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Current Progress in Hexavalent Chromium by Bibliographic Analysis

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Abstract: Hexavalent chromium contamination poses significant environmental and health challenges, particularly in developing regions where industrial and mining activities pollute water sources. Rainfall and surface runoff transport this toxic compound into groundwater and waterways, leading to severe health risks such as cancer in communities relying on untreated well water. This study employs bibliographic analysis to explore recent advancements in hexavalent chromium remediation technologies. Key approaches include physical methods like activated carbon adsorption, chemical methods such as redox reactions using zero-valent iron, and biological methods leveraging microorganisms like *Shewanella oneidensis*. Beyond technological solutions, governance frameworks addressing cross-border contamination and national pollution management are critical for sustainable remediation efforts. The study also highlights the future potential of integrating big data and machine learning to optimize remediation strategies. Predictive models trained on extensive datasets can revolutionize contamination management, providing scalable, efficient solutions for mitigating the global risks of hexavalent chromium pollution.

Keywords: hexavalent chromium; bibliography; VOSviewer; big data; machine learning

1. Introduction

Hexavalent chromium is a critical concern in the environmental and water pollution sectors due to its toxic nature and severe health implications [1,2]. In many developing countries and regions, mining and industrial production activities release substantial amounts of hexavalent chromium into the environment [3,4]. This pollutant often infiltrates groundwater or waterway systems through rainfall and surface runoff, posing a significant risk to human health [5,6]. The issue is particularly pronounced in underdeveloped areas where communities rely on well water for their daily needs, making them vulnerable to contamination from polluted upstream sources [7]. Exposure to hexavalent chromium has been linked to severe health conditions, including cancer, underscoring the urgent need for effective remediation and management strategies [8,9].

To address the challenges posed by hexavalent chromium contamination, this study employs bibliographic analysis to explore recent advancements and critical findings in this field [10,11]. By systematically analyzing the literature, the research identifies and evaluates the most prominent technological solutions for hexavalent chromium remediation [12,13]. These solutions can be broadly categorized into three primary methods: physical, chemical, and biological. Physical methods, such as adsorption using activated carbon, have been widely utilized due to their efficiency in removing hexavalent chromium from water [14,15]. Chemical methods, including redox reactions, demonstrate significant potential, with materials like zero-valent iron playing a pivotal role [16,17]. Biological approaches leverage the capabilities of microorganisms, such as *Shewanella oneidensis*, which can immobilize hexavalent chromium through biofilm formation [18]. These diverse methodologies provide a comprehensive framework for tackling contamination in various environmental contexts.

Beyond technological approaches, effective governance strategies are essential to manage hexavalent chromium pollution effectively [19,20]. This includes addressing cross-border

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contamination issues, where pollution generated in one country adversely affects downstream regions in another [21,22]. Resolving such challenges requires international cooperation and the establishment of transnational agreements to ensure equitable and sustainable solutions. Within national boundaries, designing robust regulatory frameworks is vital to enforce pollution controls, promote technological innovations, and facilitate timely interventions [23,24]. Governance strategies must balance the complexities of environmental, social, and economic factors to create effective and sustainable management practices for hexavalent chromium contamination.

Looking forward, the study also highlights the transformative potential of integrating big data and machine learning into hexavalent chromium research and remediation [25,26]. These advanced technologies have already demonstrated significant success in fields such as autonomous driving [27], facial recognition [28], and ecological prediction [29]. Applying these tools to hexavalent chromium research could enable the development of predictive models based on extensive datasets that capture contamination patterns, environmental variables, and remediation outcomes. Such models could optimize remediation strategies for unique contamination scenarios and offer scalable solutions for global applications. By combining cutting-edge technologies with robust policy frameworks, this study aims to provide a comprehensive roadmap for addressing the multifaceted challenges posed by hexavalent chromium pollution.

2. Materials and Methods

The bibliographic analysis methods followed previous studies with slightly modifications [30,31]. To investigate the research landscape of hexavalent chromium, we conducted a comprehensive bibliometric analysis using the Web of Science database [32,33]. On January 20, 2025, we performed a keyword search with the term "hexavalent chromium," which yielded a total of 18,098 articles. For the purpose of our study, we limited the analysis to the default selection of the 1,000 most relevant articles provided by the platform.

For the keyword co-occurrence analysis, we utilized the bibliometric software VOSviewer (Version 1.6.20) to identify patterns and trends in the literature [34]. A threshold of a minimum of five occurrences per keyword was applied, allowing us to focus on terms with substantial representation across the dataset. This criterion ensured that the analysis captured the most prominent research topics and thematic clusters while excluding infrequently mentioned terms that might introduce noise.

The organizational analysis involved examining the contributions of institutions to hexavalent chromium research. To identify the leading organizations, we applied a threshold requiring each organization to have published a minimum of four documents within the selected dataset. This threshold provided a balanced representation of institutional contributions without overemphasizing institutions with minimal engagement in the topic.

In the country and region analysis, we aimed to evaluate the geographical distribution of research activity. A threshold of a minimum of 15 publications per country or region was set to highlight areas with significant research output. This approach allowed us to identify global hotspots for hexavalent chromium research and assess the collaborative dynamics among different regions. Together, these criteria and analytical methods facilitated a robust understanding of the research trends and contributions in the field.

3. Results

Figure 1 illustrates the prominent keywords within the research field of hexavalent chromium, revealing their intricate connections and diverse implications. Among these, several keywords are closely linked to various elements, highlighting the intersection of hexavalent chromium research with studies on metals like "aluminum", "cadmium", "copper", and "nickel". This association reflects the multifaceted nature of hexavalent chromium's interactions with other chemical substances, which is critical for understanding its behavior in different environments and its role in industrial processes.

These connections underscore the need for comprehensive studies that consider the interplay between hexavalent chromium and other elements, as this knowledge is essential for developing effective strategies for monitoring and mitigating its impacts.

In addition to its elemental associations, certain keywords in the analysis point to hexavalent chromium's relationship with diseases and its implications for human health. Terms such as "damage," "DNA-damage," "cancer," and "carcinogenicity" highlight the toxicological concerns surrounding exposure to this compound. These keywords signify its potential to cause severe harm at both molecular and systemic levels, including its role as a known carcinogen. The prominence of these terms in the research indicates a significant focus on understanding the health risks posed by hexavalent chromium and developing measures to prevent its adverse effects. This area of study is critical for informing public health policies and setting safety standards to protect communities and ecosystems from its harmful impacts.

The analysis also reveals a strong emphasis on methodologies and technologies for addressing hexavalent chromium contamination. Keywords such as "biosorption," "biosorbent," "degradation," "separation," and "removal" underscore the active exploration of remediation techniques aimed at mitigating the environmental and health challenges posed by this compound. These terms reflect an ongoing effort to innovate and refine methods for effectively removing hexavalent chromium from contaminated sites, including water, soil, and industrial waste streams. The focus on these remediation strategies highlights the importance of integrating scientific advancements with practical applications to address the global challenges associated with hexavalent chromium pollution. Together, these findings provide a comprehensive overview of the research priorities and key themes within this critical area of study.

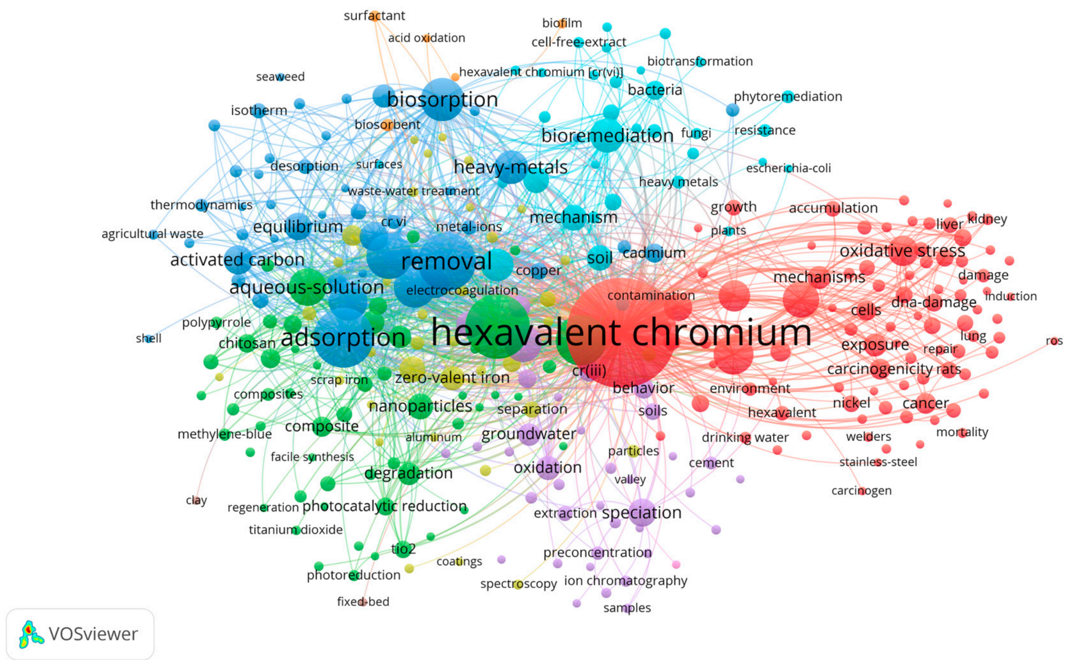

Figure 1. Keyword analysis generated by VOSviewer, with lines representing keyword correlations.

Figure 2 presents a detailed visualization of the leading organizations contributing to research on hexavalent chromium, with significant insights into the global landscape of academic and institutional collaboration. At the core of this network is the Chinese Academy of Sciences, which emerges as a central hub, reflecting its substantial influence and prolific output in this field. This prominence highlights the academy's pivotal role in driving innovation and advancing the understanding of hexavalent chromium, including its environmental behavior, toxicological impacts, and remediation strategies. The central positioning of this institution underscores the emphasis

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placed by China on addressing environmental challenges and the critical role of its scientific community in shaping global research directions.

Beyond the Chinese Academy of Sciences, other organizations also make notable contributions to hexavalent chromium research. Institutions such as the National University of Singapore and the Chinese Research Academy of Environmental Sciences demonstrate their strong presence in the network. These organizations play critical roles in fostering collaborative efforts and expanding the scope of research, particularly in areas like environmental remediation, material innovation, and toxicology. Their active engagement underscores the importance of a multidisciplinary approach to tackling the complexities of hexavalent chromium contamination, with a focus on generating solutions that are not only effective but also sustainable in the long term.

In addition to these leading institutions, several universities, including the University of Hong Kong, Central South University, and Huazhong Agricultural University, contribute significantly to the field. These universities act as key nodes in the research network, bringing together expertise across disciplines and facilitating knowledge exchange on a global scale. Their involvement highlights the collaborative nature of research on hexavalent chromium, as diverse academic institutions contribute to advancing scientific understanding and developing innovative technologies. Collectively, the contributions of these organizations reflect a robust and interconnected research community, emphasizing the global importance of addressing hexavalent chromium pollution and fostering sustainable environmental practices.

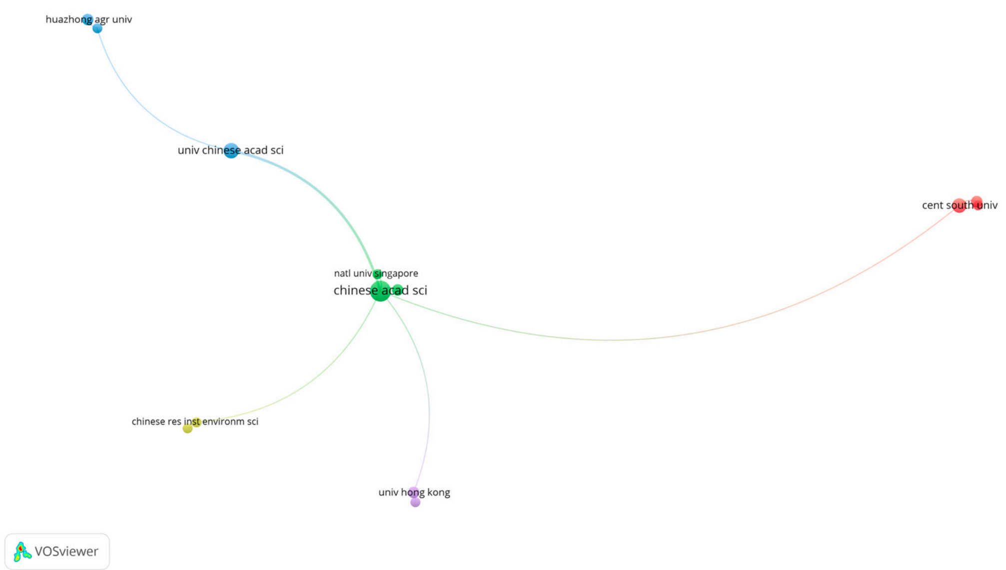

Figure 2. Organization analysis generated by VOSviewer, with lines representing research collaboration.

Figure 3 illustrates the primary countries and regions contributing to research on hexavalent chromium, highlighting the global nature of this field. At the core of the research network are the United States, China, and India, which emerge as the most prominent contributors. These nations demonstrate their leadership through extensive publication records, advanced research facilities, and a concerted focus on tackling environmental pollution.

Beyond the three leading nations, other countries also play significant roles in the research landscape. Spain, Greece, Japan, France, Italy, the United Kingdom, Mexico, Canada, Brazil, Egypt, Iran, South Korea, and Pakistan have all made notable contributions to advancing knowledge in this area. These nations bring diverse perspectives and expertise, enriching the field through regional research initiatives and innovative approaches.

Developed countries often leverage their advanced scientific capabilities to develop new remediation technologies and deepen the understanding of hexavalent chromium's environmental

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impact. Simultaneously, many developing countries focus on addressing local contamination issues, reflecting the global urgency of managing and mitigating the risks associated with this pollutant. The interconnectedness of countries in this field highlights the importance of international collaboration in overcoming the challenges posed by hexavalent chromium.

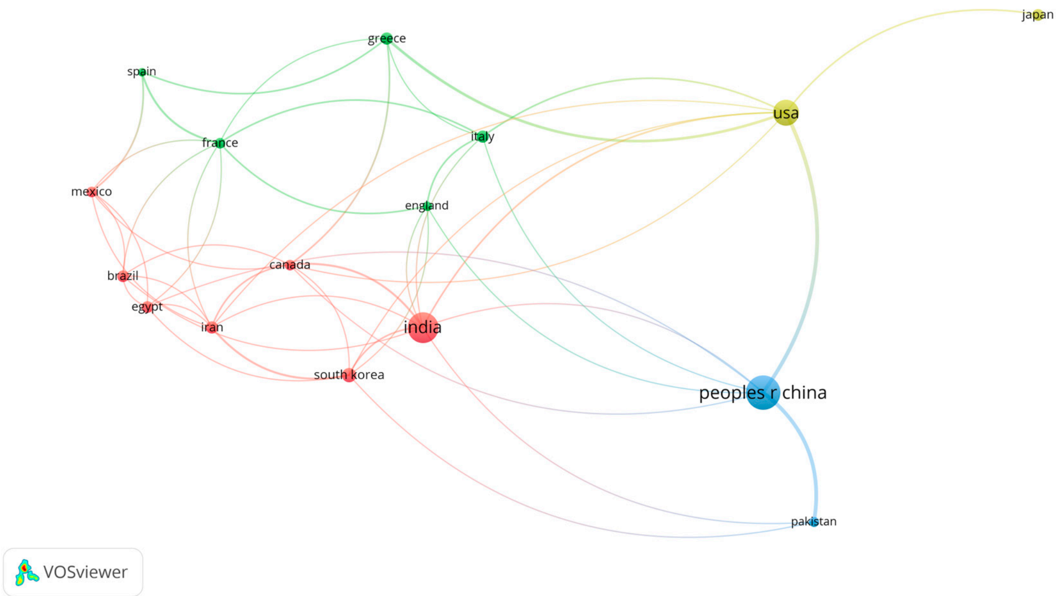

Figure 3. Country/region analysis generated by VOSviewer, with lines representing research collaboration.

4. Discussion

4.1. Addressing Environmental Challenges of Hexavalent Chromium

After reviewing the literature on hexavalent chromium, it is evident that this pollutant poses significant environmental challenges [13,35]. Hexavalent chromium contamination often originates from mining activities and various industrial processes, releasing harmful levels of this compound into the environment [36,37]. The situation is particularly concerning in less developed areas where groundwater is a primary drinking water source [38,39]. Rainwater and subsurface flows can transport hexavalent chromium into wells, resulting in contaminated drinking water [40,41]. This contamination has been linked to severe health risks, including cancer and other diseases [42,43]. Such scenarios highlight the urgent need for effective remediation techniques and prevention strategies, especially in regions with limited access to clean water and robust environmental regulations [44,45].

Technological approaches to addressing hexavalent chromium contamination can be broadly categorized into physical, chemical, and biological methods [46]. Physical methods, such as adsorption techniques, are widely used, with activated carbon being a powerful adsorbent for removing hexavalent chromium from water [47,48]. Recent advances in materials science have introduced innovative options, such as biowaste-derived magnetic carbonaceous materials [49], which show great promise for future applications. Chemical methods frequently utilize redox reactions, with zero-valent iron, which can be delivered via foam-assisted techniques [50,51], proving highly effective for hexavalent chromium remediation due to its strong reducing properties [52,53]. Biological methods, on the other hand, leverage the natural processes of microorganisms. For instance, *Shewanella oneidensis*, a bacterium capable of electron transfer [54,55], has shown potential in immobilizing hexavalent chromium through its biofilm formation [56,57]. These varied technological strategies provide a multi-faceted approach to tackling contamination, each with unique advantages depending on the context [58,59].

Beyond technological solutions, effective governance and policy frameworks are critical for managing hexavalent chromium contamination [60,61]. Addressing cross-border pollution requires international cooperation and agreements, as upstream activities in one country can have downstream consequences for another [62]. Negotiating solutions to such disputes demands robust diplomatic and scientific engagement. Within national borders, developing efficient regulatory systems is essential for ensuring rapid and effective response to contamination incidents. Policymakers must prioritize creating frameworks that promote accountability, foster innovation in remediation technologies, and encourage public awareness [63]. Comprehensive solutions to hexavalent chromium pollution require not only advancements in science and technology but also the establishment of governance models capable of addressing the complex, interconnected challenges of environmental management [64,65].

4.2. Future in Hexavalent Chromium Research with Big Data and Machine Learning

The future of hexavalent chromium research lies in the intersection of big data and machine learning. These technologies have already demonstrated remarkable success in fields such as facial recognition [66,67], autonomous driving [68,69], global species distribution prediction [70], and education performance forecast [71]. In the context of hexavalent chromium contamination, the integration of big data and machine learning holds great promise for revolutionizing how we approach the identification, analysis, and remediation of this toxic pollutant [26,72]. By harnessing large datasets and sophisticated algorithms, we can create more efficient, accurate, and scalable solutions to combat hexavalent chromium contamination.

One potential approach involves building a massive global database that tracks the spread of hexavalent chromium contamination across various regions [73,74]. This database could store a wide range of data, such as the specific locations of contamination, the concentration levels of hexavalent chromium, and relevant environmental factors like temperature, humidity, rainfall, and soil composition. Additionally, information on existing remediation methods, their effectiveness, and environmental variables associated with these approaches could be incorporated. By accumulating such data, we could gain a deeper understanding of the factors that influence the distribution and persistence of hexavalent chromium in different environments, thus enabling more informed decision-making in addressing this issue.

Machine learning algorithms, such as neural networks [75,76], could then be applied to this vast repository of data. By training these models on historical cases, they could learn to predict the most effective remediation strategies based on specific conditions. For example, if a new contamination event occurs in an area with limited historical data, the machine learning model could recommend an appropriate method for remediation by drawing on similar cases and environmental factors. This approach could help overcome the challenges posed by unique contamination scenarios and optimize the response strategies, providing valuable insights and solutions that may not have been considered by traditional methods. Ultimately, the fusion of big data and machine learning could significantly enhance our ability to manage and mitigate the environmental and health risks associated with hexavalent chromium contamination.

5. Conclusions

Hexavalent chromium remains a critical environmental and public health concern, especially in regions where industrial and mining activities contaminate water sources. This study highlights the importance of effective remediation technologies and governance strategies to address the widespread challenges posed by this pollutant. Physical methods, such as activated carbon adsorption, and chemical approaches, like redox reactions using zero-valent iron, offer promising solutions. Biological methods, including the use of microorganisms like *Shewanella oneidensis*, present innovative opportunities for sustainable remediation. Additionally, addressing governance

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challenges, such as cross-border pollution and the establishment of national regulatory frameworks, is vital for ensuring equitable and effective solutions. Future research should focus on integrating big data and machine learning to enhance remediation efforts. Predictive models trained on diverse environmental datasets can identify optimal strategies for unique contamination scenarios, offering scalable and efficient approaches. These advancements hold the potential to significantly reduce the environmental and health risks associated with hexavalent chromium pollution.

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