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Tackling Heavy Metal Pollution: Evaluating Governance Models and Frameworks

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Abstract: Water pollution by heavy metals represents a significant threat to both the environment and public health, with a pronounced risk of stomach cancer and fatalities linked to the consumption of heavy metal-contaminated water. Consequently, the need for effective governance in heavy metal remediation is paramount. Employing a comprehensive review of the existing literature, this study delves into prevalent governance models, including state-centric governance, market governance, network governance, and voluntary governance. The primary objective of this research is to pinpoint the optimal framework for heavy metal remediation and the most efficient governance model. Through an analysis informed by the simplified Multi-Criteria Decision Analysis (MCDA) method, this study presents key findings, offering valuable insights for policymakers, environmental agencies, and industries seeking holistic strategies to combat heavy metal pollution and alleviate its detrimental consequences. These findings significantly contribute to the ongoing global efforts to safeguard the environment, enhance public health, and mitigate the adverse impacts of heavy metal contamination.

Keywords: heavy metal pollution; governance mode; state-centric governance; market governance; network governance; voluntary governance

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1. Introduction

Heavy metals, such as lead, cadmium, mercury, and arsenic, have found their way into the environment through a myriad of human activities, including industrial processes, mining, agriculture, and the disposal of electronic waste [1]. The persistence of these metals in the environment, their bioaccumulate nature, and their propensity to migrate through the food chain have all magnified their harmful impact on the ecosystem and public health [2]. The consumption of heavy metal-contaminated water is a particularly concerning route of exposure [3]. Heavy metals can infiltrate water sources through leaching from industrial sites, improperly disposed waste, and runoff from agricultural areas where metal-based pesticides and fertilizers are used [4]. When humans consume water contaminated with heavy metals, they are at risk of developing various health issues [5]. Notably, stomach cancer has been identified as one of the most severe consequences of chronic heavy metal exposure, particularly in regions where contaminated water is a primary source of drinking water [6]. Moreover, water pollution by heavy metals affects aquatic ecosystems, threatening the survival of aquatic life and destabilizing food chains [7]. The release of heavy metals into the air, often through industrial emissions, can also contribute to soil and water contamination, ultimately affecting the health of terrestrial ecosystems [8].

Given the far-reaching and severe consequences of heavy metal pollution, the need for effective governance to mitigate this threat is undeniable [9]. Effective governance in this context refers to the strategies, regulations, and mechanisms put in place to prevent, control, and remediate heavy metal pollution [10]. Such governance is essential to safeguard both the environment and public health [11]. One of the primary challenges in addressing heavy metal pollution is that it is often a transboundary issue [12]. Pollution originating in one location can have cascading effects on neighboring areas, making cooperation and coordinated governance imperative [13]. The governance of heavy metal pollutants requires a multi-faceted approach that considers environmental, social, and economic factors [14]. This necessitates the evaluation and selection of suitable governance models that are adaptable to diverse contexts and challenges [15].

The primary governance modes under scrutiny include state-centric governance, market governance, network governance, and voluntary governance [16]. Each of these approaches presents unique advantages and disadvantages, and the selection of the most appropriate model should be informed by the specific needs and characteristics of the region or industry in question. The principal objective of this research is to assess and compare the effectiveness of different governance models in addressing heavy metal pollution and guiding the selection of the optimal framework for heavy metal remediation. Specifically, this study aims to:

(1) Utilize bibliographic and bibliometric methods to examine the most important papers in the field of heavy metal remediation governance.
(2) Evaluate prevalent governance models: through an extensive review of the existing literature, we will analyze the strengths, weaknesses, and case studies associated with state-centric governance, market governance, network governance, and voluntary governance.
(3) Apply the simplified Multi-Criteria Decision Analysis (MCDA) method [17]: this research will employ the MCDA to provide a structured and comprehensive evaluation of the selected governance models, considering multiple criteria and expert opinions.
(4) Offer insights for policymakers, environmental agencies, and industries: by synthesizing the findings, this research will provide actionable recommendations and insights to guide decision-makers in the field of heavy metal pollution remediation.

2. Materials and Methods

In October 2023, we conducted a comprehensive data collection using the widely respected database, Web of Science, which encompasses a variety of subdatabases. The primary motivation behind this choice was to ensure data reliability and its relevance to a broader audience. Our research was focused on "Heavy metal governance", and we collected and analyzed a total of 220 articles from the Web of Science. We opted for Web of Science as our main database due to its longstanding reputation as a reliable and extensively utilized resource in the academic community [18].

To generate visual representations for bibliographic and bibliometric analysis, we utilized the VOSviewer data visualization tool [19]. We imported the acquired data files into VOSviewer, enabling us to tailor and adjust parameters to align with our specific research objectives and the diverse sources of data at our disposal. It is worth emphasizing that generating maps from web data often requires rigorous data-cleaning procedures to ensure the highest levels of accuracy and reliability. In this aspect, VOSviewer played a central role in streamlining these data-cleaning operations, contributing significantly to the development of robust and semantically meaningful visualizations [20].

In line with established conventions, unless explicitly specified otherwise, our mapping procedures using VOSviewer followed the default settings adopted in previous scholarly research [21]. In our keyword analysis, we applied a minimum keyword occurrence threshold of "10". For our country/region analysis, we set the requirement of a minimum of "2" documents from a specific country for inclusion. Similarly, in our organization-centered analysis, we considered a minimum of "2" documents associated with a particular organization for further scrutiny.

3. Results

Figure 1a serves as an illustrative representation of our comprehensive analysis centered around the pivotal topic of "keywords". Our meticulous examination has unearthed an intricate web of associations, with a particular emphasis on "heavy metals" and their pronounced connections to essential elements such as "cadmium", "lead", and "copper". These discernible links shed light on the primary focal points that researchers are vigorously pursuing within their scientific endeavors. Furthermore, our investigation revealed that "heavy metals" exhibit intricate affiliations with terms like "soil", "water", "river", "source appointment", and "source identification". These findings underscore the extensive exploration being undertaken by select scientists as they delve into the realms of various contaminated media. The scope of their research is evidently extensive and multifaceted, encompassing a wide spectrum of environmental considerations. Moreover, we observed that "heavy metals" are intricately linked to terms like "governance", "management", "removal", and "risk-assessment". This observation suggests that scientists are dedicating substantial effort and resources to the critical domain of remediation, focusing on devising strategies and methodologies for effective and sustainable heavy metal management. The significance of this focus cannot be overstated, as it has far-reaching implications for environmental preservation and public health.

Figure 1b serves as a significant visual representation of the country/region actively engaged in the critical sphere of heavy metal governance. Within this intricate tapestry of international contributions, China emerges as a central figure, wielding significant influence in this domain. This prominence is not arbitrary but can be attributed to the unique socio-economic context of China as a developing nation. China's remarkable role as a key player in heavy metal governance can be attributed to the confluence of several factors. One pivotal factor is its rapid economic development over recent decades, a transformation that has often come at the cost of environmental quality. The chemical and mining industries, essential components of China's economic growth, have, in some instances, inadvertently contributed to heavy metal pollution. Consequently, China has been compelled to embark on extensive research and innovation endeavors in the realm of heavy metal technology and management. This imperative arises from the necessity to mitigate and rectify environmental repercussions while simultaneously sustaining economic growth. Apart from China's significant role, a consortium of developed nations, including the United States, England, Italy, Portugal, Ireland, Australia, Germany, and Japan, has also emerged as pivotal contributors to the field of heavy metal governance. Within these developed countries, the imperative of environmental protection is particularly pronounced. High living standards, coupled with elevated public awareness and stringent environmental regulations, have catalyzed a collective commitment to robust governance measures. The citizens in these developed countries demand a higher level of environmental responsibility, thus motivating extensive engagement in the management of heavy metals to safeguard both ecological integrity and public health.

Figure 1c presents a vital insight into the landscape of organizations actively contributing to the expansive realm of heavy metal governance. At the forefront of this collective effort stands the Chinese Academy of Sciences (CAS), a veritable powerhouse in the field, offering substantial contributions that significantly shape the discourse and progress of heavy metal governance. However, it is essential to delve deeper into the dynamic tapestry of organizations involved, as numerous entities, both in China and around the globe, are making substantial strides in this area. CAS's pivotal role in the heavy metal governance field is a testament to its rigorous research endeavors and dedication to advancing knowledge and solutions in this crucial area. Their multifaceted contributions encompass a wide range of research, technological innovation, and policy recommendations, driving forward the understanding and management of heavy metals in diverse environmental contexts. Complementing CAS's efforts, several esteemed Chinese universities have made notable contributions. These institutions include Peking University (PKU), Nanjing University (NJU), Shandong University (SDU), Shanghai Jiao Tong University (SJTU), Huazhong University of Science and Technology (HUST), China University of Geosciences (CUG), and China University of Mining and Technology (CUMT). Their involvement is a testament to the pivotal role of academia in advancing research and fostering the next generation of experts in the heavy metal governance domain. Outside of China, significant international contributors to the field have emerged. Ghent University in Belgium, King Khalid University in Saudi Arabia, and Chulalongkorn University in Thailand have all published a substantial body of work, further enriching the global knowledge base on heavy metal governance. This international dimension highlights the universal nature of the challenges posed by heavy metal pollution and the imperative for global collaboration and knowledge sharing in addressing these issues.

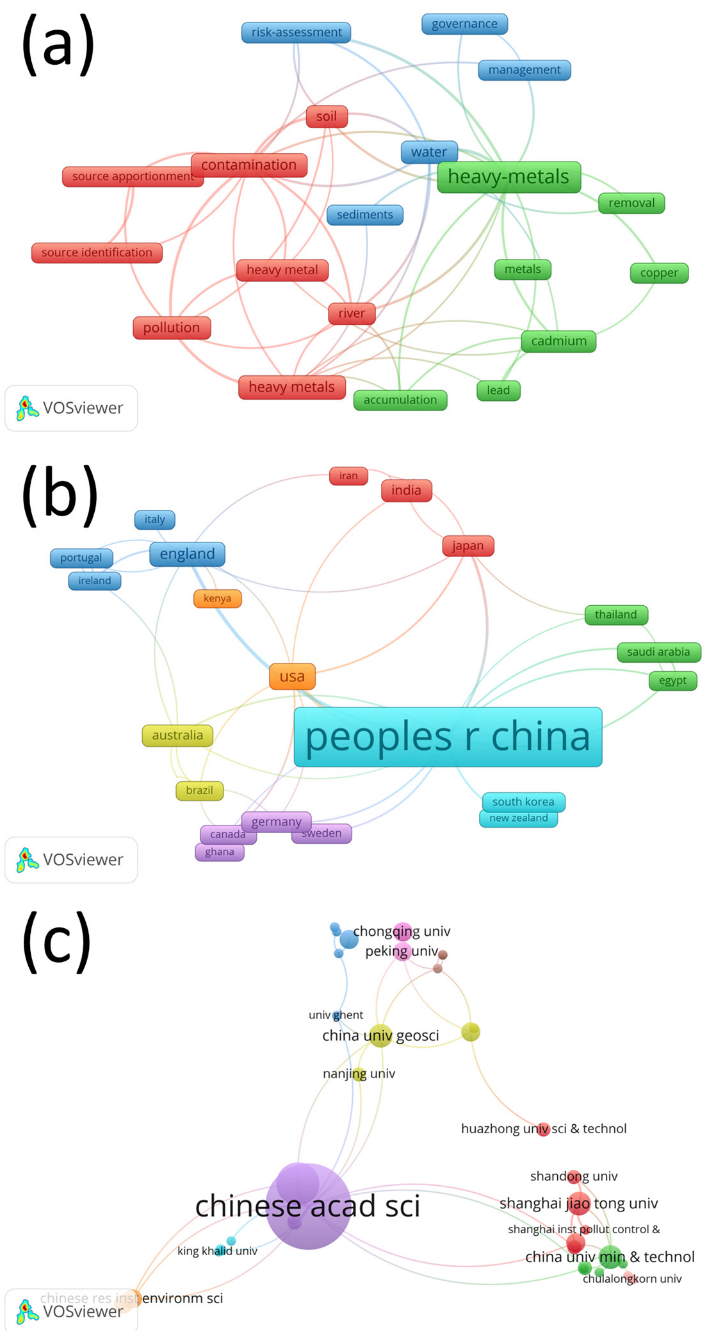

Figure 1. The VOSviewer displays the main keywords (**a**), the main countries/regions (**b**), the main organizations (**c**), and their connections. Colors in these networks indicate different clusters, while the lines indicate the interconnections.

4. Discussion

4.1. The Pivotal Roles of Static-Centric, Market, Network, and Voluntary Governance

By delving into an extensive review of the existing literature, we can establish a profound foundation for comprehending the intricacies of various governance modes [22]. The framework presented in Table 1 plays a pivotal role as an invaluable resource for analyzing and dissecting the myriad approaches and strategies that are intricately woven into the complex tapestry of environmental governance. This study is particularly distinguished by its identification of four overarching governance modes that have consistently held the spotlight in scholarly discussions and research endeavors. These governance modes, namely static-centric governance, market governance, network governance, and voluntary governance, constitute the focal points of the contemporary discourse on environmental governance and are vividly illustrated in Figure 2.

As we embark on this exploration, it becomes evident that the multifaceted nature of environmental governance necessitates a systematic and comprehensive approach to study and understand its various facets [23]. Table 1 stands as a testament to this necessity, offering a structured lens through which we can examine the diverse methodologies and strategies employed in the quest to manage and protect our environment. These four governance modes, which have emerged as prominent actors on the environmental governance stage, each bring their own unique set of principles, practices, and objectives. As we proceed, we will delve deeper into these modes, shedding light on their strengths, limitations, and the dynamic interplay between them in the complex world of environmental governance.

Table 1. Four governance modes and their characteristics.

Governance Modes	Description	Key Features	Examples
State-Centric Governance	Government authorities at the local, regional, or national levels play a central role in regulating and managing heavy metal pollutants. They establish and enforce environmental laws, standards, and regulations.	State agencies set emissions limits, conduct inspections, and levy fines or penalties for non-compliance. They may also conduct environmental impact assessments and oversee permitting processes for industries.	Environmental Protection Agency (EPA) in the United States, Ministry of Environment in Canada.
Market governance	Market governance relies on economic incentives and mechanisms to reduce heavy metal pollution.	Emissions trading systems (e.g., cap-and-trade) allow companies to buy and sell pollution permits, encouraging emissions reduction.	European Union Emissions Trading System (EU ETS), California's cap-and-trade program.
Network Governance	Network governance involves collaboration among multiple stakeholders. These networks work together to address heavy metal pollution.	Stakeholders participate in decision-making processes, share information, and collectively develop pollution reduction strategies.	Watershed management partnerships and public–private partnerships for environmental initiatives.
Voluntary Governance	Industries and organizations voluntarily commit to reducing heavy metal pollution without strict regulatory mandates.	Companies develop sustainability initiatives, adopt the best practices, and report on their progress voluntarily. This approach relies on corporate social responsibility and industry self-regulation.	The Responsible Care program in the chemical industry, corporate sustainability initiatives.

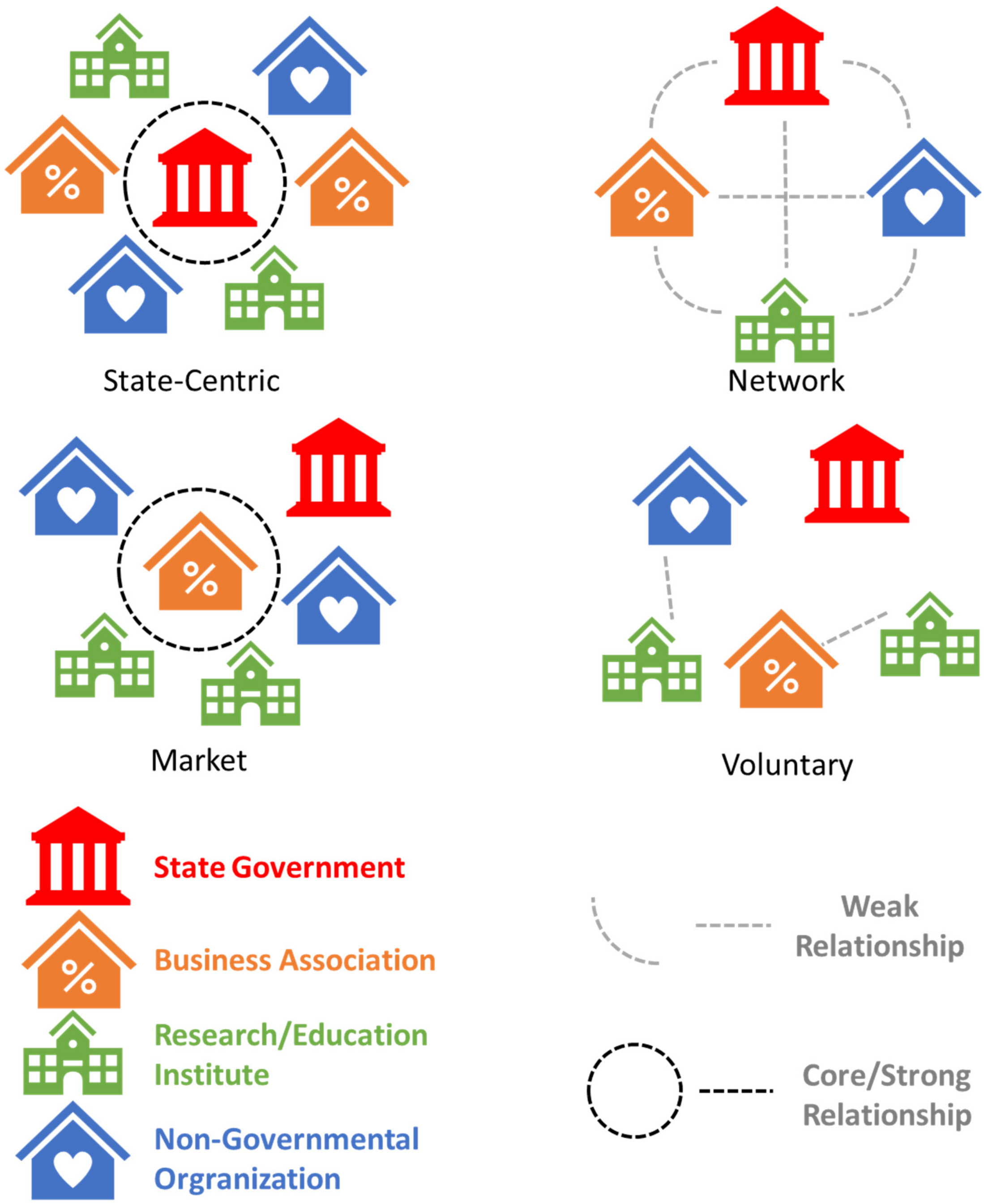

Figure 2. A schematic illustration of governance modes in heavy metal remediation.

4.2. Exploring Pollution Control Governance Trends in Scholarly Research

Table 2, a fundamental cornerstone of this study, stands as an invaluable resource, meticulously crafted to provide readers with an extensive and intricately detailed overview of the most recent developments within the multifaceted realm of pollution control governance modes. Within the vast and ever-expanding landscape of scholarly investigations that characterizes the field of environmental governance, a notable and substantial portion of research endeavors has been diligently focused on the exploration and analysis of the static-centric governance approach [24–26]. This persistent and recurring emphasis on the static-centric model not only underscores its historical significance but also highlights the pivotal and central role it plays in shaping and influencing the discourse surrounding pollution control governance. The continuing recognition of the model's importance and its comprehensive understanding are indicative of its profound influence. Moreover, the academic community, known for its rigorous pursuit of knowledge and insight, has ventured beyond the realm of mere acknowledgment to engage in comprehensive evaluations of the strengths and weaknesses inherent in the static-centric governance approach. The meticulous scrutiny applied to the model extends far beyond a mere surface-level examination, delving deep into its core components and mechanisms. This depth of analysis has unearthed not only the model's inherent limitations but has also paved the way for innovative strategies and proposals. These strategies and proposals, born from a passionate commitment to refining the existing state-centric governance model, have emerged as tangible solutions aimed at optimizing the model's functionality, efficacy, and adaptability within the dynamic and ever-evolving context of environmental governance. The importance of these endeavors cannot be overstated, as they represent a collective effort to ensure that the governance framework remains resilient, effective, and well-equipped to tackle the multifaceted and ever-changing environmental challenges that lie ahead.

Table 2. Literature analysis on pollutant control governance mode.

Governance Mode	Main Argument	Organization	Country/Region	Reference
Static-centric governance	Traditional governance blends static-centric planning and vertical accountability.	Chinese Academy of Sciences	China	[24]
Static-centric governance	State-centric planning with limited community-based solutions in Ganges is found.	The University of North Carolina at Greensboro	USA	[25]
Static-centric governance	Environmental governance has failed due to the absence of non-state actors in a state-centric system, requiring international collaboration.	Shahid Beheshti University	Iran	[26]
Market governance	Market governance's impact on water pollution varies by dimension, region, and mechanism.	Lanzhou University	China	[27]
Market governance	The expansion of small-scale wastewater treatment plants (SSTPs) requires improved market governance.	Swiss Federal Institute of Aquatic Science and Technology	Switzerland	[28]
Market governance	Water pollution has the potential to impact both water sources and food supplies. Market interventions can play a role in addressing water pollution.	Shanghai University	China	[29]
Market governance	Vegetables can be impacted by heavy metal pollution. The market plays a role in remediating water pollution.	Chongqing Jiaotong University	China	[30]
Network governance	Structuring network governance for effective coordination and goal agreement is required.	University of Melbourne	Australia	[31]
Network governance	Large-scale natural resource conservation initiatives utilize network governance, but face challenges like "network capture" and knowledge conflicts, alongside its benefits.	Texas A&M University	USA	[32]
Voluntary governance	Transboundary heavy metal pollution requires voluntary governance.	University of Oxford	UK	[12]

Although the landscape of scholarly inquiry has witnessed a notable expansion into the domain of market governance [27–30], as exemplified by the insightful research studies documented in references, it remains imperative to underscore that the integration of a pollution control framework within the market governance paradigm has not yet garnered the widespread global recognition or adoption comparable to the well-established state-centric governance model. This observation, by no means a trivial one, sheds light on the pressing necessity for ongoing discourse and comprehensive exploration within the field of environmental governance. The ultimate goal of these collective efforts is to foster a broader and more pervasive dissemination of market-based approaches, establishing them as a credible and efficacious alternative to traditional governance models. In essence, these pioneering scholars have embarked on a journey of discovery, one that takes them beyond the boundaries of conventional governance paradigms and into the uncharted territory of market-based solutions for pollution control. This progressive shift in focus is undeniably noteworthy, and their contributions to the field have enriched our understanding of alternative approaches to environmental governance. Nevertheless, it remains abundantly clear that the road to full acceptance and implementation of market governance in the domain of pollution control is still a challenging and uphill one. As we consider the implications of this observation, it becomes evident that the environmental governance community must remain steadfast in its commitment to dialogue, research, and knowledge dissemination. The innovative insights and solutions emerging from these studies call for a broader audience, requiring the academic community and policymakers to bridge the gap between theory and practice. The task at hand is not merely to recognize the potential of market governance but to initiate a collective effort that can propel it into a more prominent and influential position on the global stage. To achieve this objective, it is essential to continue the discourse, leveraging the wealth of knowledge and evidence provided by scholars who have ventured into the uncharted waters of market governance. Their pioneering spirit and dedication to expanding the frontiers of environmental governance have set the stage for a paradigm shift that has the potential to influence policy and practice. This transformation can only become a reality when the broader community of stakeholders, from academia to governmental bodies, regulatory agencies, and industries, takes up the mantle to advance the adoption and implementation of market-based pollution control approaches. As we reflect on the journey ahead, it is clear that the effort to mainstream market governance is a collective endeavor—one that holds the promise of reshaping the landscape of pollution control governance for the better.

Beyond the predominant governance paradigms mentioned earlier, the concept of network governance [31,32] has emerged as an intriguing and increasingly influential subject of inquiry within the extensive body of environmental governance literature. Researchers and scholars have been captivated by the promise and complexities associated with network governance, recognizing its potential to offer innovative solutions for contemporary environmental challenges. This heightened attention is underpinned by a growing acknowledgment of the pivotal role that well-structured network governance can play in achieving not only effective coordination but also a consensus on goals and actions among the diverse array of stakeholders engaged in environmental management. At the heart of this concept lies the recognition that environmental governance is not a monolithic and linear process but rather a multifaceted, dynamic, and often multifarious endeavor. Traditional, static paradigms of governance, while valuable in certain contexts, sometimes fall short in addressing the intricate and interconnected nature of modern environmental challenges. It is in this context that network governance takes center stage, offering an alternative path that goes beyond the confines of established governance models. This paradigm shift calls for the reevaluation and reconfiguration of how we approach environmental governance. The emphasis on structural and relational aspects within network governance underscores the need for a holistic and integrated approach—one that accommodates the complexities of contemporary environmental issues. The recognition that environmental challenges transcend geographical, political, and sectoral boundaries necessitates governance structures that are equally flexible and interconnected. Furthermore, the very nature of environmental concerns often necessitates the participation of an extensive and diverse set of stakeholders. Network governance acknowledges this inherent diversity and leverages it as a strength rather than a challenge. Through well-structured networks, stakeholders with differing perspectives and expertise can collaborate, share knowledge, and collectively navigate the intricate terrain of environmental governance.

Lastly, it is worth noting that voluntary governance [12], while sometimes viewed as a supplementary or complementary framework, rather than a completely autonomous mode of pollutant control governance, plays a pivotal role in shaping the environmental landscape. The significance of voluntary governance extends beyond its conventional categorization, and it is essential to delve deeper into its mechanisms and contributions. Voluntary governance operates on the premise of encouraging proactive environmental responsibility and fostering sustainability. Organizations and industries that voluntarily partake in pollution control actions exemplify a commitment to environmental protection that transcends the confines of legal obligations. This heightened sense of responsibility often manifests in the form of innovative practices and collaborative endeavors, ultimately contributing to more robust and sustainable environmental management. In essence, voluntary governance represents a proactive stance that organizations and industries can adopt in addressing environmental concerns. While it coexists with other governance models, it is not merely a supplement; rather, it stands as a proactive approach that goes above and beyond the minimum requirements set by regulatory frameworks. One of the central tenets of voluntary governance is the willingness of entities to take on a higher level of responsibility for their environmental impact. This willingness emanates from a recognition of the interconnectedness of environmental issues and a commitment to mitigating the detrimental effects of pollution on ecosystems and human health. In this context, voluntary governance acts as a powerful tool for promoting environmental stewardship.

4.3. MCDA Approach to Assess Governance Effectiveness

In order to assess the effectiveness of various governance methods, this paper employed a comprehensive approach known as MCDA to evaluate different governance modes [33,34], as presented in Table 3. The examination considered five distinct categories for comparative analysis, namely "connections with other stakeholders", "structure of rules and regulations", "utilization of instruments", "degree of adaptability", and "fundamental values and ethos". Among these categories, the state-centric governance approach displayed commendable performance in all respects except for "adaptability". The inflexibility of the state-centric governance model stems from prolonged reporting and decision-making processes, making it less responsive to instances of urgent heavy metal pollution. Consequently, the efficacy of state-centric governance in managing emergency heavy metal pollution cases is somewhat compromised. To address this significant challenge, the authors have recommended the incorporation of alternative governance modes, such as voluntary governance, to complement the state-centric approach in resolving issues related to emergency heavy metal pollutants. This multi-pronged approach is suggested to enhance the overall efficiency of environmental governance systems, thereby promoting a more responsive and comprehensive strategy for dealing with urgent heavy metal pollution cases and ensuring the well-being of affected communities and ecosystems. This approach not only emphasizes the importance of flexibility but also recognizes the value of diverse governance strategies in addressing complex and pressing environmental challenges, ultimately contributing to more resilient and effective environmental management.

Table 3. Simplified Multi-Criteria Decision Analysis (MCDA) of different governance modes on heavy metal remediation: 2 represents "Good"; 1 represents "Moderate"; 0 represents "Poor" or "None".

Criteria	State-Centric Governance	Market Governance	Network Governance	Voluntary Governance
Ties with others	2 (Authority)	2 (Contract)	1 (Trust)	0 (Informal)
Rule structure	2 (Regulation)	2 (Business)	1 (Teamwork)	2 (Conformity)
Instruments	2 (Tax)	1 (Standards)	2 (Certification)	1 (Morality)
Flexibility	0 (Low)	1 (Medium)	1 (Medium)	2 (High)
Ethos	2 (Formal)	0 (Skepticism)	1 (Shared gains)	1 (Friendship)
Total	8	6	6	6

4.4. Big Data and Machine Learning Opportunity in Heavy Metal Pollution Governance

A pioneering technique that integrates big data and machine learning not only heralds new prospects for effective heavy metal governance in the future but also aligns with the broader trend of harnessing these technologies [35,36]. Across various domains such as autonomous driving, ecological forecasting, and educational policy development, big data and machine learning [37] have proven invaluable, showcasing their multifaceted utility.

Formerly, heavy metal pollution governance primarily relied on human intervention [38], but the evolution of the internet and computational capabilities now presents the opportunity for automated data collection. Once data is gathered, the internet serves as the conduit for seamlessly transitioning to the machine learning phase. Here, machine learning algorithms can autonomously process the data, offering instructions to the workforce for prompt, informed actions, such as dispatching specialized vehicles equipped to address contaminated water sources [39,40]. This transformative shift empowers machines to assume decision-making roles, markedly enhancing the efficiency of heavy metal pollution governance.

By adopting this innovative approach, not only is process efficiency optimized, but the potential for human errors is significantly reduced [41]. Furthermore, the real-time responsiveness it offers to environmental challenges fosters a more proactive and data-driven approach to heavy metal pollution management. As technology continues its relentless march forward, the fusion of big data and machine learning emerges as a catalyst for reimagining environmental governance [42]. This partnership between humans and machines holds the promise of a future where heavy metal governance is not only more efficient but also aligned with the demands of a rapidly evolving technological landscape [43].

5. Conclusions

Overall, this paper emphasizes the complex network of associations within the domain of "heavy metals", illustrating its connections with terms such as "governance", "management", "removal", "risk assessment", and more. This underscores the extensive research conducted in this field through comprehensive bibliographic and bibliometric studies. The discussion delves further into static-centric, market, network, and voluntary governance, emphasizing the importance of comprehending these modes and their dynamic interactions within the complex realm of environmental governance. This study provides a comprehensive overview, with a primary focus on static-centric governance. Market governance is emerging but has not yet gained widespread recognition, while network governance and voluntary governance play significant roles. The simplified MCDA approach is employed to assess governance methods, revealing the effectiveness of state-centric governance in most areas, with the notable exception of adaptability. To address this issue, the paper recommends integrating alternative governance modes such as voluntary governance.

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