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Review

The Hotspots and Trends of Patented Technologies for Heavy Metal-Contaminated Soil Remediation: A Systematic Review

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Abstract: Heavy metal soil pollution severely threatens human health and food safety. This study used PRISMA to systematically review heavy metal-contaminated soil remediation patents in the Derwent Patent Database from 2003 to 2023. A total of 1744 patents were selected. The results of the analysis show that related patent applications are growing around the world. Among them, China has the most significant number of patents, but the layout of transnational patents needs to be revised. Countries have different preferences in transnational patent technology. Technological development is generally balanced, and there is no apparent monopoly. However, the need for continuous in-depth research on inventors is an obstacle to technological development. In addition, the technology in this field is concentrated in chemistry and engineering. Currently, the mainstream technology is soil remediation agents, and thermal desorption technology has also attracted much attention. Future technologies will use new polymer materials and advanced machinery to improve efficiency and control repair costs. In addition, remediation has shifted from the total amount of heavy metals to the control of practical parts. This study summarizes the current status of heavy metal-contaminated soil remediation technology and analyzes future development trends, providing a reference for technology development.

Keywords: soil; heavy metal remediation; patent analysis; research hotspots; research trends

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1. Introduction

Soil contamination by heavy metals is a worldwide problem regarding human health and food safety production. Heavy metal soil pollution refers to the phenomenon in which the heavy metal content in the soil is higher than the background level due to industrial and agricultural production or human activities, leading to a potential decline in soil quality and thus causing a severe impact on the ecological environment [1]. In addition to human factors, the background level of heavy metals in soil may also be high due to natural reasons such as soil-forming parent materials. For example, soils developed on serpentinite often have high cadmium/nickel content [2]. However, high levels of heavy metals in soil, whether caused by natural factors or artificial factors, without exception pose a considerable threat to agricultural production and human health. There are numerous cases of heavy metal contamination of soil around the world. It is reported that more than 5 million locations worldwide, covering 20 million hectares of land, are contaminated by various heavy metals [3]. Currently, soil contaminated with heavy metals has been detected in many countries. In the United States, there are more than 100,000 identified sites related to heavy metal pollution [4]; in Europe, contaminated soil caused by heavy metals accounts for more than one-third of all contaminated soil [5]; in Japan, a large amount of farmland soil is also contaminated by heavy metals [6]; in places such as Pakistan [7] and Egypt [8], the problem of heavy metal pollution in soil is also prominent, giving rise to tremendous pressure on local agricultural production and ecological environment. In China, the problem of heavy metal pollution in soil is severe. It has been reported that more than 1 million km^2 (100 million ha) of land in China has been contaminated by heavy metals [3], containing 20% of farmland soil [9]. It is estimated that China loses more than 10 million tons of grain every year due to heavy metal pollution, and the resulting economic losses cannot be ignored [10]. Heavy metal pollution in soil has become a common global problem that urgently needs attention.

Heavy metal pollution brings many hazards to soil. It will reduce the soil's ecological structure and function and adversely affect agricultural productivity [11]. Specifically, for farmland ecosystems, heavy metal pollution will reduce soil fertility and crop yields and lead to excessive heavy metal content in crops, thus threatening food safety [12,13]. Animals or humans can enrich heavy metal elements in the soil through the food chain. The excessive accumulation of heavy metals has severe and fatal effects on human organs, and it can easily lead to cancer, malformations, and mutations [14]. In addition, soil contaminated with heavy metals can quickly be released into the atmosphere and water, causing secondary ecological and environmental problems. Among them, heavy metals such as mercury [15], cadmium [16], lead [17], chromium (Cr), and metalloid arsenic (As) [18] are not essential for plant growth. However, they significantly impact plants and are a common element with significant biological toxicity [19]. As persistent toxic pollutants, these heavy metals are latent, long-term, cumulative, and irreversible. Their high toxicity and persistence have drawn much attention to the problem of heavy metal pollution in soil [20]. Therefore, the comprehensive management of heavy metal pollution in soil has become an important issue that needs to be solved urgently.

Given the seriousness and prevalence of heavy metal-contaminated soil, scholars have conducted extensive research to develop effective remediation strategies [21]. At present, some scholars have used bibliometric methods to conduct in-depth analyses of research on heavy metal pollution remediation technologies and their effects in academic papers [22]. However, most of these studies are based on the results of journal articles and involve relatively little patent technology literature, especially the analysis of transnational patents. Patents are an essential source of technical information utterly different from academic papers. According to the World Intellectual Property Organization (WIPO) report, patents are the world's largest source of technical information. Every year, 90% to 95% of the world's inventions and creations can be recorded in patent documents, of which about 70% have never been published in other non-patent documents. Therefore, a systematic review of patented technologies for the remediation of heavy metal-contaminated soil is an indispensable step in defining the overall technology landscape in this field.

This study used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology to rigorously examine all patents on heavy metal-contaminated soil remediation included in the Derwent Innovation Index Database over the two decades from 2003 to 2023. Patent information contains both structured and unstructured data. Through screening and evaluation, 1744 patents were obtained as the primary data of this study through the statistical analysis of structured data in patent information (such as country, year, patentee, inventor, and technology category code) and the text mining of unstructured data (such as title and abstract), comprehensively revealing the status of patented technologies for heavy metal-contaminated soil remediation. Specific contents include (1) the spatial and temporal distribution characteristics of heavy metal-contaminated soil remediation patents to reveal technology development trends and regional differences; (2) the distribution characteristics and technical characteristics of transnational patents to identify high-quality patents in this field and high-level patents in different countries (3) the distribution characteristics of patents among different patentees and inventors reflect the main structure of technological innovation; (4) the distribution characteristics of patents in technical categories reveal the diversification trend in technology application fields; (5) through the co-occurrence analysis of critical terms in text mining, the in-depth interpretation of the core technical points of heavy metal-contaminated soil remediation patents; (6) and the statistics of the frequency of critical terms to predict technology research hot spots and future development trends in this field. This study analyzes the development status and future directions of heavy metal-contaminated soil remediation technology from the perspective of patent analysis, providing scientific information reference for researchers and practitioners in related fields.

2. Materials and Methods

This study was reviewed following the Preferred Reporting Item for Systematic Reviews and Meta-Analyses guidelines [23]. PRISMA is a set of guidelines on the structure and composition of systematic reviews and other data-driven meta-analyses that can be used to report systematic reviews with different objectives [23,24].

2.1. Search Strategy

The Derwent Innovations Index database (DII), one of the world's most authoritative and comprehensive international patent databases, has been widely recognized for its authority and comprehensiveness [25,26]. This database is used and trusted by patent examiners in more than 40 countries worldwide. It contains comprehensive invention patents in many fields, such as chemistry, electronics, and electrical and engineering technology, with up to 20 million patents, covering 96% of the world's patent data [27]. The research data for this article all come from the DII. To ensure the accuracy and reliability of the study, we employed a rigorous search strategy. After many search experiments, we finally determined the subject words TS = ("heavy metal" or "lead or cadmium or chromium or mercury or arsenic or Pb or Cd or Cr or Hg or As" or "potentially toxic element" or "PTE" or "trace metal") AND (TS = ("soil remediation" or "soil repair")) as the search criteria. A total of 1744 patent records have been collected, ranging from 15 October 2004 to 15 October 2023.

2.2. Study Selection and Quality Assessment

The cleaning and quality evaluation of the original data are indispensable steps to ensure the reliability of the analysis conclusion. The original data are often complete with problems such as lexical distortion, the use of synonyms, confusion, and repeated records of different individuals with the same name. If these factors are not handled properly, they may lead to the underestimation of word frequency, statistical duplication or errors, and ultimately affect the credibility of the conclusion [28]. Therefore, this study adopted software and manual cleaning to purify the data comprehensively. In order to simplify the analysis process, this study regards the first inventor and the first patentee as the inventor and patentee of the patent and includes them in the statistics accordingly. When dealing with inventors with the same name, if the corresponding first patentee's information is consistent, they are regarded as the same inventor; otherwise, they are different inventors. At the same time, the country of the patent is calculated based on the country of the first patentee. The World Intellectual Property Organization (WIPO) and the European Patent Office (EPO), as intergovernmental organizations, play a key role in promoting intellectual property protection through cooperation between countries and with other international organizations [17]. In this study, we consider those patents filed in WO and EP organizations or two or more countries as transnational patents. It is worth noting that among the 1744 patent records, 14 records lacked inventor information, so the number of inventor records included in the final statistics was 1730. The remaining information (disclosure year, application country or organization, patentee, and technical classification) is not missing, and there are 1744 complete records included in the statistics. This rigorous data processing process ensures the accuracy and reliability of subsequent analysis.

2.3. Structural Data Analysis Methods

In order to analyze the essential information and characteristics of patent applications in depth, this study systematically collected and counted structural data such as patent disclosure year, application country or organization, inventor, patentee, and technology classification. The publication year of a patent is determined based on the earliest year information in the PI (Priority Application Information and Date) field. The first two digits of the patent number are used to identify the corresponding country of application. By integrating the application information of the same patent in different countries, we can obtain its cross-border application status. In addition, data on patent inventors, patentees, and technical classifications (IPC, DWPI Class Code, DWPI manual code) are derived from detailed records in the DII.

2.4. Unstructured Data Analysis Methods

2.4.1. Keyword Co-Occurrence Analysis

Unstructured data, including text information such as titles and abstracts, is time-consuming due to its unstructured nature, accurate positioning, and effective use of specific information [29]. The analysis of unstructured data is still in its infancy and development stage [30]. In order to extract valuable information from unstructured data, this study used two software for text mining, VOSViewer 1.6.19 [31] and Pajek 5.18 [32]. Specifically, we import the patent's Title (TI) and Abstract (AB) fields into VOSViewer and extract key terms. After merging synonyms and removing meaningless words, we conducted a keyword co-occurrence analysis on the text. Subsequently, the extracted terms were re-arranged using Pajek. This kind of keyword co-occurrence analysis helps us reveal important content such as clustering, correlation, and knowledge structure in the research field [33]. Keywords with high co-occurrence intensity mean these words frequently appear together in the same patent document. Based on the results of quantitative analysis, VOSviewer draws the association network diagram between terms, that is, the knowledge graph, clusters, and groups the most relevant keywords, and conducts an in-depth analysis of the connections between different keywords. This method helps us understand the correlation between keywords more comprehensively and precisely. It provides a powerful tool for constructing an in-depth understanding of the nature of the research field.

2.4.2. Technology Hot Spots and Trend Analysis

To provide an in-depth analysis of patent evolution trends, we divide patents into two periods: long-term patents (2004 to 2018) and recent patents (2019 to 2023). Next, we imported these two periods' patent title (TI) and abstract (AB) fields into the VOSViewer software. Through this step, we can extract the keywords of the patents in the two periods and the frequency of occurrence of the keywords. Then, the trend factor (T) is used to quantify the degree of the keyword's upward or downward trend [34]. However, due to the different patent cycles between the two periods, it is not appropriate to directly compare the frequency of occurrence of keywords. Therefore, we introduce an improved trend factor (T') to quantify keyword development trends. The calculation formula is:

$$T' = \log\left(\frac{R/t}{P/t'}\right) \tag{1}$$

Here, R represents the normalized cumulative frequency of keywords appearing in recent patents (2019–2023), t represents the period of recent patents, and the period from 2019 to 2023 is five years; and P represents the distant the normalized cumulative frequency of keywords appearing in long-term patents (2004–2018), t' represents the period of long-term patents, and the period from 2004 to 2018 is fifteen years. T' is the trend factor of the keyword. When the T' value is greater than 0, the keyword frequency increases; that is, the keyword may show an upward trend. Conversely, if the T' value is less than 0, the keyword frequency is decreasing, showing a downward trend.

In order to display the trends of these hot keywords more intuitively, we created a logarithmic scale bubble chart. In this figure, each bubble represents a keyword, and the color of the bubble is used to distinguish the trend factor of the keyword. Red represents an uptrend, and blue represents a downtrend. Through this visualization method, we can gain insight into each keyword's development dynamics in different periods.

3. Results and Discussion

3.1. Spatiotemporal Distribution Characteristics of Patent Applications

3.1.1. Time Distribution Characteristics of Patent Applications

Figure 1 depicts the world patent application trends in heavy metal-contaminated soil remediation. Before 2013, the number of global patent applications in this field was less than 15 yearly. However, since 2013, the number of patent applications has steadily grown. Especially between 2014 and 2016, the number of patent applications doubled almost yearly, reaching 120 in 2016. This growth trend continued into 2020, with the number of patent applications reaching a historical peak, totaling 287. Although the number of applications has declined, it remains at more than 100 annually. Overall, the cumulative number of patent applications in this field has shown a continuous upward trend, increasing from 9 in 2004 to 1744 in October 2023, demonstrating the continued technological innovation and intellectual property protection activity.

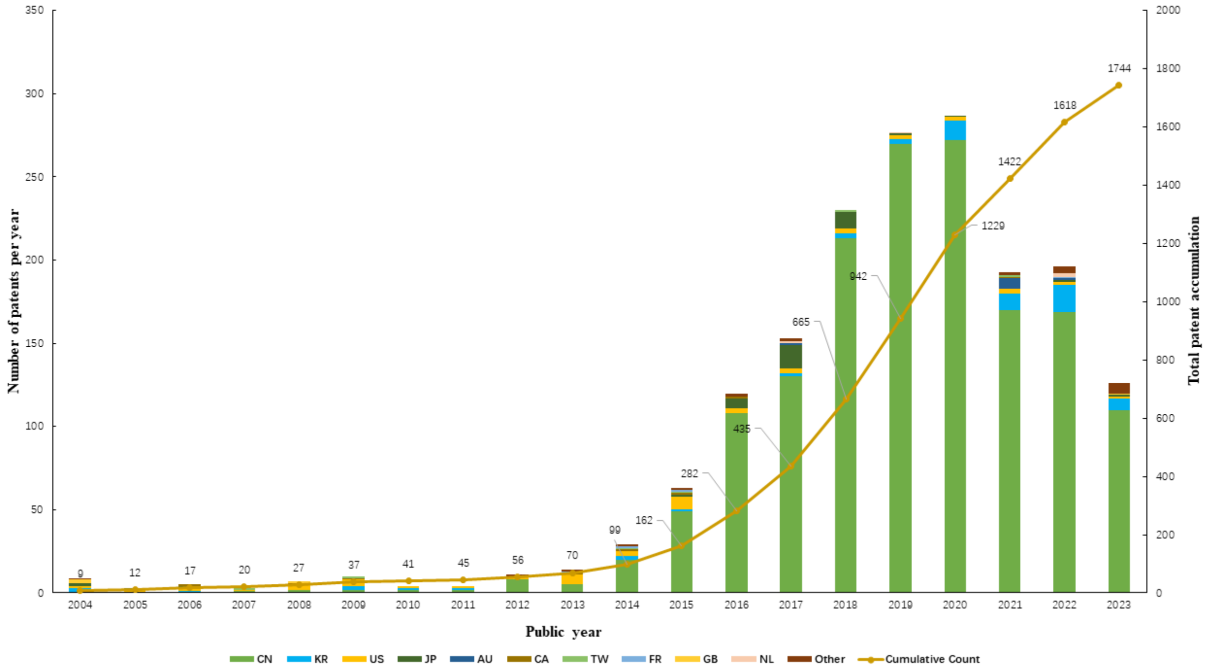

Figure 1. Spatiotemporal distribution characteristics of patent applications of heavy metal-contaminated soil remediation.

3.1.2. Distribution Characteristics of Patent Applications in Different Countries or Regions

The patent priority country usually refers to the country to which the patent belongs when the patent application is first filed. By analyzing the number of patent applications in heavy metal-contaminated soil remediation in various countries, we can gain insight into which countries are more active in this technology field and have more substantial technological competitiveness. Of the 1744 patent records examined, 87 were filed in two or more countries. In addition, eight patents were filed only in the World Intellectual Property Organization, while three patents were applied for only in the European Patent Office (EPO). In this study, the country of these patents is based on the country of the first patentee as the country of ownership. Statistics show that patents in this field involve 22 different countries or regions. Among them, China has the highest number of patent applications, with 1533 patent applications, far exceeding that of other countries, showing that China has significant technological advantages in this field. China was followed by South Korea, the United States, and Japan, with 65, 53, and 39 patent applications, respectively, ranking second to fourth (Figure 1). These countries have also shown a certain technological competitiveness in this field. The number of patent applications in other countries is less than 10, and the total number of applications in other countries accounts for 3.15%. This shows that China is in the leading position in the number of patent applications in heavy metal-contaminated soil remediation. At the same time, South Korea, the United States and Japan also have certain technological competitive advantages.

3.2. High-Quality Transnational Patent Situation

3.2.1. Distribution Characteristics of High-Quality Transnational Patents

In addition to the number of patents, the quality of patents is also increasingly valued. A country has more patents entering the patent market of other countries, meaning the country's patent quality is generally higher [35,36]. This study considers transnational patents as high-quality patent representatives of that country or organization. The World Intellectual Property Organization (WIPO) and the European Patent Office (EPO), as inter-governmental organizations, play a key role in promoting intellectual property protection through cooperation between countries and with other international organizations [37].

The analysis shows that of the 1744 patent records, there are 98 transnational patent applications involving 14 different countries. Regarding the number of transnational patent applications, South Korea, the United States, and China ranked in the top three, having submitted 35, 23, and 15 transnational patents, respectively. However, judging from the proportion of transnational patents in each country's total patent applications, transnational patents in South Korea and the United States account for about half of the country's total patent applications, indicating that these countries have a relatively balanced international patent layout. In contrast, China's transnational patents account for only 1% of its total patent applications, showing that China's international patent layout in heavy metal-contaminated soil remediation is seriously lagging, which should attract sufficient attention from relevant parties in China.

Regarding destinations for transnational patent applications, WO and EP are the two most important organizations, receiving 88 and 57 transnational patent applications, respectively. In addition, China, the United States, and Japan are the main target markets for transnational patent layout, receiving 44, 42, and 38 transnational patent applications, respectively. These data further confirm the critical status of WO and EP in international patent applications and highlight the vital role of China, the United States, and Japan as major countries in technological innovation and patent layout in global competition.

In summary, although China's total number of patent applications in heavy metal-contaminated soil remediation is vast, there are obvious deficiencies in the international patent layout. In order to enhance its position in the global technology competition, China needs to strengthen its transnational patent application and layout strategies better to protect its innovative technologies and intellectual property rights.

3.2.2. Technical Characteristics of High-Quality Patents (Transnational Patents) in Different Countries

Regarding transnational patents, different countries have different technical characteristics. South Korea tends to develop and utilize highly water-absorbent polymers. Applying these highly water-absorbent polymers to the soil affects the soil's absorption of harmful substances to achieve the purpose of soil remediation [38,39].

The United States exhibits great technological diversity. These include the use of genetically engineered plant technology [40], the application of microbial film repair technology [41], the use of solvents and microbial compositions to wash contaminated soil [42], and polysulfide compositions to capture metal ions in soil [43]. In addition, soil remediation encapsulation agents use surfactants, alcohols, and pine oil [44] and remediation technologies that apply conductive thermal [45,46]. These patents reflect the fact that the United States has a significant advantage in soil remediation technology research and development and innovation.

China mainly focuses on researching and developing various soil remediation agents with various components. These patents involve the use of repair agents composed of phenolic benzene ring compounds and their calcium salts [47] and the use of raw materials such as limestone, gypsum ore, bauxite, medical stone, and biochar to prepare repair agents [48], and some use biogas residue, carbon sources and sulfates to prepare remediation agents [49]. In addition, there are also methods to prepare soil remediation agents using chitosan/polypyrrole [50] and using modified zeolite, organic matter, plant ash, cellulose, and biological bacteria to prepare soil remediation agents [51] and other innovative technologies. At the same time, China's transnational patents also include methods of using microorganisms to remediate contaminated soil, such as composite microbial inoculants [52] and phosphate-solubilizing strains (*Bacillus tianshenii*) [53]. In addition, there are also methods involving electrodynamic remediation technology [54,55] and solar-driven bionic soil remediation technology [56].

Regarding other countries, Japan uses vacuum consolidation to remove harmful ions from soil and remediate [57]; Italy uses diaphragm pumps to remediate contaminated soil [58]; Israel uses calcium bromide tetrahydrate as a soil remediation agent [59]; the United Kingdom uses an electric field to force the directional migration of contaminated leachate and centralized treatment [60]; and Belgium's electric heating repair technology forms polluted steam through heating and introduces a control device for removal [61,62]. There are also technologies, such as vapor recovery through nanoparticles at specific depths, to stabilize heavy metals in soil [63]. These demonstrate various countries' technical paths and innovation directions in soil remediation. It is worth noting that the remediation effect of heavy metals in soil will vary due to differences in pollution levels, metal types, and soil characteristics in different regions. Therefore, this may be one of the factors influencing the technology preferences for heavy metal-contaminated soil remediation in different countries.

3.3. Distribution Characteristics of Patent Applications among Different Patentees and Inventors

Figure 2a shows the number of patents owned by the top twenty patentees in heavy metal-contaminated soil remediation. South Korea's "Lg Chem Ltd." has the most significant number of patent applications with 48 records. They are followed by Japan's "Yamazaki K", with 27 patent applications, ranking second. China's "Nanjing Inst Environmental Sci Nat Burea" ranks third with 14 patent applications. Since then, almost all of the top 20 patent applications are from Chinese universities, research institutes, and some technology companies (Figure 2a). This shows that China's development in this field is relatively balanced, with a hundred schools of thought contending, and no institution with an absolute advantage has emerged. However, South Korea and Japan have situations where one company is dominant and individual patent holders have absolute monopoly advantages.

In addition, Derwent assigns a unique four-letter code to approximately 21,000 companies worldwide to standard company names. These companies are regarded as standard companies and regularly file many patent applications. The use of these codes retrieves subsidiaries and related holdings of the company. Other companies and individual patent assignees are given a non-standard four-letter code, which is unique [64]. Based on the analysis of the retrieved patentee codes, it was found that in heavy metal-contaminated soil remediation, there are 743 patentees, including 283 standard companies, 258 non-standard companies, and 202 individual applicants, which account for the total patent rights, respectively, 38%, 35%, and 27% of the number of people. We consider standard firms to be large-scale firms and non-standard firms to be small-scale firms.

Figure 2b shows the number of patents of the top 20 inventors in the field of heavy metal-contaminated soil remediation. Excluding 14 records with missing inventors, there were 1477 different inventors in the remaining 1730 patent records. Japan's "YAMAZAKI K" has become the inventor with the most invention patents in this field, with 25 patents accounting for 1.45% of the total invention patents. WENG of China's "UNIV INNER MONGOLIA" ranked second with eight records, accounting for 0.46% of the total invention patents. Two individuals from China, "CHENG G" (Cheng Gang) and "CHENG G" (Cheng Gongbi), tied for third place with seven records, each accounting for 0.4% of the total invention patents (Figure 2b). Notably, 89.30% of the inventors have only one patent record, and only 3% have three or more invention patents. This shows that most inventors' technical research lacks continuity and depth in heavy metal-contaminated soil remediation.

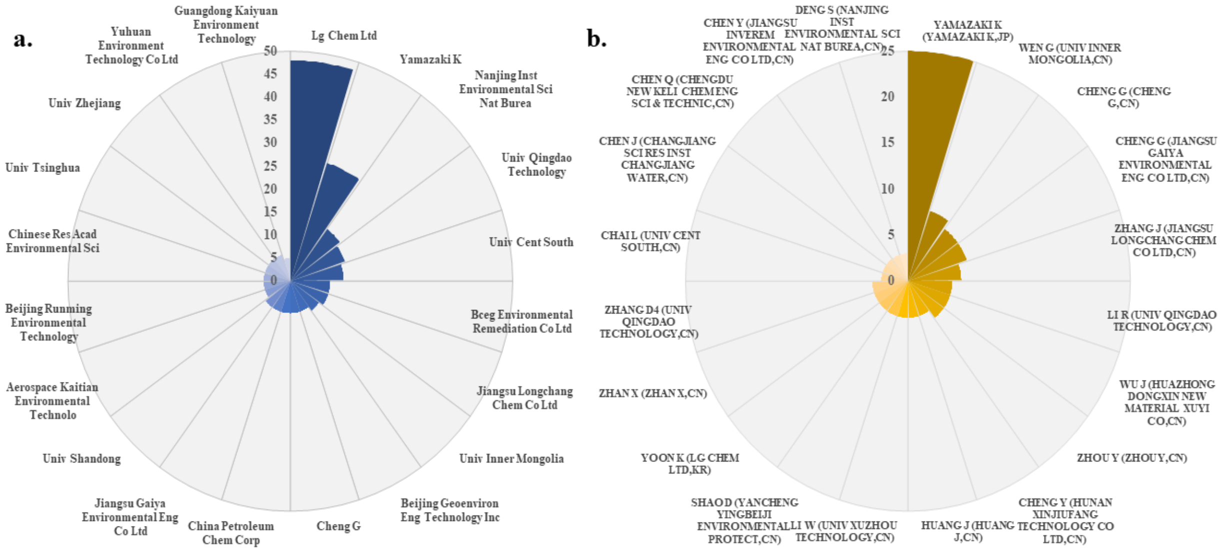

Figure 2. Distribution characteristics of patent applications of heavy metal-contaminated soil remediation among different patentees (**a**) and inventors (**b**). Note: the number axis represents the number of patents.

To sum up, from the perspective of patent holders, South Korea and Japan have a dominant patent application in heavy metal-contaminated soil remediation. At the same time, China's technological development is relatively balanced, showing a situation where a hundred schools of thought are contending. From the perspective of inventors, although some inventors have many patent applications, overall, most inventors' technical research lacks continuity, which may mean that there is still much room for developing technological innovation in this field.

3.4. Distribution Characteristics of Patent Applications by Technology Category

3.4.1. IPC Distribution Characteristics of Patent Applications

This patented technology involves all invention patent fields from A to H of IPC (Figure 3). Among them, patents in Fields C and B account for the most, accounting for 45.70% and 40.63% of the total patent records, respectively. Field A ranked third with a share of 7.86%. Looking at different categories, B09 (processing of solid waste; regeneration of contaminated soil) accounts for 26% of the total patent applications and 64% of Field B. The C09 (dyes; paints; polishes; natural resins; adhesives; compositions not otherwise provided for; applications of materials not otherwise provided for) accounts for 16% of the total number of patent applications and 34% of Field C. Among them, the subcategory c of B09 (regeneration of contaminated soil (collection machines for removing stones or similar debris from soil)) accounts for 96% of this category, and group 001/08 in subcategory c (using chemical methods) and Group 001/00 (rehabilitation of contaminated soil) rank in the top two in terms of number of patents, accounting for 43% and 23% of this subcategory, respectively. Among them, subcategory k of C09 (various application materials not included in other categories; various applications of materials not included in other categories) accounts for 99% of this category, and 017/40 in the groups of subcategory k (containing mixtures of inorganic and organic compounds) and 101/00 (agricultural use) account for the highest proportions of subcategory k, accounting for 37% and 24%, respectively.

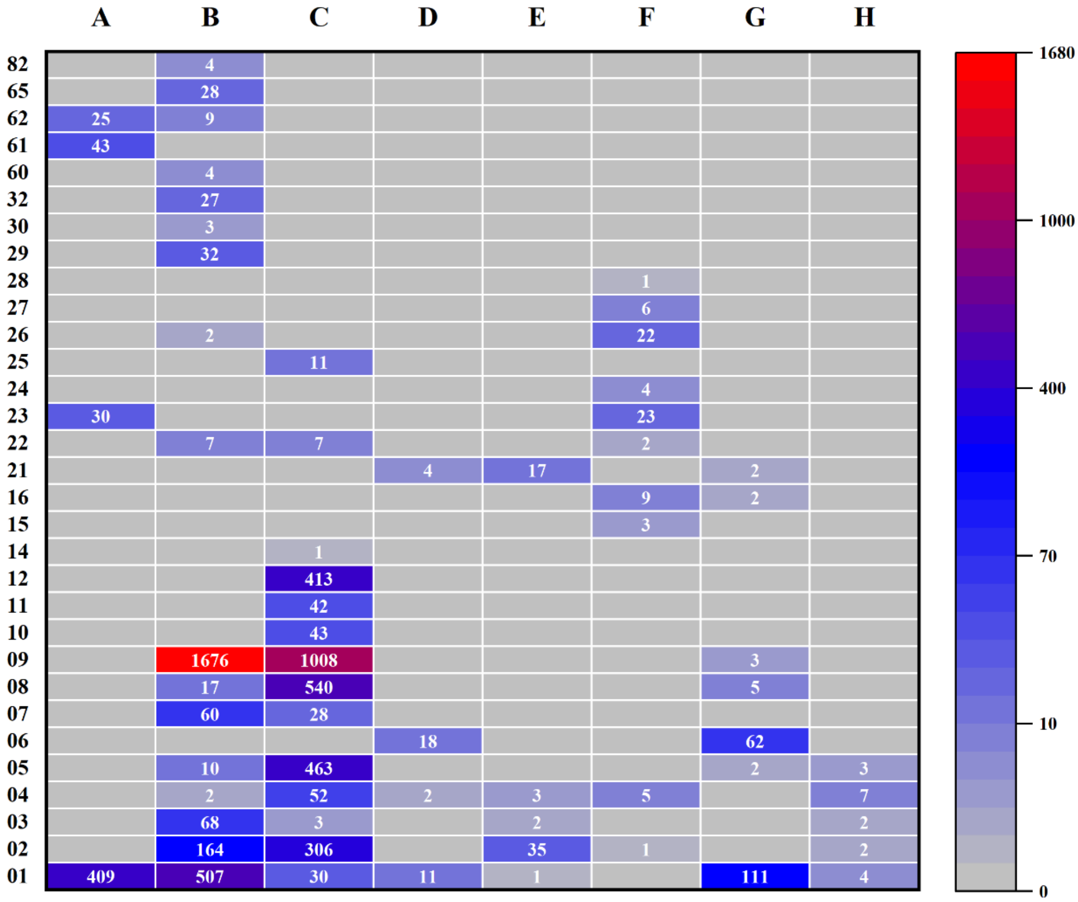

Figure 3. IPC distribution characteristics of heavy metal-contaminated soil remediation patent. Note: the number axis represents the number of patents. The Supplementary Material Table S1 details the description of IPC classification codes.

To sum up, this patented technology is widely involved in many fields of IPC, among which Field C and Field B are the core fields, B09 and C09 are essential categories, and the subcategory c of B09 and the small k of C09 classes are key technical subcategories. The patent layout and technological innovation in these fields provide strong technical support and broad application prospects for heavy metal-contaminated soil remediation development.

3.4.2. DWPI Classification Code Distribution Characteristics of Patent Applications

From the DWPI classification code perspective, this patented technology is involved in all three major categories (Figure 4a). However, it is mainly concentrated in the chemical sections (AM) field, accounting for as much as 61%, showing that chemical technology dominates heavy metal-contaminated soil remediation. Engineering sections (PQ) account for 34%, indicating that engineering technology also plays a vital role in this field. In comparison, the number of patents in the electrical and electronic sections (SX) field is smaller, accounting for only 5%, but it is still an indispensable part. In the chemical section, 14 subareas are involved, of which Area A, Area D, and Area C rank among the top three in terms of number of patents, accounting for 26%, 22%, and 19%, respectively. This shows that polymer plastics, food and biotechnology, and agricultural chemicals have extensive applications and in-depth heavy metal-contaminated soil remediation research. In the engineering sections, two subareas are involved, of which the P-area patents are as high as 94%, showing this field's broad application and importance in engineering technology. Looking at the more specific class fields, patent data in P43, C04, and D16 rank among the top three, accounting for 25%, 9%, and 8%, respectively. This further confirms the importance and technological innovation of waste treatment, fertilizer production, and fermentation industries in heavy metal-contaminated soil remediation.

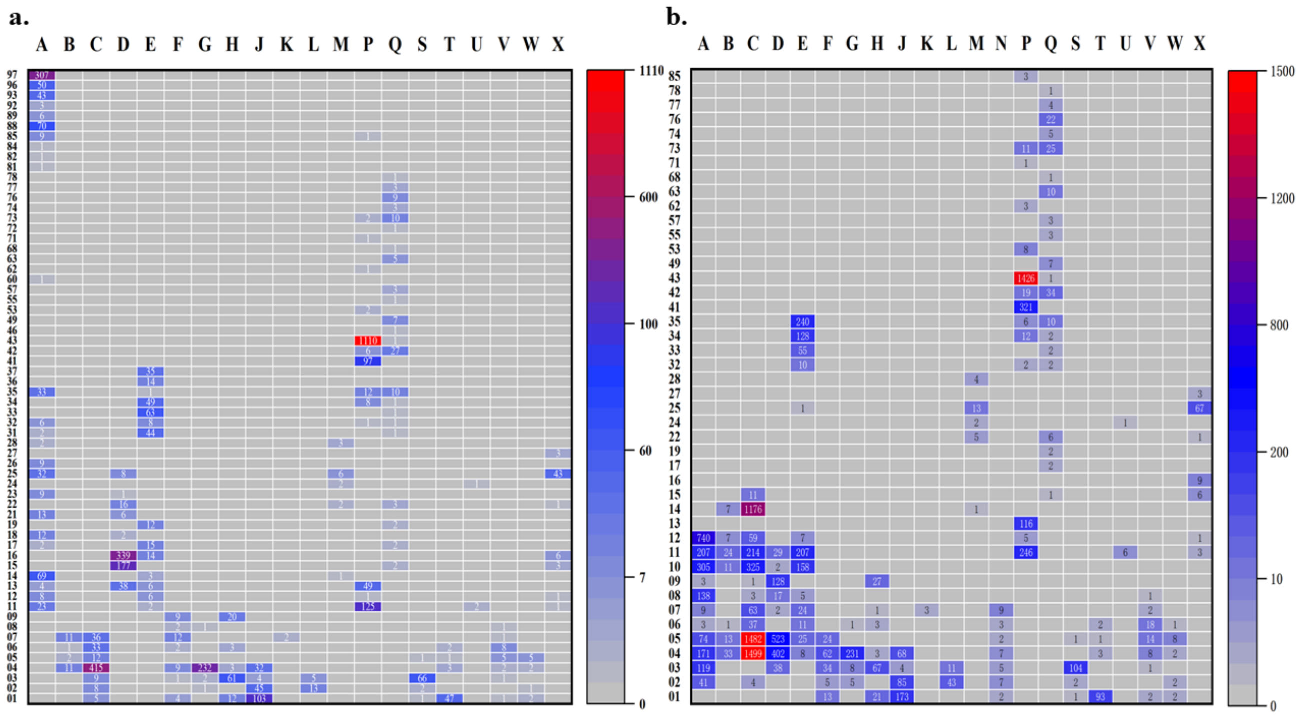

Figure 4. DWPI classification codes (**a**) and manually coded (**b**) distribution characteristics of heavy metal-contaminated soil remediation patent. Note: the number axis represents the number of patents. The Supplementary Materials contain Tables S2 and S3, which describe the DWPI classification codes and manual codes in detail.

To sum up, this patented technology is widely involved in multiple fields and divisions of the DWPI classification codes, mainly in chemistry and engineering technology and in the electrical and electronic fields. Some critical technical nodes and innovation points in each field provide strong technical support and broad application prospects for heavy metal-contaminated soil remediation development.

3.4.3. Patent Application for DWPI Manually Coded Distribution Characteristics

After excluding 22 records that did not contain the DWPI manual code, manual code analysis was performed on the remaining patent records. The analysis results showed (Figure 4b) that this technology was used in three areas of DWPI manual code, namely Section AN, Chemical Among the Patents Index (CPI); Section PQ, General and Mechanical Patents Index (GMPI); and Section SX, Electrical Patents Index, with the number of patents in the CPI field accounting for the highest proportion, reaching 79%, indicating that heavy metal-contaminated soil remediation technology is mainly based on technology in the chemical field. The GMPI field accounts for 18%, while the Electrical Patents Index field accounts for only 3%, which is relatively small. Specifically, Category C (agricultural chemicals) accounts for 48% of the total CPI. Of the GMPI, the P category (general) is the most common, accounting for 94% of the total GMPI. These two categories are also the top two with the most significant number of patents, accounting for 38% and 17% of the total number of patents, respectively. In the Category C of CPI, C04 (natural polymer products or genetically engineered polymers), C05 (miscellaneous), and C14 (agricultural production activities) have the most patents. The proportions in these categories reached 31%, 30%, and 24%, respectively. GMPI's Category P is divided into P43 (generating and using mechanical vibrations, cleaning, waste disposal), P41 (crushing, centrifuging, separating solids, sorting), and P11 (soil working, planting, planting), which have the most patents, accounting for 65%, 15%, and 11%, respectively. Further breakdown found that P43-j (contaminated soil or ground treatment) has the most patents, accounting for 48% of Category P and 8% of the total number of patents, and the rest of the patents account for less than 2%.

To sum up, this technology is widely involved in various fields of DWPI manual code, among which the CPI and GMPI fields are the main patent layout fields. In the CPI field, technological innovation in agrochemicals is particularly prominent; in the GMPI field, waste treatment and contaminated soil treatment technology are the core of this technology.

3.5. Main Technical Content of Heavy Metal-Contaminated Soil Patents—Co-Occurrence Analysis of Main Key Terms

After deleting terms with little meaning, such as data units, and merging synonyms, 25620 terms were obtained. The minimum number of occurrences was set to five, and 1290 terms were obtained. The normalization method used the association strength method to analyze 1290 entries. These terms formed five main clusters in terms of relevance. Different clusters reveal technical directions and concerns in heavy metal-contaminated soil remediation (Figure 5). Cluster 1 (red) is the largest, containing 609 entries, mainly involving heavy metal-contaminated soil remediation agents. It can be seen from keywords such as "Bacillus", "fertilizer", "composition", "mixture", and "powder". The central theme is to use a mixture of microbial agents and particles of different powders to form a soil remediation agent. In addition, there is also a high degree of concern about the two heavy metals, "cadmium" and "lead", indicating that the control of cadmium and lead is significant in soil remediation. Cluster 2 (green) contains 378 entries, mainly focusing on the schematic diagram of contaminated soil remediation equipment and the framework design of remediation. This shows that soil remediation, in addition to using remediation agents, also involves developing and designing remediation equipment. The design of this equipment is crucial to improving remediation efficiency and quality. Cluster 3 (blue) contains 173 entries, mainly focusing on soil thermal desorption technology. Direct or indirect heating separates pollutants from the soil using a relatively low boiling point and thermal desorption [65]. This method has the advantages of a short treatment cycle, high efficiency, high safety, no secondary pollution, and the recycling of soil and pollutants [66]. However, thermal desorption is limited by expensive equipment and long desorption time and is only suitable for removing volatile pollutants [3]. Soil thermal desorption technology has been widely used in the petroleum, paper industry, and gardening. This shows that heat treatment technology plays an essential role in soil remediation. It can not only be used to remediate contaminated soil but can also be applied to other industrial fields. Cluster 4 (yellow) contains 73 entries, mainly focusing on issues such as the cost of repairing the systems and involving low-cost chelates and compounds. This shows that in soil remediation, in addition to technical efficiency and effectiveness, remediation cost is also an important consideration. Finding low-cost remediation methods and materials is significant for promoting and applying soil remediation technology. Cluster 5 (purple) contains 57 entries, mainly focusing on specific technical repair details and operation methods. This shows that in soil remediation, it is also essential to master technical details and operating methods. These details and methods directly affect the effect and quality of remediation.

To sum up, the technology in this field uses repair agents as the primary technical method, and at the same time, attention to heat treatment technology is also increasing. Restoration costs and technical details are also important considerations during the restoration process.

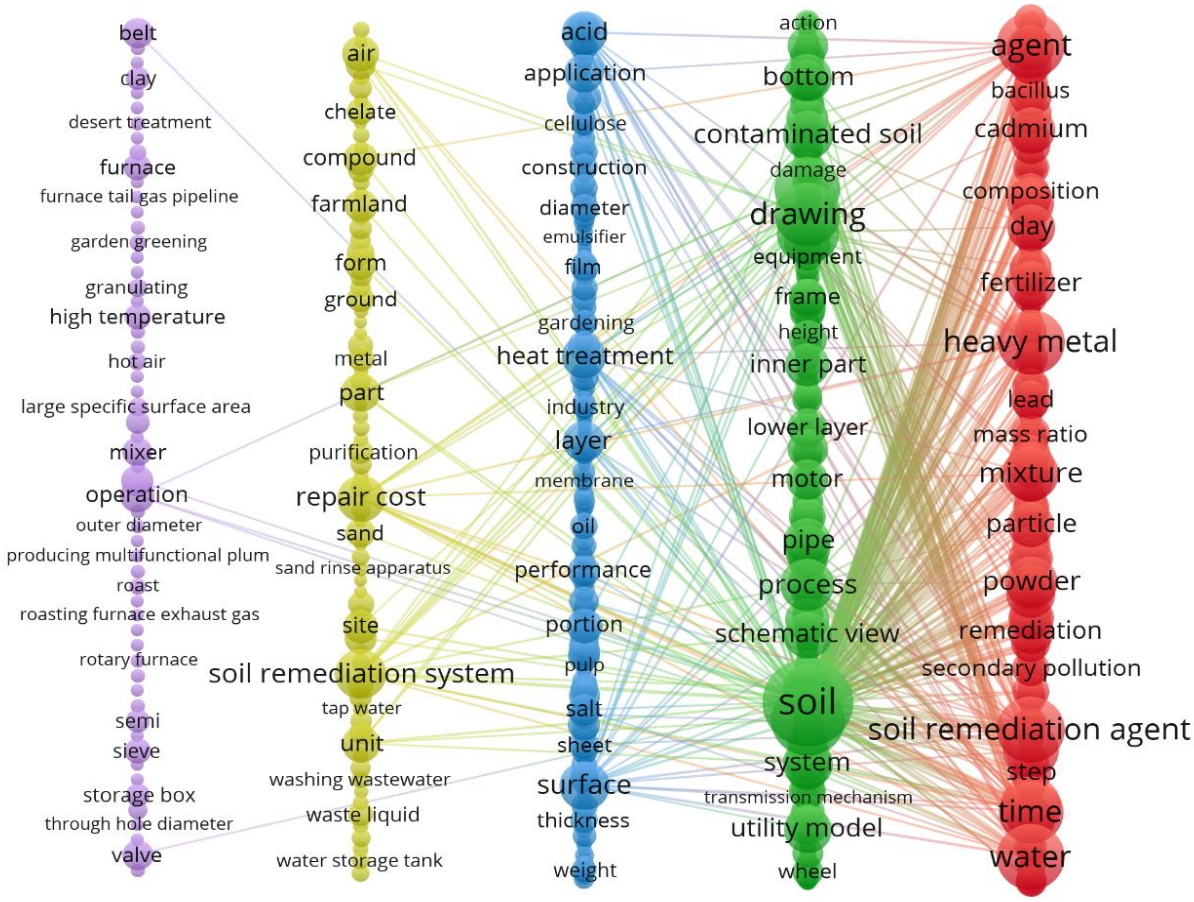

Figure 5. Co-occurrence analysis of main key terms of heavy metal-contaminated soil remediation patents.

3.6. Analysis of Heavy Metals in Soil Patent Technology Hot Spots and Future Trend Analysis

Figure 6 shows the changes in popularity for different keywords in heavy metal-contaminated soil remediation, revealing the trends and priorities of technological development in this field. First, "soil restoration agent" and "additive" are the most popular keywords, highlighting the core position of soil restoration agents and additives in soil restoration. These repair agents and additives are usually made from agricultural waste, microorganisms, planting, fertilizer, biochar, and animal manure. These traditional repair materials have been widely used in past research. However, their popularity has decreased in recent years because researchers are beginning to look for more efficient and innovative repair methods.

It is worth noting that in recent years, the popularity of keywords such as motor, mechanism, sanitary product, super absorbent polymer, crosslinking agent, and resin has proliferated. This shows that using new polymer materials and mechanical equipment to treat heavy metals in soil has gradually become a research hotspot. These new materials and mechanical equipment may have higher remediation efficiency and better environmental friendliness, providing new solutions for heavy metal-contaminated soil remediation.

In addition, the increased popularity of keywords such as bioavailability and absorption rate are also worthy of attention. This shows that the control strategy of heavy metals in soil is shifting from total control to effective heavy metal control. Researchers have begun to pay more attention to the bioavailability of heavy metals in soil and the degree of absorption by plants, which is of great significance for improving the effect of soil remediation and reducing environmental pollution.

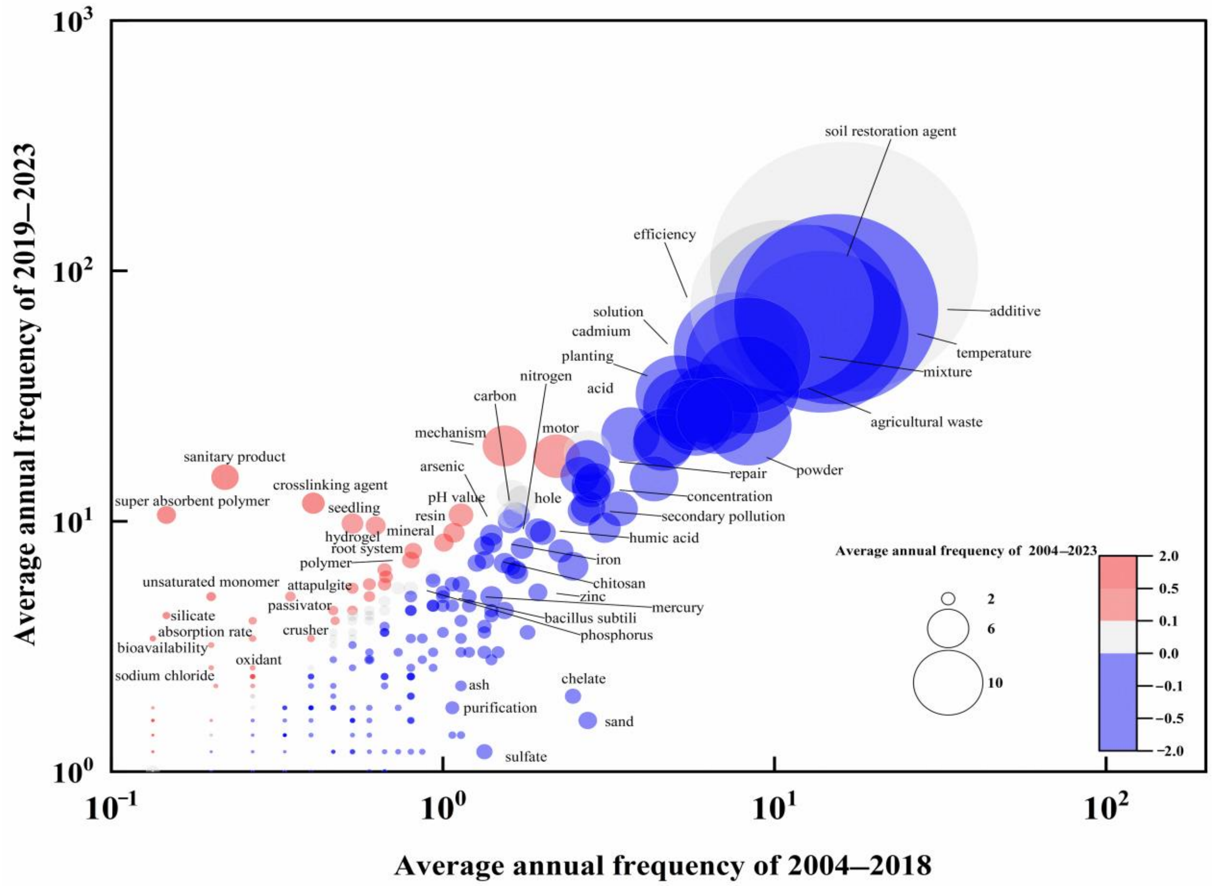

Figure 6. Technology hot spots and future trends of heavy metal-contaminated soil remediation patents.

4. Conclusions

The number of patent applications in heavy metal-contaminated soil remediation shows rapid yearly growth, fully reflecting this field's active and prosperous technological innovation activities. China has demonstrated solid technological competitiveness as the leading patent applicant in this field. However, we must also face a problem. Despite the vast number of patent applications, China must catch up in transnational patent layouts, which may impact our technological competitiveness. What is gratifying is that there is no technological monopoly between large- and small-scale enterprises and individual inventors in heavy metal repair technology, and technological development is relatively balanced. This diverse R&D landscape helps promote the widespread dissemination and application of technology and promotes progress in the entire field. However, we also noticed that most inventors in this field need more continuity in technical research. This may be due to the rapid technological updates and the need for inventors to adapt constantly to new research directions and technological trends. Therefore, maintaining the continuity and depth of technical research will be a significant challenge. Regarding patent application categories, applications in this field are mainly concentrated in the two major categories of IPC B09 and C09, the DWPI class code P43, and the DWPI manual codes C04, C05, and P43. These classifications reflect this field's main technical directions and R&D priorities, providing valuable reference information. From the analysis of key terms, soil remediation agents are undoubtedly the primary technical method in this field. At the same time, attention to heat treatment technology is also increasing, which shows that this technology has broad application prospects in heavy metal-contaminated soil remediation. In addition, repair costs are a critical factor in this field, reflecting the importance of reducing costs while ensuring repair effects in practical applications. In the future, using new polymer materials and mechanical equipment to treat heavy metals will become an essential direction for technological development. This new treatment method is expected to bring a more efficient and environmentally friendly solution to heavy metal-contaminated soil remediation. At the same time, we have also seen that the control strategy for heavy metals in soil is gradually changing from total control to the control of the practical portion of heavy metals. This transformation reflects the deepening and refinement of heavy metal pollution control strategies, helps to assess and manage heavy metal pollution risks more accurately, and improves the effectiveness and efficiency of soil remediation.

In summary, the technological development in heavy metal-contaminated soil remediation is full of opportunities and challenges. We need to continue to strengthen technological innovation and R&D investment, improve our ability to deploy transnational patents and pay attention to the continuity and in-depthness of technological research. Through these efforts, we are expected to promote the further development and application of technology in this field and make more excellent contributions to environmental protection and sustainable development.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14050715/s1. Table S1: IPC Classification; Table S2: DWPI Classification Code; Table S3: DWPI Manual coded.

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