RESEARCH ON THE IDENTIFICATION OF KEY INDUSTRIES FOR SOIL AND GROUNDWATER ENVIRONMENTAL CONTROL AND THEIR POLLUTION CHARACTERISTICS IN CHINA

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SUMMARY

With rapid industrial development, environmental pollution particularly soil and groundwater has become a critical concern in China. Identification of high-risk industries and implementing targeted management strategies is essential for effective ecological protection and pollution control. This study, systematically screened and identified key industries contributing to soil and groundwater contamination by integrating extensive enterprises data, pollutant discharge profile and national policy framework. Ten major medium-size industries were recognized as priority targets for environmental oversight including coal processing and metal surface treatment and heat treatment. These industries were characterized by high enterprise density, substantial pollutant emissions, and complex production processes. Detailed analysis of the process stages and typical pollutants in these two representative sectors revealed that specific operation are closely linked to the release of heavy metals, persistent organic pollutants, and other hazardous substances. Based on these findings, the study proposes targeted management strategies to strengthen pollution prevention and control at grass root level. The results provide a scientific landscape for regulatory decision making, support the formulation of industry specific guidelines and contributes to the advancement of national efforts for soil and groundwater protection. Additionally, this work highlights the need for risk-based, industry focused approaches to address environmental pollution in the context of sustainable industrial development.

KEY WORDS: Soil and groundwater, Key industries, Characteristic pollutants

1. INTRODUCTION

China's rapid socio-economic and industrial development has led to significant environmental concerns. Industrial activities often involve comlex processes using diverse raw material, generating pollutants with high toxicity and chemical complexity. The release of untreated or inadequately managed wastewater, exhaust gases and soil wastes during raw material transports, production distribution, and storage has severely impacted soil and groundwater ecosystems. These contaminants including heavy metals, persistent organic pollutants and volatile compounds, threaten environmental sustainability and pose serious risks to human health and ecological integrity. Inadequate waste management further exacerbates contaminations, highlighting the urgent need for effective remediation strategies to mitigate environmental degradation and protect public health.

During the 13th Five-Year Plan, China achieved notable progress in pollution prevention at sites of decommissioned or relocated enterprises. However, active industrial enterprises remain a significant yet under-addressed or relocated enterprises. Reconsidering this gape, the "14th Five-Year Plan for Soil, Groundwater, and Rural Ecological Environmental Protection" call for targeted pollution control in key regions and industries, emphasizing enhanced regulatory oversight of high- risk enterprises. Effective implementation demands a systematic multi-criteria screening framework to identify priority industries, assess their pollution profiles, and delineate production processes. This approach enables the accurate identification of industry-specific pollutants and facilitate precision in pollution source management. Establishing such a foundation is essential for advancing soil and groundwater pollution risk assessment in operational industrial settings and for developing robust technical systems for long-term pollution prevention and control.

The data for this study were obtained from the "Soil and Groundwater Investigation Disclosure" module of the National Construction Project Environmental Information Disclosure Platform (gs.eiacloud.com). From October 8, 2021, to March 13, 2023, 6,780 investigation reports were reviewed, with 1,079 self-monitoring reports and 278 reports indicating soil contamination above regulatory limits selected for analysis. This resulted in a comprehensive database of 950 active industrial enterprises. Current study, aims to identify characteristic pollutants, map pollution discharge sources analyze industrial processes, contributing to contamination, and pinpoint important enterprises, thereby providing a scientific basis for targeted soil pollution control and environmental management.

2. KEY INDUSTRY SELECTION OF DOMESTIC ENTERPRISES

2.1 STATISTICAL ANALYSIS OF THE NUMBER OF ENTERPRISES IN DIFFERNT INDUSTRIES

This study categorizes 950 active enterprises using the Industrial Classification for National Economic Activities (GB/T 4754—2017), based on industry types reported in self-monitoring and investigation reports. These classifications were verified through the National Pollutant Discharge Permit Management Information Platform (http://permit.mee.gov.cn/) and additional online data. The enterprises were systematically organized into broad, medium, and sub-categories with particular emphases on the 148 medium-level industry categories. This classification framework provides a structured basis for analyzing industrial distribution and environmental management across diverse sector.

Statistical analysis of enterprise distribution across 148 medium industry categories reveals a pattern approximating a normal distribution (Figure 1). In statistics, term the 1σ confidence interval (mean ± one standard deviation) emphases approximately 68.27% of the data making it a valuable matric for identifying representative subset (Sarkar et al., 2023). Applying this principle, the top 25 medium industry categories fall within the 1σ range and collectively represents 66.8% of the total enterprises, exceeding two third of the dataset (Figure 1). This concentration highlights their significance within the industrial structure. Consequently these 25 categories are identified as representative for further analysis, enabling more focused insight while maintaining statistical robustness.

Based on the quantitative analysis, the top 25 leading medium industry categories, ranked by the number of enterprises, were selected as the primary focus of this study. These industries represent the core sectors for evaluation with detail enterprise distribution presented in Table 1.

2.2 STATISTICAL ANALYSIS OF INDUSTRIAL POLLUTION LOAD INFORMATION

This study investigates pollution discharge capacities across key industrial sectors by analyzing data from 635 active enterprises within 25 selected industry subcategories, extracted from a broader database of 950 enterprises spanning 148 subcategories. Utilizing the "*National Pollutant Discharge Permit Management Information Platform*" we collected data on the "*Annual Permitted Emission Limits*" for both "Total Air Emission Permits" and "Plant-wide Wastewater Discharge Outlet Permits." These limits reflect the upper bound of allowable emissions, determined through a comprehensive evaluation of regulatory policies, industry characteristics, production scale, technological processes, pollution control efficiency, and regional environmental capacity.

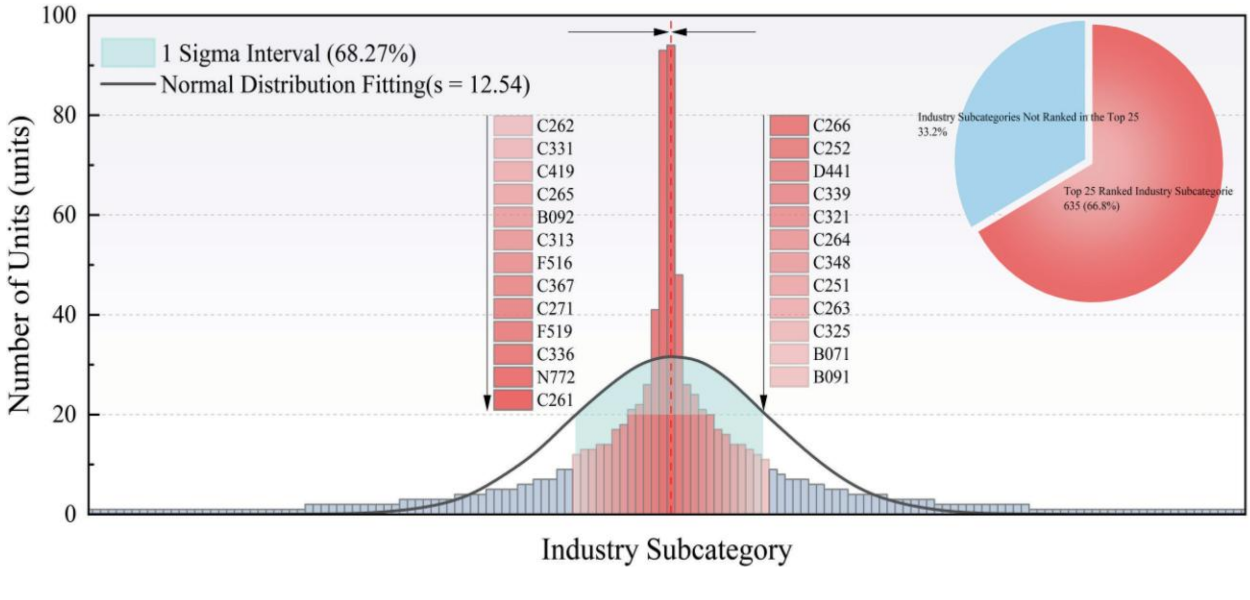

Figure 1. The quantitative distribution across 148 industry categories

Table 1. First round of selected industry sub-list

NO.	Medium industry category	Number of enterprises
1	C261 Manufacture of Basic Chemical Raw Materials	94
2	N772 Environmental Governance	93
3	C266 Manufacture of Specialty Chemical Products	48
4	C336 Metal Surface Treatment and Heat Processing	43
5	F519 Other Wholesale Activities	26
6	C252 Coal Processing	26
7	D441 Electric Power Production	24
8	C271 Manufacture of Chemical Drug APIs	22
9	C339 Casting and Other Metal Products Manufacturing	21
10	C367 Manufacture of Automotive Parts and Accessories	21
11	C321 Smelting of Common Non-ferrous Metals	20
12	F516 Wholesale of Mineral Products, Building Materials, and Chemical Products	18
13	C264 Manufacture of Paints, Inks, Pigments, and Similar Products	17
14	C313 Steel Rolling Processing	17
15	C348 Manufacture of General Components	16
16	B092 Mining of Precious Metal Ores	15
17	C251 Manufacture of Refined Petroleum Products	14
18	C265 Manufacture of Synthetic Materials	14
19	C263 Manufacture of Pesticides	14
20	C331 Manufacture of Structural Metal Products	13
21	C419 Other Unclassified Manufacturing	13
22	C325 Processing of Non-ferrous Metal Rolling	13
23	C262 Manufacture of Fertilizers	12
24	B071 Petroleum Extraction	12
25	B091 Mining of Common Non-ferrous Metal Ores	11

Additional considerations include local environmental quality targets and existing pollutant load. The Annual Application Emission Limits" thus serve as proxies for the pollution discharge potential and environmental burden of enterprises. To quantify and compare pollution discharge patterns, the study focused on six key quality pollutants: particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxide (NO_X), volatile organic compounds (VOCs), chemical oxygen demand (COD-cr), and ammonia nitrogen (NH_3-N). For each pollutant, maximum, minimum and average permitted emission value were identified, providing insight into industrial emission profiles and regulatory stringency.

According to article 6 of the Classification Management Catalog for Fixed Pollution Source Discharge Permits (2017 Edition) enterprises are classifies as key management industries if their annual emission exceeds specific threshold: sulfur dioxide or nitrogen oxides (>250 tons), smoke and dust (>1000 tons), chemical oxygen demand (>30 tons), and combined emissions of ammonia nitrogen, petroleum, and volatile phenols (>30 tons). Exceeding these thresholds suggests a substantial pollution load and significant environmental impact warranting strict regulatory oversight. Identifying enterprises that meet or surpass these limits is essential for effective environmental governance and targeted pollution control. This study analyzes emission permit data from 635 enterprises, comparing the maximum, minimum and average annual permitted emission limits for six key indicators against the national threshold criteria. The objective is to evaluate the pollution intensity of these enterprises and determine their compliance status relative to key management classification benchmarks.

Considering differences in enterprise size and regional distribution, industry subcategories are classified as having relatively high pollution loads if any single enterprise exceeds predefined threshold for key indicator or if the subcategory's average indicator values surpass these limits. This approach allows for a more nuanced assessment of environmental impact across 25 industry subcategories. Subcategories meeting either condition are flagged for priority attention. The resulting list of high-pollution subcategories, summarized in Table 2, provides the foundation for subsequent screening and targeted environmental management efforts in the next phase of analysis.

2.3 ANALYSIS OF KEY INDUSTRIES IN RELEVANT POLICY DOCUMENTS

Environmental management authorities have issued series of policy frameworks aimed to regulate the key industrial sector to mitigate environmental pollution. These documents such as the *Soil Pollution Prevention and Control Action Plan and the Water Pollution Prevention and Control Action Plan* issued by the State Council, stablished strategic guidelines for national pollution control and cooperate environmental responsibility. They highlight the substantial environmental impact of key industries and underscore the need for targeted regulatory

Table 2. Second round of selected industry sub-list

NO.	Medium Industry Category
1	C261 Manufacture of Basic Chemical Raw Materials
2	C336 Metal Surface Treatment and Heat Processing
3	D441 Electric Power Production
4	C271 Manufacture of Chemical Drug APIs
5	C252 Coal Processing
6	C321 Smelting of Common
7	C264 Manufacture of Paints, Inks, Pigments, and Similar Products
8	C313 Steel Rolling Processing
9	C251 Manufacture of Refined Petroleum Products
10	C265 Manufacture of Synthetic Materials
11	C263 Manufacture of Pesticides
12	C419 Other Unclassified Manufacturing
13	C325 Processing of Non-ferrous Metal
14	B071 Petroleum Extraction
15	B091 Mining of Common Non-ferrous Metal Ores
16	N772 Environmental Governance

measures. By identifying priority sectors contributing to soil and water pollution, these policies provide a scientific basis for pollution source control, industrial risk assessment, and remediation planning. This study systematically analyzes the key industries listed in these policies, as detailed in Table 3, to inform future research and environmental management strategies.

Secondly, we systematically reviewed the relevant regulatory documents issued by the Ministry of Ecology and Environment to guide the identification of priority industries for environmental supervision. These include the Management Measures for the List of Key Units under Environmental Supervision, the Trial Measures for Soil Environment in Industrial and Mining Land, Regulations on the Management of the List of Key Pollutant Discharge Units, Opinions on Further Strengthening the Prevention and Control of Heavy Metal Pollution, and Technical Policy for the Prevention and Control of Volatile Organic Compounds (VOCs) Pollution Control. These policies collectively outline criteria for industry classification based on pollutant discharge levels, environmental risk and regulatory importance. The industries identified across these documents, which are critical for targeted environmental interventions are summarize in Table 4.

Table 3. Key industry sub-categories mentioned in the regulations

No.	Soil Pollution Prevention and Control Action Plan	Water Pollution Prevention and Control Action Plan
1	Coke (C252 Coal Processing)	Coke (C252 Coal Processing)
2	Non-ferrous Metal Mining (B091 Common Non-ferrous Metal Mining)	Non-ferrous Metals (B091 Common Non-ferrous Metal Mining, C321 Non-ferrous Metal Smelting)
3	Non-ferrous Metal Smelting (C321 Non-ferrous Metal Smelting)	Non-ferrous Metals (B091 Common Non-ferrous Metal Mining, C321 Non-ferrous Metal Smelting)
4	Leather Processing (C191 Leather Tanning and Processing)	Leather Processing (C191 Leather Tanning and Processing)
5	Electroplating (C336 Metal Surface Treatment and Heat Treatment)	Electroplating (C336 Metal Surface Treatment and Heat Treatment)
6	Petroleum Refining (C251 Petroleum Refining)	-
7	Petroleum Extraction (B071 Petroleum Extraction)	-
8	Chemical Industry (C261 Basic Chemical Raw Materials Manufacturing)	-
9	-	Papermaking (C222 Papermaking)
10	-	Nitrogen Fertilizer (C262 Fertilizer Manufacturing)
11	-	Printing and Dyeing (C171 Cotton Textile and Printing, C174 Silk Textile and Printing, C175 Chemical Fiber Weaving and Printing)
12	-	Agricultural and Sideline Food Processing (C31 Agricultural and Sideline Food Processing)
13	-	Pesticides (C263 Pesticide Manufacturing)

Note: “-” indicates that the industry is not mentioned in the policy document.

Table 4. The key industry categories mentioned in various methods and regulations

No.	Management measures for environmental supervision key units	Regulations on the management of the key polluting units list	Soil environmental management measures for industrial and mining land (trial)	Technical policies for the prevention and control of volatile organic compounds (VOCs) pollution	Opinions on further strengthening the prevention and control of heavy metal pollution
1	Coking (C252 Coal Processing)	–	Coking (C252 Coal Processing)	C252 Coal Processing	–
2	Non-ferrous Metal Mining and Selection (B091 Common Non-ferrous Metal Mining and Selection)	Non-ferrous Metal Mining and Selection (B091 Common Non-ferrous Metal Mining and Selection)	Non-ferrous Metal Mining and Selection (B091 Common Non-ferrous Metal Mining and Selection)	–	Non-ferrous Metal Mining and Selection (B091 Common Non-ferrous Metal Mining and Selection)
3	Non-ferrous Metal Smelting (C321 Common Non-ferrous Metal Smelting)	Non-ferrous Metal Smelting (C321 Common Non-ferrous Metal Smelting)	Non-ferrous Metal Smelting (C321 Common Non-ferrous Metal Smelting)	–	Non-ferrous Metal Smelting (C321 Common Non-ferrous Metal Smelting)
4	Leather Manufacturing (C191 Leather Tanning and Processing)	Leather Manufacturing (C191 Leather Tanning and Processing)	Leather Manufacturing (C191 Leather Tanning and Processing)	–	Leather Manufacturing (C191 Leather Tanning and Processing)
5	Petroleum Refining (C251 Refining Petroleum Products Manufacturing)	–	Petroleum Refining (C251 Refining Petroleum Products Manufacturing)	Petroleum Refining and Petrochemical (C251 Refining Petroleum Products Manufacturing)	–
6	Petroleum Extraction (B071 Petroleum Extraction)	–	Petroleum Extraction (B071 Petroleum Extraction)	–	–
7	Chemical Industry (C261 Basic Chemical Raw Materials Manufacturing)	Chemical Raw Materials and Chemical Products Manufacturing (C261 Basic Chemical Raw Materials Manufacturing)	Chemical Industry (C261 Basic Chemical Raw Materials Manufacturing)	–	Chemical Raw Materials and Chemical Products Manufacturing (C261 Basic Chemical Raw Materials Manufacturing)
8	–	Lead-acid Battery Manufacturing (C384 Battery Manufacturing)	–	–	Lead-acid Battery Manufacturing (C384 Battery Manufacturing)
9	–	–	C264 Manufacturing of Paints, Inks, Pigments, and Similar Products	–	–
10	–	–	C263 Pesticide Manufacturing	–	–

Note: “-” indicates that the industry is not mentioned in the policy document

In recent years, China has intensified efforts to assess soil contamination across industrial lands, particularly in environmentally sensitive sectors, to established a robust scientific foundation for risk management and remediation strategies. According to a press briefing by the Ministry of Ecology and Environment in April 2022, Su Kejing, Director-General of the Soil Ecological Environment Department, reported that comprehensive investigations revealed significant soil pollution risk in specific industries. These includes non-ferrous metal smelting,

Table 5. Statistical analysis of the frequency of industry categories mentioned in documents and "speeches"

No.	Industry category in the second round of selection	Mentions in documents	Mentions in the speech
1	C261 Basic Chemical Raw Materials Manufacturing	5	1
2	C336 Metal Surface Treatment and Heat Treatment Processing	2	1
3	D441 Electricity Production	-	–
4	C271 Chemical Pharmaceutical Raw Materials Manufacturing	–	–
5	C252 Coal Processing	5	1
6	C321 Common Non-ferrous Metal Smelting	6	1
7	C264 Manufacture of Paints, Inks, Pigments, and Similar Products	1	–
8	C313 Steel Rolling Processing	–	–
9	C251 Refined Petroleum Products Manufacturing	4	1
10	C265 Synthetic Materials Manufacturing	–	–
11	C263 Pesticide Manufacturing	1	1
12	C419 Other Unspecified Manufacturing Industries	–	–
13	C325 Non-ferrous Metal Rolling Processing	–	–
14	B071 Petroleum Extraction	3	1
15	B091 Common Non-ferrous Metal Ore Mining and Selection	6	1
16	N772 Environmental Governance Industry	–	–

Note: "-" indicates that the industry is not mentioned in the policy document.

oil extraction, oil processing, chemicals manufacturing, coking, electroplating, and leather tanning. Evaluated concentration of heavy metals, petroleum hydrocarbons, and persistent organic pollutants in soil and ground water were frequently detected at sites within these sectors, indicating sever environmental hazards.

The eight industries have since been prioritizing under national environmental governance policies due to their substantial contribution to soil and groundwater contamination. Their destination as key regulatory targets reflect China's shift towards precision environmental management focusing on high-risk sector to improve intervention effectiveness.

In alignment with this national strategy, the present study adopts these eight industries as key criteria for industrial site selection. This approach ensures the relevance and policy consistency of the research framework. Furthermore, the secondary screening of additional industries was guided by their frequency of reference in national and provincial policy documents, providing an evidence-based rationale for inclusion. The final selection of industries is summarized in Table 5 and forms the basis for subsequent risk assessment and management recommendations.

Based on comprehensive analysis of relevant policy documents and the referenced speech, nine priority industries have been identified for inclusion in the third round of industrial categorization. These include: C261 Basic Chemical Raw Materials Manufacturing, C336 Metal Surface Treatment and Heat Treatment Processing, C252 Coal Processing, C321 Non-ferrous Metal Smelting, C264 Paints, Inks and Pigments manufacturing, C251 Refined Petroleum Products Manufacturing, C263 Pesticide Manufacturing, B071 Petroleum Extraction, and B091 Common Non-ferrous Metal Ore Mining. These sectors reflect strategic emphasis on high-impact, resource-intensive and environmentally significant industries in national industrial policy planning.

Additionally, a comprehensive analysis of policy documents and official speeches reveals that the C191 Leather Tanning and Processing industry as a key industry in six documents and one speech. These evidences underscore its strategic significance, substantial environmental pollution burden, and heightened regulatory attention. Although, absent from the third-round selection list, the industry's high ecological impact and policy relevance justify its direct inclusion in the key industry categories for targeted environmental management and sustainable development efforts.

2.4 SCREENING AND ANALYSIS RESULTS

A comprehensive analysis of self-conducted test reports, site investigation, discharge data, and policy documents enable systematic screening, resulting in the identification of the top ten key polluting industries, as summarized in Table 6.

3. KEY INDUSTRY TYPICAL PRODUCTION PROCESSES AND POLLUTION DISCHRARGE LINKS

3.1 OVERVIEW AND CLASSIFICATION OF THE TEN KEY INDUSTRY CATEGORIES

After identifying the ten key industries, the focus shifts to implementing targeted environmental management

Table 6. List of key sub-categories in the top ten industries

NO.	Key industries
1	C261 Manufacture of Basic Chemical Raw Materials
2	C336 Metal Surface Treatment and Heat Processing
3	C252 Coal Processing
4	C321 Smelting of Common Non-ferrous Metals
5	C264 Manufacture of Paints, Inks, Pigments, and Similar Products
6	C251 Manufacture of Refined Petroleum Products
7	C263 Manufacture of Pesticides
8	B071 Petroleum Extraction
9	B091 Mining of Common Non-ferrous Metal Ores
10	C191 Leather Tanning and Processing

strategies. To enable precise and practical interventions, it is crucial to analyze typical production processes, pollution discharge stages, and industry-specific pollutants. This study recommends classifying these industries based on their production characteristics and pollution profiles to support differentiated regulatory approaches. Such classification will facilitate the development of tailored pollution control measures and inform future research on sustainable industrial practices.

Based on the National Economic Industry Classification (GB/T 4754–2017), the ten key industry categories encompass multiple subcategories. To enhance scientific validity, a systematic classification approach was applied. First subcategory homogeneity within each industry was assessed based on production processes and pollutant profiles. For categories with similar subcategories exhibiting analogous processes and pollutant characteristics, industry level analysis was deemed appropriate. Conversely, for categories with pronounced variation among subcategories, due to distinct production methods or divergent emissions, a subcategory-level analysis was implemented. This dual approach ensures methodological precision and enhances the reliability and applicability of the findings for environmental policy and industrial regulation.

This classification framework enables precise identification and analysis of industrial environmental issues. For industry categories with high internal homogeneity, analyzing data at the industry category level effectively capture common production features and pollutant profiles. Conversely, for categories with significant industrial heterogeneity, such as differing processes, raw materials or emission characteristics, a subcategory-level approach ensure more accurate representation. This dual-level methodology not only address practical needs in environmental management but also offers a theoretical basis for formulating precise and effective regulatory strategies.

Based on self-monitored reports, site investigation reports, and comprehensive-level database environmental characteristics of ten key industrial categories were analyzed. The findings are summarized as follows:

In B091 Non-ferrous Metal Ore Mining and Selection: This category includes eight subcategories with mainly consistent production processes, involving ore liberation, sorting and final product treatment. The standard flow of process comprising crushing, screening, grinding, classification, selection, concentrate dewatering, and tailings disposal, is widely shared across subcategories. Although the main technology is similar, differences in raw ore composition result in various pollutant profiles, especially in heavy metals and suspended solids.

Whereas, in C336 Metal Surface Treatment and Heat Treatment Processing and C191 Leather Tanning and Processing categories, results indicated that enterprises in these sectors, typically implement multiple standardized processing techniques as a part of integrated production lines. The uniformity in operational procedures and pollution characteristics across enterprises indicates minimal variation with in the category, supporting the use of the industry category as a primary research unit.

Accordingly, the B091, C336 and C191 categories exhibits sufficient internal consistency to warrant industry-level analysis. This method ensures both analytical rigor and practical relevance for environmental policy making, particularly in designing targeted pollution control strategies and compliance framework.

The C336 Metal Surface Treatment and Heat Treatment Processing industry is prominent in the database due to its large number of entries and substantial pollution load. Literature and policy analysis indicate that this industry primarily is a major source of heavy metal emissions, including chromium, nickel, copper, zinc and cadmium (Tingting Liu, 2024, Quanheng Li, 2024). These pollutants are associated with significant environmental health risks and ecological toxicity. Notably, the electroplating process within this industry poses high risk and has been frequently emphasized in national policy documents, underscoring sustained regulatory attention. Given its environmental relevance and representativeness, the C336 industry serves as a suitable focus for in-depth analysis to inform targeted pollution control and environment management strategies.

However, the industry categories category falls under B071 Petroleum Extraction, C251 Refined Petroleum Products Manufacturing, C252 Coal Processing, C261 Basic Chemical Raw Materials Manufacturing, C263 Pesticide Manufacturing, C264 Paints, Inks, Pigments and Similar Products Manufacturing, and C321 Common Non-ferrous

Metal Smelting, exhibit substantial heterogeneity among their subcategories in terms of production processes and pollutant discharge profiles. In future research, subcategories with high pollution loads, distinct pollution characteristics, and significant economic relevance should be prioritized as representative cases.

During the industry screening Phase, C252 coal processing emerged as a key focus due to its high proportion of enterprises and substantial pollutant discharge loads in database. This industry is characterized by the release of hazardous organic pollutants primarily polycyclic aromatic hydrocarbons (PAHs) and benzene derivatives (BTEX), which pose significant environmental and public health risks (Qiaofeng Ai, 2023, Ziye Liu, 2024, Mu et al., 2023, Chen et al., 2025). Consequently, C252 is selected as a representative small-category industry for further investigation.

Based on the above classification strategy, this study identifies C336 Metal Surface Treatment and Heat Treatment as a representative medium-category industry, and C252 Coal Processing as a representative small-category industry, for in-depth analysis of production processes and pollutant discharge characteristics.

3.2 C336: METAL SURFACE TREATMENT AND HEAT TREATMENT

1. Industry Overview

The C336 industry category encompasses two key manufacturing processes: metal surface treatment and heat treatment, both of which are critical for improving the performance, appearance and durability of metal products. Metal surface treatment involves chemical, physical, chemical, or electrochemical processes to clean, modify or coat the surface of metal components. Common method includes electroplating, anodizing and passivation. Heat treatment on the other hand, involves controlled heating and cooling to alter the microstructure and mechanical properties of metals, such as hardness, ductility, and tensile strength. These processes are widely employed across industries including automotive, aerospace, electronics and precision machinery. However, due to the extensive use of toxic chemicals, such as acids, alkalis, surfactants, cyanides and heavy metal salts, these operations generates considerable quantities of wastewater, sludge and air emissions, often containing hazardous and environmentally persistent pollutants (Xing et al., 2016).

Amongthevariousprocesseswithinthiscategoryelectroplating play a pivotal role. It is not only fundamental to improving surface properties such as corrosion resistance and aesthetic but also hold significant industrial representativeness due to its widespread application and prominence in environmental regulatory frameworks. Electroplating is therefore selected as the representative medium-category industry for in-depth analysis in this study.

2. Typical Production Process and Pollutant Discharge Pathway

Electroplating involves a series of tightly linked operations including degreasing, activation, pre-plating, plating assistance, coating, passivation, polishing, cleaning, and drying. Each of these steps contributes to the generation of processes-specific pollutants. The detailed description of each and its associated environmental impact is presented below and depicted in (Figure 2).

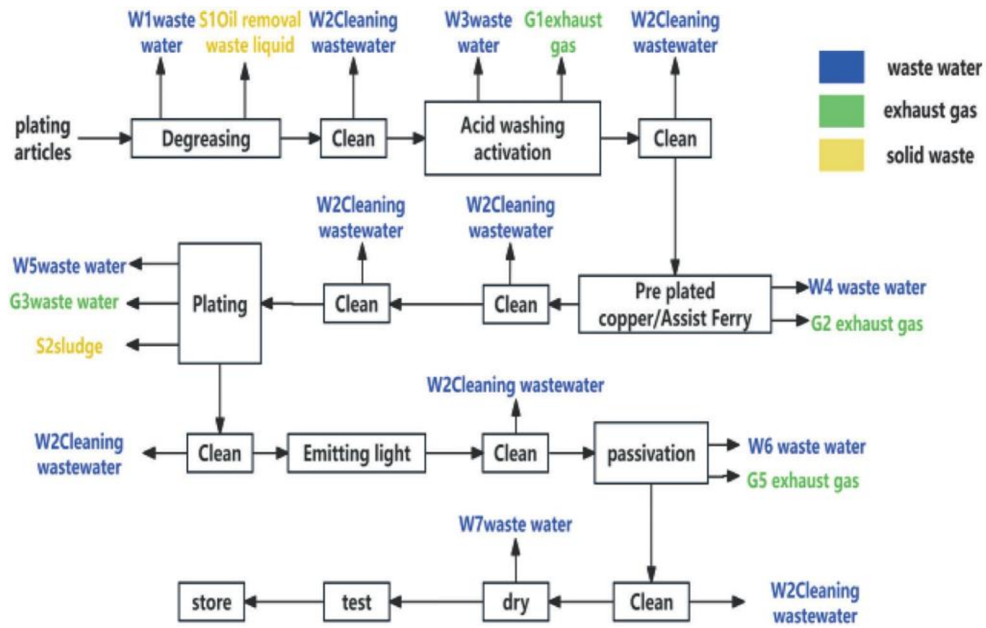

Figure 2. Typical production process and pollution emission points in metal surface treatment and heat treatment processing

Main Processes:

1. Degreasing involves cleaning the surface of pre-plated parts using alkaline agents or surfactants to eliminate oil stains. The cleaning solutions often contain fluorides, and the process generates petroleum hydrocarbons (C_{10}–C_{40}). The removed contaminants may include heavy metals such as arsenic, cadmium, hexavalent chromium, copper, lead, mercury, nickel, tin, iron, zinc, total chromium, and total phosphorus. These pollutants are typically discharged through wastewater and spent degreasing solutions, contributing to environmental contamination.
2. Pickling and Activation Process: The pickling and activation process involves treating pre-plated parts with hydrochloric, sulfuric, or nitric acid to remove oxides and rust, thereby exposing the base metal and enhancing adhesion of the plating layer. This process generates hydrogen chloride gas and contributes to chloride ion accumulation. Additionally, oxides and rust may contain hazardous heavy metals such as arsenic, cadmium, hexavalent chromium, copper, lead, mercury, nickel, tin, iron, zinc, total chromium, and phosphorus. These pollutants are released through wastewater and exhaust emissions, posing significant environmental and health risks if not properly managed through effective treatment and containment systems.
3. Pre-plating with copper using cyanide copper (alkaline), copper sulfate, or sulfuric acid (acidic) is widely employed in electroplating to enhance adhesion and bonding strength of subsequent coatings. As a commonly used base layer, it significantly improves overall plating quality. However, the process generates pollutants, including copper ions and cyanide complexes, which are released through wastewater and waste gases, posing environmental concerns.
4. Plating assistance, commonly employed in hot-dip galvanizing, utilizes a flux solution—typically a mixture of zinc chloride and ammonium chloride— to prevent oxidation of steel surfaces before zinc immersion. This pre-treatment maintains surface reactivity and promotes strong metallurgical bonding between the zinc coating and the substrate. Scientifically, the flux removes residual oxides and facilitates uniform coating adhesion. However, the process generates significant environmental pollutants: zinc ions from the reaction and acid mist containing volatile chlorides are released, contributing to air and water pollution. These byproducts necessitate stringent emission controls and wastewater treatment to mitigate ecological and health risks.
5. Coating Process and Pollutant Profile: Electroplating involves depositing metals like nickel, copper, zinc, and chromium onto work pieces via electrolysis to enhance corrosion resistance, appearance, or functionality. However, the process releases substantial quantities of heavy metal ions into the environment due to metal dissolution and deposition cycles. Additives containing fluorine contribute to fluoride formation, while nitrites and nitrates serve as oxidizing agents that facilitate metal ion reduction. Cyanide compounds (sodium or potassium cyanide), widely used as complexing agents to stabilize metal ions, generate highly toxic cyanide residues. These pollutants contaminate wastewater, off-gases, and electroplating sludge, posing serious risks to aquatic ecosystems and human health.
6. Passivation involves treating plated surfaces with chromic acid or chromate salts to form a stable, protective oxide layer that significantly enhances corrosion resistance by inhibiting electrochemical reactions with environmental agents. This chemically inert layer not only prolongs the durability of metal components but also improves their surface appearance. However, the process poses environmental and health concerns due to the use of hexavalent chromium compounds, which release toxic chromic acid mist and result in the accumulation of chromium ions. These pollutants can contaminate air and water through emissions and wastewater discharge, necessitating stringent control measures and alternative eco-friendly passivation technologies.
7. Polishing involves mechanical techniques to enhance surface smoothness, improving product aesthetics and reducing microbial adhesion. As it is a dry process without chemical use or emissions, it does not generate pollutants or environmental contaminants.
8. Cleaning procedures are strategically integrated between processing steps, utilizing water, alkaline agents, or solvent cleaners tailored to specific residues. These agents effectively remove organic and inorganic contaminants, ensuring product integrity and equipment hygiene. However, solvent-based cleaners often contain petroleum hydrocarbons (C_{10}–C_{40}), which, upon use, enter the wastewater stream, posing environmental risks due to their persistence and potential toxicity, necessitating proper treatment before discharge.

3.3 C252 COAL PROCESSING

1. Industry Overview: Coal processing involves the removal of mineral impurities and harmful elements from coal through physical, chemical, or physicochemical methods, producing coal varieties with different qualities to meet diverse industrial demands. A major sector within this industry is the C2521 coking process, which utilizes heating methods to carbonize raw coal into coke, generating valuable by-products such as coal gas, tar, ammonia, and crude benzene. This sector is foundational to the coal chemical industry (Jovanovski et al., 2023). China dominates global coke production, contributing 70% of total output, with the coking industry accounting

for 58% of the nation's coke production in regions prioritized for air pollution control (Mu et al., 2017). While economically significant, the coking industry poses substantial environmental and public health risks. It is a major source of volatile organic compound (VOC) emissions(Wen et al., 2024, Liu et al., 2023, Wang et al., 2023, Zhang et al., 2019), and exposure to polycyclic aromatic hydrocarbons in coking plants is linked to heightened risks of cardiovascular diseases and diabetes (Yang et al., 2019, Yang et al., 2017). Given its economic importance and the environmental and health challenges it presents, the C2521 coking industry serves as a critical focus for research on the coal processing sector.

2. Typical Production Process and Pollutant Discharge Stages: The coking industry comprises complex processes—such as coal preparation, coking, condensate blowing, ammonium sulfate production, benzene washing, and desulfurization—that collectively contribute to significant environmental pollution. Each stage generates diverse pollutants, including toxic gases (e.g., SO_2, NO_x, and volatile organic compounds), wastewater containing phenols and ammonia, and solid waste like tar sludge. These pollutants are known to pose severe risks to human health and ecosystems due to their carcinogenicity, mutagenicity, and persistence in the environment (Savchenko et al., 2019; Zhang, 2023). Accordingly, regulatory bodies have implemented stringent emission standards to mitigate these impacts. The pollutant discharge stages and their associated risks are summarized based on industrial reports and literature sources (Figure 3).

Main Processes:

1. The crushing section, comprising coal blending, washing, and pulverizing, facilitates size reduction and impurity removal but also generates significant coal dust containing hazardous heavy metals like mercury, arsenic, cadmium, and lead. These toxic elements, naturally present in raw coal, become airborne during processing, posing environmental and health risks through inhalation and soil or water contamination.
2. The coking section encompasses the high-temperature dry distillation of coal to produce coke and crude gas, followed by coke quenching, screening, and storage. During coking, coal undergoes pyrolysis at 1000–1100 °C in the absence of oxygen, releasing volatile matter and yielding coke, a porous carbon- rich solid used in metallurgical processes. Water quenching rapidly cools the red-hot coke, preventing combustion but generating wastewater rich in phenolic and cyanide compounds. Simultaneously, high-temperature reactions of coal's organic matrix release a spectrum of hazardous pollutants. Aromatic hydrocarbons, particularly benzene series and polycyclic aromatic hydrocarbons (PAHs), are formed due to thermal cracking of organic material, posing carcinogenic risks. Nitrogenous compounds degrade into ammonia and hydrogen cyanide, while halogen-containing impurities (Cl, F, I) form volatile halides, which, under the presence of sulfur and high temperatures, can contribute to dioxin formation persistent organic pollutants with severe toxicological profiles. Additionally, the crude gas carries petroleum hydrocarbons that require subsequent purification.

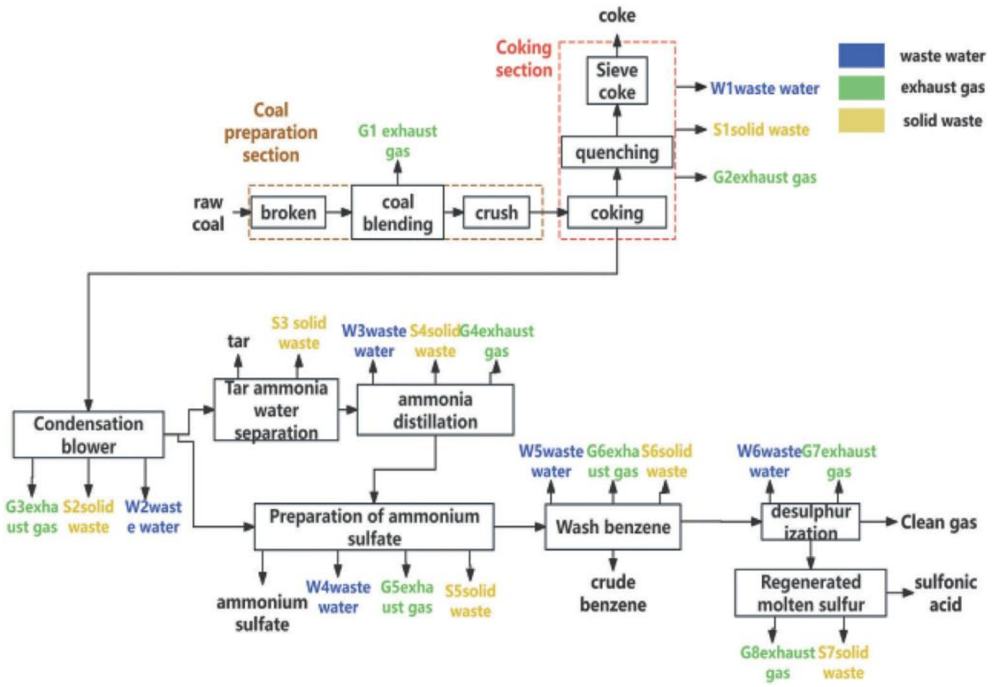

Figure 3. Typical production process and pollution emission points in the coking industry

Heavy metals present in coal may volatilize or adhere to coke particles, later dispersing into the environment as fugitive dust during handling and transport. These emissions airborne and aqueous pose significant environmental and health hazards, necessitating advanced control technologies (Zhang and Lin, 2024).

3. Condensation and Blowing: During condensation and blowing, crude gas undergoes phase separation via a gas-liquid separator, isolating tar, ammonia water, and purified gas. This process emits pollutants such as phenolic compounds and petroleum hydrocarbons due to incomplete condensation. Additionally, wastewater and exhaust gases enriched with PAHs, phenols, and hydrocarbons pose significant environmental and health risks.
4. Tar-Ammonia water separation: Tar and ammonia water are separated using a mechanical ammonia water clarifier, enabling efficient phase separation based on density differences. Tar, containing hazardous pollutants like benzene series, polycyclic aromatic hydrocarbons (PAHs), and cyanides (Si et al., 2017), is directed to storage, while ammonia water proceeds to distillation for pollutant recovery and reuse.
5. Ammonia Distillation: This process involves absorbing ammonia in sulfuric acid mother liquor to produce ammonium sulfate, with the mixture directed to benzene removal. This process emits organic exhaust gases rich in polycyclic aromatic hydrocarbons (PAHs). Wastewater contains ammonia nitrogen, cyanides, phenols, sulfides, petroleum hydrocarbons, and PAHs, posing significant environmental risks. Additionally, tar residues, a by-product of incomplete combustion, further contribute to pollution load.
6. Ammonium Sulfate Production: This process involves continuous crystallization from mother liquor, followed by centrifugation, drying, and cooling. However, the process generates significant pollutants: waste acid tar from the saturator contains hazardous polycyclic aromatic hydrocarbons (PAHs), cyanides, and ammonia nitrogen, posing serious environmental and health risks. Additionally, wastewater and exhaust gases contribute to aquatic and atmospheric pollution, necessitating efficient emission control and waste treatment strategies.
7. Benzene Washing and Removal: The benzene washing and removal process involves cooling gas from the ammonium sulfate section before it enters the benzene washing tower, where heated circulating wash oil absorbs benzene. The oil is then distilled in a benzene removal tower to recover crude benzene, which is condensed, separated, and stored. Despite its efficiency, this process emits hazardous volatile organic compounds (VOCs), particularly benzene derivatives, through wastewater and exhaust gases, posing significant environmental and health risks due to their carcinogenic nature.
8. Desulfurization: In the desulfurization process, incoming gas is treated in a tower where hydrogen sulfide (H_2S) and hydrogen cyanide (HCN) are chemically absorbed by the desulfurization liquid, forming sulfur compounds. The resulting sulfur foam is separated and transferred to a melting pot. This process generates waste liquid rich in sulfides, sulfates, and cyanides, with potential H_2S emissions due to incomplete absorption or system inefficiencies.
9. Regeneration and Sulfur Melting: In the regeneration and sulfur melting process, sulfur foam undergoes high-temperature treatment in the regeneration tower and melting pot to recover elemental sulfur for commercial use. However, this process emits significant sulfide pollutants into wastewater, exhaust gases, and desulfurization waste liquids, which also contain sulfates. These emissions pose environmental risks due to the toxicity and persistence of sulfur compounds in aquatic and atmospheric systems.

4. ANALYSIS OF CHARACTERISTIC POLLUTANTS IN KEY INDUSTRIES

Characteristic pollutants are representative contaminants that generated from the specific raw materials, processes, or emission characteristics of an industry and pose considerable risk to environmental and human health. In the context of soil and groundwater pollution control, managing all possible is impractical due to the complexity and variability of industrial emissions. Therefore, identifying characteristic pollutants enable targeted, efficient and scientifically grounded pollution management. This study advances that approach by analyzing pollutant profiles in key industries.

For the metal surface treatment and heat treatment processing industry (C336), which consist of single subclass, the medium category itself is used as the analytical basis. In contrast the coal processing industry (C252) shown substantial variation among subclasses, necessitating a subclass-specific approach. Among these, the coking industry (C2521) is identified as the most representative due to its consistent process characteristics and significant environmental burden. Accordingly, this study focusses on pollutant data from 41 metal surface treatment and heat treatment processing industries and 16 coking industries sites, drawing from self-monitoring reports and site investigation reports to extract pollutant of concern and key cumulative factors, as summarized in in Table 7.

This study systematically identifies characteristic pollutants in the metal surface and heat treatment industry, such as arsenic, cadmium, hexavalent chromium, and petroleum hydrocarbons (C_{10}–C_{40}), by analyzing over-limit factors, accumulation trends, and industry-specific reports, providing a scientifically grounded basis for targeted pollution control, as these contaminants pose significant risks to environmental and human health due to their toxicity, persistence, and bio-accumulative nature.

Table 7. Characteristics factors of metal surface treatment and heat treatment processing, focus on pollutants and exceeding pollutants

Industries	Soil		Groundwater		Industry characteristic pollutants
	Explicitly mentioned characteristic factors or pollutants of concern	**Exceeded pollutants**	**Explicitly mentioned characteristic factors or pollutants of concern**	**Exceeded pollutants**	
C336 Metal Surface Treatment and Heat Processing	Arsenic, cadmium, hexavalent chromium, copper, lead, mercury, nickel, tin, iron, zinc, total chromium, pH, ammonia nitrogen, cyanide, chlorides, nitrate, petroleum hydrocarbons (C_{10}–C_{40}).	Total chromium, hexavalent chromium, nickel, zinc, ammonia nitrogen, chlorides.	pH, nickel, total chromium, hexavalent chromium, arsenic, lead, cadmium, copper, tin, zinc, iron, total phosphorus, ammonia nitrogen, chlorides, fluoride, nitrate, nitrite, petroleum hydrocarbons (C_{10}–C_{40})	Zinc, nickel, total chromium, fluoride, ammonia nitrogen	Arsenic, cadmium, hexavalent chromium, copper, lead, mercury, nickel, tin, iron, zinc, total chromium, total phosphorus, pH, ammonia nitrogen, cyanide, chlorides, fluoride, petroleum hydrocarbons (C_{10}–C_{40}), nitrate, nitrite.

The analysis of the frequency and concentration of characteristic pollutants reveals that heavy metal contamination is the predominant environmental concern in the industry. Heavy metals such as cadmium, lead, chromium, and copper are the primary contributors to groundwater and soil pollution due to their high persistence, bioaccumulation potential, and strong biological toxicity (Tang et al., 2019, Li et al., 2023, Hao et al., 2024, Tiwari et al., 2016). These pollutants pose long-term ecological risks as they are not readily biodegradable and can enter the food chain, causing adverse effects in humans and wildlife (M et al., 2022, Plekhanova et al., 2019, G et al., 2024). Additionally, cyanides recognized for their acute toxicity and rapid action were also identified among the critical pollutants, warranting close scrutiny of the production stages where they are generated.

Process analysis indicates that heavy metals are primarily released during degreasing, pre-plating, electroplating assistance, passivation, and coating stages, while cyanides are mainly associated with pre-plating and coating. Notably, the coating process emerges as the most critical due to its large-scale operation, extensive use of metal-ion-rich electroplating solutions, and reliance on cyanide-based complexing agents. This stage contributes the highest volume of pollutants in the form of wastewater, exhaust gases, and solid waste, with the heaviest pollutant load. Furthermore, the pre-plating and electroplating assistance stages also use substantial amounts of copper-based plating solutions and cyanide compounds. Therefore, the coating and pre-plating processes should be prioritized for pollution control and environmental management due to their significant contributions to heavy metal and cyanide pollution.

Based on the processes and pollutants outlined above, the potential environmental migration pathways in this industry primarily involve three routes. First, the storage and use of high-risk chemicals such as electroplating solutions and complexing agents pose significant risks; accidental leaks or drips during handling or plating operations may infiltrate through surface cracks, leading to soil and groundwater contamination due to the high mobility and persistence of certain heavy metals and organic compounds. Second, prolonged operation can cause equipment aging, corrosion, or mechanical failure, resulting in unintended leakage of hazardous raw or auxiliary materials, further exacerbating subsurface pollution. Third, inadequate or inefficient end-of-pipe treatment systems may lead to the discharge of substandard wastewater and exhaust gases, contributing to environmental burden through atmospheric dispersion, runoff, and infiltration. Given these potential pathways, a science-based environmental management strategy is essential. This includes implementing full-process risk control for stages involving toxic substances, conducting routine inspection and maintenance of equipment and containment systems to prevent leaks, and ensuring continuous monitoring and compliance of emissions and effluents with regulatory standards. These actions collectively mitigate pollutant release and reduce the risk of long-term environmental degradation.

Based on a systematic screening of characteristic factors, pollutants of concern, and compounds exceeding regulatory thresholds from industry reports, a group of industry-specific pollutants has been identified, reflecting both organic and inorganic contamination profiles. These include volatile and semi-volatile organic compounds such as benzene, toluene, xylene, chlorinated benzenes, nitrobenzene, aniline, phenolic derivatives, polycyclic aromatic hydrocarbons (pyrene, fluoranthene, benzo pyrene), and dioxins substances known for their persistence, bioaccumulation, and carcinogenic or mutagenic potential. Additionally, heavy metals such as

Table 8. Characteristic factors of the coking industry, focus on pollutants and exceeding pollutants

Indust-ries	Soil		Groundwater		Industry characteristic pollutants
	Explicitly mentioned characteristic factors or pollutants of concern	Exceeded pollutants	Explicitly mentioned characteristic factors or pollutants of concern	Exceeded pollutants	
C2521Coking Industry	Benzene, Toluene, Xylene, Chloro-benzene, 1,2-Di-chlorobenzene, 1,4-Dichlorobenzene, Ethylbenzene, Sty-rene, Nitrobenzene, Aniline, 2-Chlorophe-nol, 1,2,4-Trimeth-ylbenzene, Phenol, Pyrene, Fluoranthene, Anthracene, Chrysene, Fluorene, Phenan-threne, 2-Methyl-naphthalene, Benzo[a] pyrene, Carbazole, Naphthalene, Dioxins, Petroleum Hydro-carbons (C_{10}-C_{40}), Cyanides, Arsenic, Cadmium, Hexavalent Chromium, Copper, Lead, Mercury, Nickel	Benzene, Naphthalene, Benzo[a] anthracene, Benzo[b] fluoranthene, Benzo[k] fluoranthene, Benzo[a] pyrene, Inde-no[1,2,3-cd] pyrene, Dibenz[a,h] anthracene, Carbazole, Diben-zofuran, Quinoline, Petroleum Hydrocarbons (C_{10}-C_{40}), Dioxins, Ar-senic, Vana-dium, Cobalt, Hexavalent Chromium, Manganese, Total Chro-mium	Benzene, Toluene, 1,2-Dichlorobenzene, 1,4-Dichlorobenzene, Anthracene, Fluo-ranthene, Benzo[b] fluoranthene, Benzo[a] pyrene, Naphthalene, Mercury, Phenolic Compounds, Anionic Surfactants, Petroleum Hydrocarbons (C_{10}-C_{40}), pH, Total Hardness, Dissolved Total Solids, Sulfates, Chlorides, Oxygen Demand, Ammonia Nitrogen, Sulfides, Cyanides, Flu-orides, Iodides, Arsenic, Selenium, Cadmium, Hexavalent Chromium, Lead, Cobalt, Vana-dium, Nickel, Iron, Manganese, Copper, Zinc, Aluminum	Total Hardness, Dissolved Total Solids, Sulfates, Chlorides, Oxygen Demand, Fluorides, Ammonia Nitrogen, Petroleum Hydro-carbons (C_{10}-C_{40}), Iron, Cad-mium	Benzene, Toluene, Xylene, Chlorobenzene, 1,2-Di-chlorobenzene, 1,4-Dichlo-robenzene, Ethylbenzene, Styrene, Nitrobenzene, Aniline, 2-Chlorophenol, 1,2,4-Trimethylbenzene, Phenol, Pyrene, Fluoran-thene, Anthracene, Chrysene, Fluorene, Phenanthrene, 2-Methylnaphthalene, Benzo[a]pyrene, Carbazole, Naphthalene, Benzo[b]fluo-ranthene, Benzo[a]anthra-cene, Benzo[k]fluoranthene, Indeno[1,2,3-cd]pyrene, Dibenz[a,h]anthracene, Dibenzofuran, Quinoline, Dioxins, Petroleum Hydro-carbons (C_{10}-C_{40}), Phenolic Compounds, pH, Total Hardness, Dissolved Total Solids, Sulfates, Chlorides, Oxygen Demand, Ammonia Nitrogen, Sulfides, Cyanides, Fluorides, Iodides, Mercury, Arsenic, Selenium, Cadmi-um, Hexavalent Chromium, Total Chromium, Lead, Co-balt, Vanadium, Nickel, Iron, Manganese, Copper, Zinc, Aluminum

mercury, arsenic, lead, cadmium, and hexavalent chromium were frequently reported, posing serious risks due to their toxicity, environmental persistence, and potential for bio-magnification in food chains. Trace metals including nickel, vanadium, cobalt, and copper further indicate industrial discharge and metallurgical activities. Petroleum hydrocarbons (C_{10}–C_{40}) and related compounds highlight the contribution of petrochemical operations. Inorganic indicators such as pH, total dissolved solids, total hardness, sulfates, chlorides, and oxygen demand provide insight into the physicochemical characteristics of wastewater, while nitrogenous compounds (ammonia nitrogen) and toxic anions (cyanides, iodides, sulfides) signify nutrient loading and acute toxicity risks. Collectively, these pollutants underscore the necessity for targeted monitoring and advanced treatment strategies, as they pose significant ecological and human health concerns due to their toxicokinetics and environmental fate.

The pollution profile of the industry is dominated by organic compounds and heavy metals, reflecting a complex contamination pattern driven by the discharge of various pollutants. The coking process emerges as the primary source of this dual pollution, attributed to its large production scale, high raw material consumption, and numerous discharge channels. This process generates the highest volumes of organic wastewater and exhaust gases, releasing harmful substances such as benzene compounds, polycyclic aromatic hydrocarbons (PAHs), cyanides, fluorides, iodides, chlorides, dioxins, petroleum hydrocarbons, phenolic compounds, and heavy metals. Notably, benzene compounds, PAHs, cyanides, and heavy metals pose significant risks to both the environment and human health, necessitating focused attention on the stages that produced and discharge into environment. Benzene compounds and PAHs are predominantly found in wastewater, exhaust gases, and solid waste produced during the coking and de-benzene processes, while cyanides are primarily generated from wastewater associated with coal combustion, coke oven gas, and related by-products like tar ammonia water. Heavy metals, including arsenic, selenium, cadmium, hexavalent chromium, lead, cobalt, and others, are largely released during coal preparation and the coking process through gas and wastewater discharges. Therefore, critical stages requiring monitoring include coal preparation, coking, de-benzene processes, and the ammonium sulfide preparation and tar ammonia water separation stages. Focusing on these processes is essential due to their high pollutant generation potential, which poses long-term environmental and health hazards.

The major industrial processes within this sector are associated with significant environmental pollutant migration, which can follow three primary pathways: coal dust emissions, leakage risks from aging infrastructure, and hazardous waste disposal. The handling, unloading, and transportation of coal generates substantial coal dust, which is an unorganized emission source, with pollutants likely to be deposited into the environment via atmospheric sedimentation. The second pathway concerns the aging tanks, pipelines, and storage pits used for transporting coal gas. Over time, inadequate maintenance or prolonged use of these structures increases the risk of leakage and seepage. Finally, the generation of hazardous waste, such as tar slag, waste liquids, and oils, poses a serious environmental threat if not properly stored or disposed of, leading to potential leakage and contamination.

To address these risks, several environmental management measures are recommended. Companies should focus on managing unorganized emissions by implementing anti-permeability measures, such as ground road hardening, to prevent coal dust migration. Regular inspections and maintenance of storage tanks and pipelines are critical in minimizing leakage risks, with periodic soil or groundwater monitoring to identify potential contamination in areas where direct equipment testing is challenging. Additionally, hazardous waste storage should be rigorously managed through enhanced capacity, efficient transportation, and proper record-keeping. Containers should be regularly inspected for their sealing and permeability, and facilities should be constructed with anti-permeability features. For enterprises with sufficient resources, installing leak detection systems may further minimize risks.

Furthermore, soil and groundwater management should include developing a list of enterprises with significant environmental impacts for closer supervision. Routine hazard assessments, self-monitoring, and investigations, particularly in high-risk stages, should be conducted. Pollution sources such as waste gas, wastewater, and solid waste must be carefully managed, with detailed production and pollution discharge records established. Regular environmental quality analyses are essential to track changes and ensure compliance with environmental standards.

5. CONCLUSION

This study systematically identified ten key industries for soil and groundwater environmental management based on three critical criteria: (1) high industry participation, (2) significant pollutant discharge, and (3) prioritization in major policy documents. The selected industries include petroleum extraction, non-ferrous metal mining, leather tanning, refined petroleum production, coal processing, basic chemical raw materials, pesticide manufacturing, paint and pigment production, non-ferrous metal smelting, and metal surface treatment and heat treatment.

To support precise environmental management, the study emphasized the importance of adapting standards to the specific characteristics of each industry. Focusing on the metal surface treatment and coal processing industries representing medium- and small-scale sectors typical production processes were analyzed to identify major pollutant discharge points. Characteristic pollutant lists were then compiled, and their sources were systematically traced. These findings offer practical guidance for enterprises to implement targeted pollution control strategies and strengthen their environmental performance. Moreover, the results provide a valuable scientific foundation for national soil and groundwater quality investigations, risk assessments, and future remediation planning efforts.

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