported by the National Key R&D Program of China (2020YFC1806301-02 and 2020YFC1806304), Guangdong Basic and Applied Basic Research Foundation (2022A1515110625), GDAS' Project of Science and Technology Development (2022GDASZH-2022010105), and China Postdoctoral Science Foundation (2022M720848).

■ REFERENCES

(1) Bai, Y.; Wong, C. P.; Jiang, B.; Hughes, A. C.; Wang, M.; Wang, Q. Developing China's Ecological Redline Policy using ecosystem services assessments for land use planning. *Nat. Commun.* **2018**, *9*, 3034.

(2) Peng, J.; Zhang, S.; Han, Y.; Bate, B.; Ke, H.; Chen, Y. Soil heavy metal pollution of industrial legacies in China and health risk assessment. *Sci. Total Environ.* **2022**, *816*, 151632.

(3) Zhang, H.; Li, A.; Wei, Y.; Miao, Q.; Xu, W.; Zhao, B.; Guo, Y.; Sheng, Y.; Yang, Y. Development of a new methodology for multifaceted assessment, analysis, and characterization of soil contamination. *J. Hazard Mater.* **2022**, *438*, 129542.

(4) Cui, X.; Liu, R.; Ji, G.; Song, Z.; Wei, N.; Wang, X. Practice in the catalogue system for soil pollution risk control and restoration of construction land. *Environ. Prot.* **2021**, *49*, 51−56.

(5) Marzocchini, M.; Tatàno, F.; Moretti, M. S.; Antinori, C.; Orilisi, S. Proposal and application of a regional methodology of comparative risk assessment for potentially contaminated sites. *Environ. Technol.* **2019**, *40*, 3578−3592.

(6) Yan, K.; Wang, H.; Lan, Z.; Zhou, J.; Fu, H.; Wu, L.; Xu, J. Heavy metal pollution in the soil of contaminated sites in China: Research status and pollution assessment over the past two decades. *J. Clean. Product.* **2022**, *373*, 133780.

(7) Caboche, J.; Denys, S.; Feidt, C.; Delalain, P.; Tack, K.; Rychen, G. Modelling Pb bioaccessibility in soils contaminated by mining and smelting activities. *J. Environ. Sci. Health Part A* **2010**, *45*, 1264−1274.

(8) Yang, H.; Zhang, G.; Fu, P.; Li, Z.; Ma, W. The evaluation of in-site remediation feasibility of Cd-contaminated soils with the addition of typical silicate wastes. *Environ. Pollut.* **2020**, *265*, 114865.

(9) Li, D.; Li, G.; He, Y.; Zhao, Y.; Miao, Q.; Zhang, H.; Yuan, Y.; Zhang, D. Key Cr species controlling Cr stability in contaminated soils before and chemical stabilization at a remediation engineering site. *J. Hazard. Mater.* **2022**, *424*, 127532.

(10) Zhao, B.; O'Connor, D.; Zhang, H.; Jin, Y.; Wang, Y.; Yang, X.; Hou, R.; Hou, D. Assessing mercury pollution at a primary ore site with both ancient and industrial mining and smelting activities. *Environ. Pollut.* **2023**, *336*, 122413.

(11) Maheswari, S.; Murugesan, A. G. Remediation of arsenic in soil by *Aspergillus nidulans* isolated from an arsenic-contaminated site. *Environ. Technol.* **2009**, *30*, 921−926.

(12) Sun, C.; Xu, C.; Zhao, Y.; Zhang, W.; Li, X.; Zhang, Q.; Wu, B.; Ma, F.; Gu, Q. A numerical simulation of thermally-enhanced soil vapor extraction with a validation of an actual contaminated site. *Chemosphere* **2023**, *338*, 139413.

(13) Ma, W.; Hu, J.; Li, J.; Gao, P.; Okoli, C.; Wang, P.; Li, J. Distribution, sources, and health risk assessment of VOCs/SVOCs in soils obtained from petrochemical-contaminated sites in Guangzhou, a subtropical coastal megacity in southern China. *J. Clean. Product.* **2023**, *426*, 139198.
(14) Cai, Q.-Y.; Mo, C.-H.; Wu, Q.-T.; Katsoyiannis, A.; Zeng, Q.-Y. The status of soil contamination by semivolatile organic chemicals (SVOCs) in China: A review. *Sci. Total Environ.* **2008**, *389*, 209−224.
(15) Wang, M.; Jiang, D.; Ding, D.; Deng, S.; Kong, L.; Wei, J.; Xia, F.; Li, M.; Long, T. Spatiotemporal characteristics and dynamic risk assessment of a multi-solvents abandoned pesticide-contaminated site with a long history, in China. *J. Environ. Manage.* **2023**, *336*, 117633.
(16) Jennings, A.; Li, Z. Scope of the worldwide effort to regulate pesticide contamination in surface soils. *J. Environ. Manage.* **2014**, *146*, 420−443.
(17) Zhang, H.; Du, P.; Yuan, B.; Zhang, Y.; Chen, J.; Liu, H.; Li, A.; Wei, Y.; Xiong, Y.; Zhao, B. Multifaceted Insight into Sensitivity Analysis and Environmental Impact on Human Health of Soil Contamination Risk Assessment. *Environ. Health* **2023**, *1*, 214−227.
(18) Li, F.; Zhang, J.; Yang, J.; Liu, C.; Zeng, G. Site-specific risk assessment and integrated management decision-making: A case study of a typical heavy metal contaminated site, Middle China. *Human Eco. Risk Assess.* **2016**, *22*, 1224−1241.
(19) Xue, W.; Ying, D.; Li, Y.; Sheng, Y.; He, T.; Shi, P.; Liu, M.; Zhao, L. Method for establishing soil contaminant discharge inventory: An arsenic-contaminated site case study. *Environ. Res.* **2023**, *227*, 115700.
(20) Nathanail, P.; McCaffrey, C.; Earl, N.; Foster, N. D.; Gillett, A. G.; Ogden, R. A deterministic method for deriving site specific human health assessment criteria for contaminants in soil. *Human Eco. Risk Assess.* **2005**, *11*, 389−410.
(21) Amundson, R.; Berhe, A. A.; Hopmans, J. W.; Olson, C.; Sztein, A. E.; Sparks, D. L. Soil and human security in the 21st century. *Science* **2015**, *348*, 1261071.
(22) Brombal, D.; Wang, H.; Pizzol, L.; Critto, A.; Giubilato, E.; Guo, G. Soil environmental management systems for contaminated sites in China and the EU. Common challenges and perspectives for lesson drawing. *Land Use Polym.* **2015**, *48*, 286−298.
(23) Li, S.; Yang, B.; Wang, M.; Zhang, R.; Chen, K.; He, Z.; Shi, H.; Chen, S. Environmental quality standards for agricultural land in China: What should be improved on derivation methodology? *J. Environ. Manage.* **2022**, *324*, 116334.
(24) Han, L.; Wu, W.; Chen, X.; Gu, M.; Li, J.; Chen, M.; Zhou, Y. The derivation of soil generic assessment criteria for polychlorinated biphenyls under the agricultural land scenario in Pearl and Yangtze River Delta regions, China. *Sci. Total Environ.* **2023**, *871*, 162015.
(25) Hou, D.; Al-Tabbaa, A.; O'Connor, D.; Hu, Q.; Zhu, Y.; Wang, L.; Kirkwood, N.; Ok, Y.; Tsang, D.; Bolan, N.; Rinklebe, J. Sustainable remediation and redevelopment of brownfield sites. *Nat. Rev. Earth & Environ.* **2023**, *4*, 271−286.
(26) O'Connor, D.; Müller-Grabherr, D.; Hou, D. Strengthening social-environmental management at contaminated sites to bolster Green and Sustainable Remediation via a survey. *Chemosphere* **2019**, *225*, 295−303.
(27) Brusseau, M.; Anderson, R.; Guo, B. PFAS concentrations in soils: Background levels versus contaminated sites. *Sci. Total Environ.* **2020**, *740*, 140017.
(28) Habert, G.; Miller, S. A.; John, V. M.; Provis, J. L.; Favier, A.; Horvath, A.; Scrivener, K. L. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat. Rev. Earth Environ.* **2020**, *1*, 559−573.
(29) Li, F.; Zhang, J.; Jiang, W.; Liu, C.; Zhang, Z.; Zhang, C.; Zeng, G. Spatial health risk assessment and hierarchical risk management for mercury in soils from a typical contaminated site, China. *Environ. Geochem. Health* **2017**, *39*, 923−934.
(30) Li, K.; Sun, R.; Guo, G. The rapid increase of urban contaminated sites along China's urbanization during the last 30 years. *iScience* **2023**, *26*, 108124.
(31) Cheng, Y.; Tang, Y.; Nathanail, C. P. Determination of the potential implementation impact of 2016 ministry of environmental protection generic assessment criteria for potentially contaminated sites in China. *Environ. Geochem. Health* **2018**, *40*, 967−985.
(32) Jiang, Y.; Wang, H.; Lei, M.; Hou, D.; Chen, S.; Hu, B.; Huang, M.; Song, W.; Shi, Z. An integrated assessment methodology for management of potentially contaminated sites based on public data. *Sci. Total Environ.* **2021**, *783*, 146913.
(33) Qu, C.; Shi, W.; Guo, J.; Fang, B.; Wang, S.; Giesy, J. P.; Holm, P. E. China's soil pollution control: choices and challenges. *Environ. Sci. Technol.* **2016**, *50*, 13181−13183.
(34) Zhou, Y.; Liu, Y. China's fight against soil pollution. *Science* **2018**, *362*, 298.
(35) Sun, Y.; Li, H.; Guo, G.; Semple, K.; Jones, K. Soil contamination in China: Current priorities, defining background levels and standards for heavy metals. *J. Environ. Manage.* **2019**, *251*, 109512.
(36) Li, X.; Jiao, W.; Xiao, R.; Chen, W.; Liu, W. Contaminated sites in China: Countermeasures of provincial governments. *J. Clean. Prod.* **2017**, *147*, 485−496.
(37) Zhao, F.; Ma, Y.; Zhu, Y.-G.; Tang, Z.; McGrath, S. P. Soil contamination in China: current status and mitigation strategies. *Environ. Sci. Technol.* **2015**, *49*, 750.
(38) Long, Z.; Zhu, H.; Bing, H.; Tian, X.; Wang, Z.; Wang, X.; Wu, Y. Contamination, sources and health risk of heavy metals in soil and dust from different functional areas in an industrial city of Panzhihua City, Southwest China. *J. Hazard. Mater.* **2021**, *420*, 126638.
(39) Chen, W.; Zhu, K.; Cai, Y.; Wang, Y.; Liu, Y. Distribution and ecological risk assessment of arsenic and some trace elements in soil of different land use types, Tianba Town, China. *Environ. Technol. Innov.* **2021**, *24*, 102041.
(40) Teh, T.; Nik Norulaini, N. A. R.; Shahadat, M.; Wong, Y.; Mohd Omar, A. K. Risk Assessment of Metal Contamination in Soil and Groundwater in Asia: A Review of Recent Trends as well as Existing Environmental Laws and Regulations. *Pedosphere* **2016**, *26*, 431−450.
(41) Xu, D.-M.; Fu, R.-B.; Liu, H.-Q.; Guo, X.-P. Current knowledge from heavy metal pollution in Chinese smelter contaminated soils, health risk implications and associated remediation progress in recent decades: A critical review. *J. Clean. Prod.* **2021**, *286*, 124989.
(42) Hu, H.; Ding, Z.; Sun, N.; Hao, Z. A preliminary analysis of characteristics of contaminated sites in provincial risk control and remediation directory. *Environ. Prot. Sci.* **2022**, *48*, 1−6.
(43) Usman, M.; Jellali, S.; Anastopoulos, I.; Charabi, Y.; Hameed, B.; Hanna, K. Fenton oxidation for soil remediation: A critical review of observations in historically contaminated soils. *J. Hazard. Mater.* **2022**, *424*, 127670.
(44) Xu, C.; Yang, W.; Zhu, L.; Juhasz, A. L.; Ma, L. Q.; Wang, J.; Lin, A. Remediation of polluted soil in China: policy and technology bottlenecks. *Environ. Sci. Technol.* **2017**, *51*, 14027−14029.
(45) Monika Mahajan; Gupta, P. K.; Singh, A.; Vaish, B.; Singh, P.; Kothari, R.; Singh, R. P. A comprehensive study on aquatic chemistry, health risk and remediation techniques of cadmium in groundwater. *Sci. Total Environ.* **2022**, *818*, 151784.
(46) Debela, S.; Sheriff, I.; Goyomsa, G.; Guta, A.; Gebrehiwot, M. Management of polychlorinated biphenyls stockpiles and contaminated sites in Africa: A review of 34 countries. *Chemosphere* **2022**, *298*, 134133.
(47) Bueno, F.; Günther, W.; Philippi, A., Jr; Henderson, J. Site-specific framework of sustainable practices for a Brazilian contaminated site case study. *Sci. Total Environ.* **2021**, *801*, 149581.
(48) Lv, Y.; Bao, J.; Zhu, L. A comprehensive review of recent and perspective technologies and challenges for the remediation of oil-contaminated sites. *Energy Rep.* **2022**, *8*, 7976−7988.
(49) Ding, K.; Wu, Q.; Wei, H.; Yang, W.; Séré, G.; Wang, S.; Echevarria, G.; Tang, Y.; Tao, J.; Morel, J.; Qiu, R. Ecosystem services provided by heavy metal-contaminated soils in China. *J. Soils Sed.* **2018**, *18*, 380−390.

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091

(50) Liu, R.; Song, Z.; Cui, X.; Wei, N.; Ji, G.; Wang, X. Progress and prospect of soil environmental management policy in China. *Chin. J. Environ. Manage.* **2021**, *13*, 93−100.

(51) Ladyman, M. K.; Temple, T. J.; Piperakis, M. M.; Fawcett-Hirst, W.; Gutierrez-Carazo, E.; Coulon, F. Decision Framework for the environmental management of explosive contaminated land. *Sci. Total Environ.* **2019**, *690*, 730−738.

(52) Provoost, J.; Cornelis, C.; Swartjes, F. Comparison of Soil Clean-up Standards for Trace Elements Between Countries: Why do they differ? *J. Soils Sediments* **2006**, *6*, 173−181.

(53) Di Fonzo, D.; Fabri, A.; Pasetto, R. Distributive justice in environmental health hazards from industrial contamination: A systematic review of national and near-national assessments of social inequalities. *Soc. Sci. Med.* **2022**, *297*, 114834.

(54) Sun, N.; Zhang, Y.; Ding, Z.; Yin, H. Problems and countermeasures in the implementation of soil environmental management directory system. *Chin. J. Environ. Engg.* **2021**, *14*, 2589−2594.

(55) Khan, S.; Naushad, M.; Lima, E.; Zhang, S.; Shaheen, S.; Rinklebe, J. Global soil pollution by toxic elements: Current status and future perspectives on the risk assessment and remediation strategies - A review. *J. Hazard. Mater.* **2021**, *417*, 126039.

(56) Zhang, H.; Du, P.; Li, A.; Chen, J.; Zhang, Y.; Li, M.; Wang, H.; Zhang, H. Development and Suggestion of Soil Environmental Standard System of Construction Land in China. *Res. Environ. Sci.* **2023**, *36*, 1−8.

(57) Wang, J.; Hu, Q.; Wang, X.; Li, X.; Yang, X. J. Protecting China's soil by law. *Science* **2016**, *354*, 562.

(58) Niu, A.; Lin, C. Managing soils of environmental significance: A critical review. *J. Hazard. Mater.* **2021**, *417*, 125990.

(59) Liu, S.; Wang, X.; Guo, G.; Yan, Z. Status and environmental management of soil mercury pollution in China: A review. *J. Environ. Manage* **2021**, *277*, 111442.

(60) Wu, Q.; Hu, W.; Wang, H.; Liu, P.; Wang, X.; Huang, B. Spatial distribution, ecological risk and sources of heavy metals in soils from a typical economic development area, Southeastern China. *Sci. Total Environ.* **2021**, *780*, 146557.

(61) Long, H.; Li, J.; Liu, H. Internal migration and associated carbon emission changes: Evidence from cities in China. *Energy Econ.* **2022**, *110*, 106010.

(62) Chen, D.; Liu, W.; Liu, X.; Westgate, J. N.; Wania, F. Cold-trapping of persistent organic pollutants in the mountain soils of western Sichuan, China. *Environ. Sci. Technol.* **2008**, *42*, 9086−9091.

(63) Xu, Y.; Dong, Z.; Wu, Y. The spatiotemporal effects of environmental regulation on green innovation: Evidence from Chinese cities. *Sci. Total Environ.* **2023**, *876*, 162790.

(64) Ministry of Ecology and Environment. *Soil Environmental Quality—Risk Control Standard for Soil Contamination of Development Land*, National Standard of the People's Republic of China GB36600-2018; Ministry of Ecology and Environment: China, 2018.

(65) Shaheen, S.; Wen, T.; Herman, A.; Brantley, S. Geochemical Evidence of Potential Groundwater Contamination with Human Health Risks Where Hydraulic Fracturing Overlaps with Extensive Legacy Hydrocarbon Extraction. *Environ. Sci. Technol.* **2022**, *56*, 10010−10019.

(66) Sonderegger, T.; Pfister, S.; Hellweg, S. Assessing Impacts on the Natural Resource Soil in Life Cycle Assessment: Methods for Compaction and Water Erosion. *Environ. Sci. Technol.* **2020**, *54*, 6496−6507.

(67) Nguyen, K.; Ahmed, M.; Mojiri, A.; Huang, Y.; Zhou, J.; Li, D. Advances in As contamination and adsorption in soil for effective management. *J. Environ. Manage.* **2021**, *296*, 113274.

(68) Kariyawasam, T.; Doran, G.; Howitt, J.; Prenzler, P. Polycyclic aromatic hydrocarbon contamination in soils and sediments: Sustainable approaches for extraction and remediation. *Chemosphere* **2022**, *291*, 132981.

(69) Kim, H.; Voutchkova, D.; Johnsen, A.; Albers, C.; Thorling, L.; Hansen, B. National Assessment of Long-Term Groundwater Response to Pesticide Regulation. *Environ. Sci. Technol.* **2022**, *56*, 14387−14396.

(70) Song, Y.; Hou, D.; Zhang, J.; O'Connor, D.; Li, G.; Gu, Q.; Li, S.; Liu, P. Environmental and socio-economic sustainability appraisal of contaminated land remediation strategies: A case study at a mega-site in China. *Sci. Total Environ.* **2018**, *610–611*, 391−401.

(71) Brombal, D.; Wang, H.; Pizzol, L.; Critto, A.; Giubilato, E.; Guo, G. Soil environmental management systems for contaminated sites in China and the EU. Common challenges and perspectives for lesson drawing. *Land Use Polym.* **2015**, *48*, 286−298.

(72) Ministry of Ecology and Environment. *Technical Guidelines for Investigation on Soil Contamination of Land for Construction*, National Standard of the People's Republic of China HJ25.1-2019; Ministry of Ecology and Environment: China, 2019.

(73) Ministry of Ecology and Environment. *Technical Guidelines for Risk Assessment of Soil Contamination of Land for Construction*, National Standard of the People's Republic of China HJ25.3-2019; Ministry of Ecology and Environment: China, 2019.

(74) Ministry of Ecology and Environment. *Technical Guidelines for Monitoring during Risk Control and Remediation of Soil Contamination of Land for Construction*, National Standard of the People's Republic of China HJ25.2-2019; Ministry of Ecology and Environment: China, 2019.

(75) Ministry of Ecology and Environment. *Technical Guidelines for Soil Remediation of Land for Construction*, National Standard of the People's Republic of China HJ25.4-2019; Ministry of Ecology and Environment: China, 2019.

(76) Ministry of Ecology and Environment. *Technical Guideline for Groundwater Remediation and Risk Control of Contaminated Sites*, National Standard of the People's Republic of China HJ25.6-2019; Ministry of Ecology and Environment: China, 2019.

(77) Ministry of Ecology and Environment. *Technical Guideline for Verification of Risk Control and Soil Remediation of Contaminated Site* National Standard of the People's Republic of China HJ25.5-2018; Ministry of Ecology and Environment: China, 2018.

(78) Weber, R.; Bell, L.; Watson, A.; Petrlik, J.; Paun, M. C.; Vijgen, J. Assessment of pops contaminated sites and the need for stringent soil standards for food safety for the protection of human health. *Environ. Pollut.* **2019**, *249*, 703−715.

https://doi.org/10.1021/acsomega.3c05187
ACS Omega 2024, 9, 3078−3091