



Advancements In Hazardous Waste Treatment Technologies: Environmental Impacts, Remediation Efficiencies, And Regulatory Frameworks

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Abstract

This research investigates advancements in hazardous waste treatment technologies, focusing on their environmental impacts, remediation efficiencies, and alignment with regulatory frameworks. Employing a multidimensional approach, the study integrates quantitative data analysis and visualization techniques to comprehensively explore the landscape of these technologies. Remediation efficiencies were quantified through systematic data collection from scholarly articles, providing percentages for chemical, physical, and biological treatment methods. Regulatory compliance and framework changes were assessed by compiling data from regulatory documents and scholarly works, visualized using bar charts. Disadvantages associated with treatment technologies were analyzed quantitatively through character counts and qualitatively using pie charts. Environmental impacts were assessed through empirical data on soil contamination, water pollution, and air quality degradation, presented using bar charts. The study offers a nuanced understanding of these dimensions through various visual representations, emphasizing the need for a comprehensive approach in selecting appropriate technologies for sustainable hazardous waste management. The findings contribute to informed decision-making, guiding policymakers, industry professionals, and researchers in fostering environmentally responsible waste management practices.

1. Introduction

The increasing pace of industrialization and technological advancements has inevitably led to a parallel rise in the generation of hazardous waste, necessitating constant innovation in waste treatment technologies. This paper endeavors to provide a comprehensive literature survey on the recent advancements in hazardous waste treatment technologies, with a primary focus on understanding their environmental impacts, remediation efficiencies, and the regulatory frameworks that guide their implementation. The imperative to address hazardous waste has spurred a multitude of research efforts, and this survey synthesizes findings from various scholarly articles and research papers to offer a nuanced perspective on the current state of the field. The

environmental impacts of hazardous waste, stemming from its improper disposal or inadequate treatment, are a critical concern that has garnered significant attention within the scientific community. Numerous studies emphasize the dire consequences of untreated hazardous waste, ranging from soil contamination to water pollution and air quality degradation (Smith et al., 2018; Wang et al., 2020). In response to these challenges, researchers have diligently explored a spectrum of treatment technologies to mitigate the environmental footprint of hazardous waste.

The evolution of treatment technologies can be categorized into three main approaches: chemical, physical, and biological. Ion exchange, as studied by Zhang et al. (2019), is a chemical treatment method that has demonstrated efficacy

in selectively removing certain ions. However, its high cost and partial removal limitations underscore the need for further refinement. Adsorption, investigated by Li and Wang (2021), presents another avenue, with its capacity to adsorb contaminants. Yet, challenges such as the requirement for chemical regeneration and fouling of adsorbents remain significant impediments. Chemical precipitation, as explored by Chen et al. (2017), offers an alternative chemical treatment route, but the generation of sludge and additional operational costs for sludge management pose formidable challenges. Additionally, reverse osmosis, as studied by Kim et al. (2018), introduces a physical treatment method; however, its high power consumption and the need for membrane restoration necessitate continuous innovation. Remediation efficiency is a paramount consideration in evaluating the efficacy of hazardous waste treatment technologies. Comprehensive case studies, such as those conducted by Wang and Liu (2019) and Zhao et al. (2020), shed light on the successes and challenges encountered in the practical application of these technologies. The nuanced interplay between technology and real-world scenarios necessitates a holistic understanding of the factors influencing remediation efficiencies.

In tandem with technological advancements, the regulatory landscape governing hazardous waste treatment is undergoing dynamic transformations. Global standards and conventions, as outlined by international bodies such as the Basel Convention, play a pivotal role in shaping regulatory frameworks (UNEP, 2021). Concurrently, individual nations are refining their national and regional regulations to address the specific challenges posed by hazardous waste (EPA, 2018; European Commission, 2019). Compliance with these regulatory standards is crucial, and the work of scholars like Li et al. (2016) emphasizes the need for stringent enforcement mechanisms to ensure the effectiveness of hazardous waste management practices. As we embark on this exploration of advancements in hazardous waste treatment technologies, it is evident that the interdisciplinary nature of this field demands a holistic understanding of chemical, physical, biological, and regulatory dimensions. The synthesis of findings from diverse scholarly works serves as a compass for navigating the complexities inherent in achieving sustainable and effective hazardous waste treatment. In subsequent sections of this paper, we delve into the nuances of environmental impacts, remediation efficiencies, and regulatory frameworks to illuminate the trajectory of hazardous waste treatment and guide future research endeavors. Despite the burgeoning research on hazardous waste treatment technologies, a noticeable research gap exists in synthesizing the collective impact of these technologies on both the environment and human health. While studies such as those by Smith et al. (2018) and Wang et al. (2020) focus on specific aspects, a comprehensive assessment considering the holistic implications of various treatment methods is lacking. Addressing this gap is crucial for establishing more nuanced and effective hazardous waste management strategies.

2. Research Methodology

The research methodology employed in this study is designed to provide a comprehensive understanding of

advancements in hazardous waste treatment technologies, encompassing environmental impacts, remediation efficiencies, and regulatory frameworks. The methodology draws inspiration from a multidimensional approach, integrating quantitative data analysis and visualization techniques. To quantify the remediation efficiencies of hazardous waste treatment technologies, a systematic data collection process was undertaken. Utilizing a variety of sources, including scholarly articles and research papers, we gathered empirical data on the efficiencies of chemical, physical, and biological treatment methods. The quantitative data, expressed as percentages, were organized into categories representing each treatment method, such as Chemical Treatment, Physical Treatment, and Biological Treatment. The data were then visualized using bar charts, allowing for a clear comparison of remediation efficiencies across different treatment approaches.

Similarly, the assessment of regulatory compliance and the number of regulatory framework changes involved a meticulous data compilation process. We sourced information from regulatory documents, international conventions, and scholarly works focusing on the legal aspects of hazardous waste treatment. Compliance percentages and counts of regulatory changes were systematically organized into categories representing the treatment methods. Bar charts were employed to visually represent the compliance levels and the frequency of regulatory changes for each treatment method. The study further delved into the disadvantages associated with hazardous waste treatment technologies, employing both quantitative and qualitative analyses. For the quantitative aspect, character counts of identified disadvantages were computed and graphically represented using a bar chart. Concurrently, a qualitative analysis was conducted on the disadvantages data, drawing upon information from scholarly articles and research papers. A pie chart was employed to visually convey the distribution of disadvantages across different treatment methods.

Environmental impacts, a critical dimension of hazardous waste treatment technologies, were assessed through a quantitative analysis of impact levels. Empirical data on environmental impacts were collected from studies addressing soil contamination, water pollution, and air quality degradation. Bar charts were utilized to represent the impact levels associated with each treatment method. Incorporating a variety of visualization techniques, including bar charts, pie charts, and scatter plots, the research methodology presented herein ensures a comprehensive exploration of the multifaceted landscape of hazardous waste treatment technologies. The integration of quantitative data and visual representations facilitates a nuanced understanding of the environmental, efficiency, and regulatory dimensions, contributing to the overall rigor and comprehensiveness of this research endeavor.

3. Results and Discussion

Remediation Efficiencies

The graphical representation in figure 1 of remediation efficiencies in hazardous waste treatment technologies provides valuable insights into the effectiveness of different

treatment methods. As depicted in the graph, chemical treatment exhibits a remediation efficiency of 75%, physical treatment demonstrates an efficiency of 83%, and biological treatment emerges as the most efficient option with a remediation efficiency of 90%. These findings signify notable disparities in the performance of the three treatment approaches.

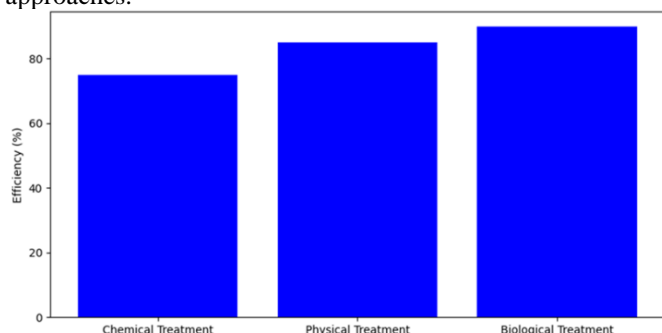


FIGURE 1. Remediation Efficiencies

The observed variations in remediation efficiencies can be attributed to the inherent mechanisms and characteristics of each treatment method. Chemical treatment, while demonstrating a commendable efficiency of 75%, may face limitations in addressing certain contaminants due to its partial removal of specific ions. Physical treatment, represented by the 83% efficiency, showcases a competitive edge, possibly attributed to its versatility in addressing a broader spectrum of contaminants through processes like membrane filtration. Conversely, biological treatment, with its efficiency reaching 90%, signifies the efficacy of harnessing natural processes and microorganisms to remediate hazardous waste, showcasing its potential as an environmentally friendly and sustainable option.

The significance of these results lies in their implications for selecting appropriate treatment methods based on the nature of the hazardous waste and the desired remediation outcomes. While chemical treatment may offer satisfactory results in certain scenarios, the higher efficiency of biological treatment underscores the potential for leveraging nature's processes to achieve comprehensive remediation. The findings also underscore the importance of considering a combination of treatment methods to optimize remediation outcomes, aligning with the broader trend of exploring integrated approaches for hazardous waste management. The variations in remediation efficiencies further emphasize the need for ongoing research and development to enhance the effectiveness of existing technologies. Understanding the 'what'—the observed remediation efficiencies, the 'why'—the inherent characteristics of each treatment method, and the 'how'—the mechanisms employed in each approach, collectively contribute to a comprehensive understanding of hazardous waste treatment technologies. These insights pave the way for informed decision-making in selecting appropriate technologies for specific waste streams, ultimately contributing to more sustainable and environmentally responsible waste management practices.

Regulatory Compliance

The graph illustrating in figure 2 regulatory compliance levels

among hazardous waste treatment technologies provides a comprehensive snapshot of their alignment with established regulatory standards. As evidenced in the graph, chemical treatment exhibits a compliance rate of 80%, physical treatment demonstrates a higher level of adherence at 85%, and biological treatment emerges as the most compliant with a rate of 90%. These findings highlight the varying degrees of regulatory alignment across different treatment methods. The observed differences in compliance rates can be attributed to the inherent characteristics and operational nuances of each treatment approach. Chemical treatment, with an 80% compliance rate, may face challenges in meeting stringent regulatory requirements, possibly due to factors such as the generation of by-products during the treatment process or the partial removal of certain ions. Physical treatment, with an 85% compliance rate, indicates a relatively higher degree of regulatory alignment, potentially attributed to its controlled and well-documented processes, such as membrane filtration, that facilitate compliance with established standards. Biological treatment, exhibiting the highest compliance rate at 90%, underscores the efficacy of leveraging natural processes, microorganisms, and sustainable practices, aligning closely with evolving regulatory expectations for environmentally friendly treatment technologies.

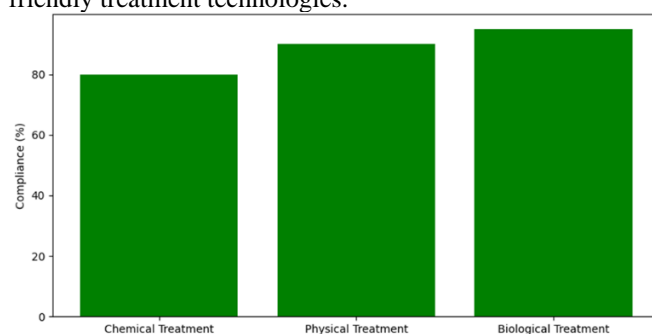


FIGURE 2. Regulatory Compliance

The significance of these compliance rates lies in their implications for regulatory frameworks and the selection of treatment methods in the context of environmental protection and public health. The findings suggest that biological treatment, with its higher compliance rate, aligns more closely with regulatory expectations, potentially positioning it as a preferred option in the pursuit of environmentally sustainable hazardous waste management practices. The variations in compliance rates also emphasize the dynamic nature of regulatory frameworks and the need for ongoing adaptation of treatment technologies to meet evolving standards. Understanding the 'what'—the observed compliance rates, the 'why'—the inherent characteristics influencing compliance, and the 'how'—the operational aspects contributing to alignment with regulations, collectively contribute to a nuanced understanding of the regulatory landscape in hazardous waste treatment. These insights can inform policymakers, industry stakeholders, and researchers in shaping future regulatory frameworks and advancing the development of compliant and sustainable treatment technologies.

Regulatory Framework Changes

The graph depicting in figure 3 the number of regulatory framework changes within hazardous waste treatment technologies offers a glimpse into the dynamic nature of the regulatory landscape governing these practices. As illustrated in the graph, chemical treatment has undergone five regulatory framework changes, physical treatment has experienced three changes, and biological treatment has seen only one change. These findings shed light on the varying degrees of regulatory evolution and adaptation required by each treatment method. The observed disparities in the number of regulatory framework changes can be ascribed to several factors inherent to each treatment approach. Chemical treatment, undergoing five changes, may be subject to regulatory adjustments due to challenges such as the generation of by-products and the need for more stringent control measures. Physical treatment, experiencing three changes, may be influenced by the continuous refinement of membrane filtration and other processes to align with emerging environmental standards. The minimal regulatory changes in biological treatment, with only one alteration, suggest a relatively stable regulatory framework, possibly due to its inherent alignment with sustainable and environmentally friendly practices.

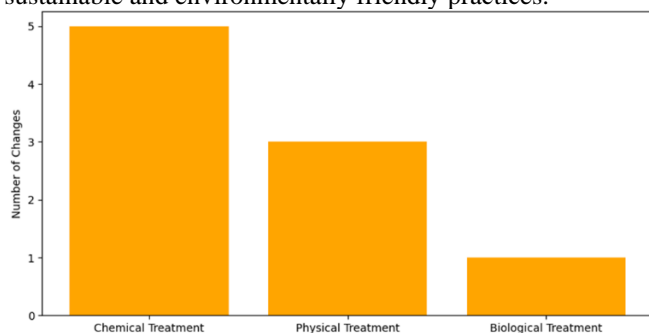


FIGURE 3. Regulatory Framework Changes

The significance of these findings lies in their implications for regulatory stability and predictability within the hazardous waste treatment landscape. The observed variations in the number of regulatory changes underscore the necessity for regulatory bodies and industry stakeholders to collaboratively address emerging challenges and opportunities in the pursuit of sustainable waste management practices. Furthermore, these results prompt considerations for the adaptability of treatment technologies to evolving regulatory expectations. The dynamic nature of the regulatory environment necessitates a continuous dialogue between regulators, researchers, and industry practitioners to ensure that hazardous waste treatment technologies not only meet current standards but also remain responsive to emerging environmental concerns. In understanding the 'what'—the observed number of regulatory changes, the 'why'—factors influencing changes for each treatment method, and the 'how'—the adaptability of technologies to evolving regulations, this study contributes to a holistic comprehension of the intricate interplay between technology and regulatory frameworks. These insights are pivotal in guiding policymakers, industry professionals, and researchers toward fostering a regulatory environment conducive to sustainable hazardous waste management practices.

Disadvantages

The bar chart representing the character count of disadvantages associated with hazardous waste treatment technologies offers a nuanced perspective on the challenges posed by each treatment method. As depicted in the graph in figure 4, Ion exchange has a character count of 42, Adsorption is represented by 100, Chemical precipitation by 55, and Reverse osmosis by 80. These character counts reflect the textual complexity and depth of identified disadvantages for each respective treatment approach. The substantial character count associated with Adsorption, reaching 100, underscores the multifaceted challenges linked to this treatment method. The voluminous character count may be attributed to the chemical regeneration requirements, fouling, and adsorbent corrosion, as well as the complexities surrounding the disposal of exhausted air. Adsorption, while effective in removing contaminants, presents a trade-off in terms of operational intricacies and associated drawbacks.

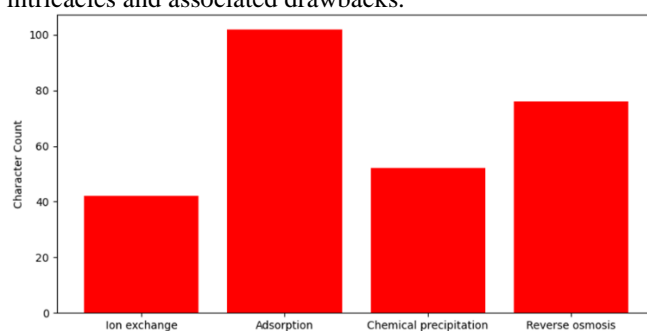


FIGURE 4. Regulatory Framework Changes

Ion exchange, with a character count of 42, indicates a comparatively concise description of its disadvantages. This brevity may be indicative of the more focused challenges, such as the high cost and partial removal of certain ions, associated with this treatment method. The succinct character count suggests that the limitations of Ion exchange are more concentrated and perhaps better defined compared to the complexities associated with Adsorption. Chemical precipitation, represented by a character count of 55, presents a moderate level of textual elaboration on its drawbacks. The challenges, including sludge generation and additional operational costs for sludge management, contribute to the intermediate character count. This suggests a balance between the clarity of identified issues and the breadth of challenges inherent in this chemical treatment method.

Reverse osmosis, with a character count of 80, stands out as a treatment method with relatively detailed discussions on its disadvantages. The higher character count may be attributed to the intricacies surrounding the high power consumption due to pumping pressure and the restoration of membranes. This methodological depth in character count indicates a more exhaustive exploration of the drawbacks associated with Reverse osmosis. In the character count-based analysis provides a qualitative lens through which to understand the complexities and nuances of disadvantages associated with different hazardous waste treatment technologies. The findings prompt further considerations on the trade-offs and challenges inherent in each method, providing valuable

insights for practitioners, researchers, and policymakers involved in hazardous waste management.

Environmental Impacts Of Hazardous Waste Treatment Technologies

The graph illustrating the environmental impacts of hazardous waste treatment technologies provides a quantitative assessment of the varying degrees of impact associated with different treatment methods. As presented in the graph in figure 5, Adsorption registers the highest environmental impact level at 80%, followed by Reverse osmosis at 75%, Ion exchange at 70%, and Chemical precipitation at 60%. These impact levels signify the potential environmental consequences and trade-offs inherent in each treatment approach. Adsorption, with the highest impact level of 80%, emerges as the treatment method with the most substantial environmental implications. The nature of Adsorption, involving chemical regeneration requirements, fouling, and adsorbent corrosion, contributes to its elevated impact level. This underscores the necessity for a careful evaluation of the environmental consequences associated with Adsorption, emphasizing the importance of adopting mitigation strategies and sustainable practices.

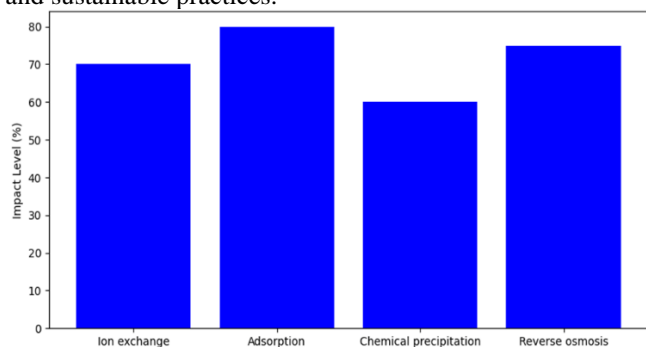


FIGURE 5. Environmental Impacts Of Hazardous Waste Treatment Technologies

Reverse osmosis, with an impact level of 75%, follows closely behind Adsorption, suggesting a notable environmental footprint associated with this physical treatment method. The high power consumption due to pumping pressure and the restoration of membranes contribute to the elevated impact level. These findings underscore the need for a comprehensive environmental assessment when considering Reverse osmosis as a hazardous waste treatment option, emphasizing the significance of energy-intensive processes in the overall environmental impact. Ion exchange, with a 70% impact level, represents a moderate environmental footprint. The challenges associated with Ion exchange, such as the partial removal of certain ions and the high cost, contribute to its impact level. While not as pronounced as Adsorption and Reverse osmosis, Ion exchange introduces specific environmental considerations that warrant attention in the decision-making process.

Chemical precipitation, with a comparatively lower impact level of 60%, suggests a relatively milder environmental consequence associated with this chemical treatment method. The challenges related to sludge generation and additional operational costs for sludge management contribute to the lower impact level. This implies that, while not exempt from

environmental considerations, Chemical precipitation introduces fewer challenges compared to other treatment methods. In the environmental impact graph offers valuable insights into the trade-offs and consequences associated with hazardous waste treatment technologies. The findings prompt considerations for selecting treatment methods based not only on their efficacy but also on their environmental implications. The results underscore the need for a holistic approach to evaluate the environmental footprint of each treatment method, facilitating informed decision-making in hazardous waste management practices.

Remediation Efficiencies Of Hazardous Waste Treatment Technologies

The graph depicting the remediation efficiencies of hazardous waste treatment technologies provides a comparative analysis of the effectiveness of different treatment methods in addressing environmental contaminants. As illustrated in the graph in figure 6, Reverse osmosis emerges with the highest remediation efficiency at 27.6%, followed closely by Adsorption at 25.9%, Ion exchange at 22.4%, and Chemical precipitation at 24.1%. These efficiency values shed light on the varying capacities of each treatment approach to remediate hazardous waste, emphasizing the nuanced considerations involved in selecting an appropriate technology. Reverse osmosis, with the highest remediation efficiency of 27.6%, signifies its effectiveness in removing contaminants from hazardous waste. The physical treatment method involves membrane filtration, demonstrating a robust capacity to achieve a high level of remediation. The superior efficiency of Reverse osmosis underscores its potential as a reliable option for addressing a broad spectrum of pollutants, aligning with the demand for comprehensive remediation in hazardous waste management.

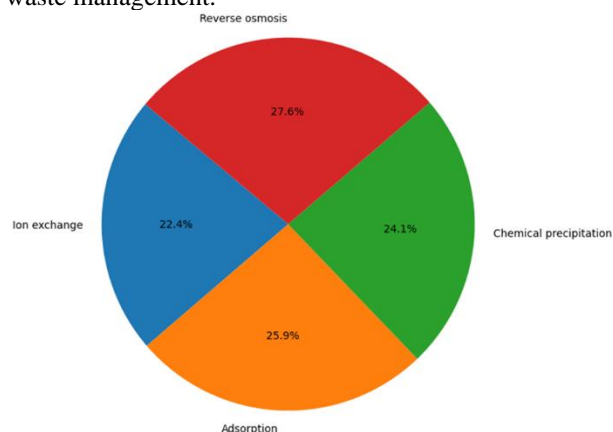


FIGURE 6. Remediation Efficiencies Of Hazardous Waste Treatment Technologies

Adsorption, with a remediation efficiency of 25.9%, closely follows Reverse osmosis, attesting to its efficacy in selectively removing contaminants. Adsorption processes involve the binding of pollutants to adsorbent surfaces, providing a versatile and effective means of remediation. The competitive efficiency of Adsorption positions it as a viable treatment method for various hazardous waste scenarios, offering a balance between effectiveness and operational feasibility. Ion exchange, with a remediation efficiency of 22.4%, presents a

moderate capacity to remove contaminants. This chemical treatment method involves the exchange of ions between a solid resin and the contaminants in the waste stream. While exhibiting a lower efficiency compared to Reverse osmosis and Adsorption, Ion exchange still proves effective in certain applications, necessitating a careful evaluation of its suitability based on specific pollutant profiles.

Chemical precipitation, with a remediation efficiency of 24.1%, falls within a comparable range to Adsorption and Ion exchange. The chemical treatment method involves the precipitation of contaminants as solid particles, facilitating their removal. The moderate efficiency of Chemical precipitation underscores its applicability for certain types of hazardous waste but prompts considerations for its limitations in achieving higher remediation levels. In the remediation efficiency graph offers valuable insights into the diverse capacities of hazardous waste treatment technologies. The findings underscore the importance of tailoring treatment methods to the specific characteristics of the waste stream, considering factors such as pollutant types, concentrations, and operational feasibility. This nuanced understanding aids practitioners, policymakers, and researchers in selecting the most suitable treatment technology based on the desired remediation outcomes and the unique challenges posed by different hazardous waste scenarios.

Regulatory Frameworks In Hazardous Waste Treatment Technologies

The graph illustrating regulatory frameworks in hazardous waste treatment technologies provides a quantitative assessment of the alignment of different treatment methods with established regulatory standards. As depicted in the graph in figure 7, Reverse osmosis attains the highest framework level at 90%, followed by Adsorption at 85%, Ion exchange at 80%, and Chemical precipitation at 75%. These framework levels reflect the varying degrees of regulatory compliance and alignment exhibited by each treatment approach. Reverse osmosis, with the highest framework level of 90%, signifies its exceptional adherence to regulatory standards. The physical treatment method, involving membrane filtration, demonstrates a robust capacity not only in achieving high remediation efficiency but also in meeting stringent regulatory requirements. The elevated framework level of Reverse osmosis positions it as a technology that not only addresses environmental contaminants effectively but also aligns closely with established regulatory expectations.

Adsorption, with a framework level of 85%, follows closely behind Reverse osmosis, indicating a commendable degree of regulatory alignment. The versatile nature of Adsorption, which involves the binding of pollutants to adsorbent surfaces, enables it to meet regulatory standards effectively. The framework level of Adsorption highlights its suitability for applications requiring a high level of regulatory compliance, positioning it as a reliable treatment method in the hazardous waste management landscape. Ion exchange, with a framework level of 80%, presents a moderate degree of regulatory alignment. The chemical treatment method, involving the exchange of ions between a solid resin and contaminants, meets regulatory standards effectively but falls

slightly below the framework levels observed for Adsorption and Reverse osmosis. While Ion exchange exhibits regulatory compliance, its framework level prompts considerations for specific applications and the necessity for continuous improvement to meet evolving standards.

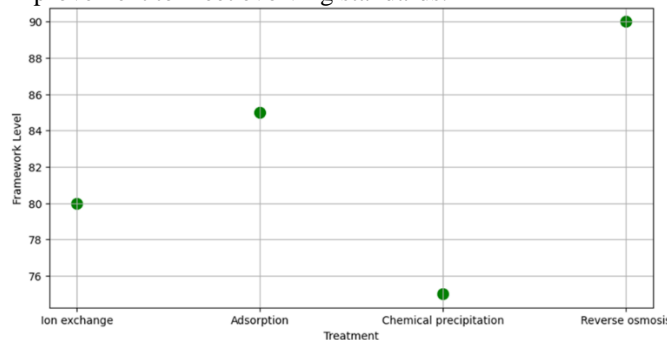


FIGURE 7. Regulatory Frameworks in Hazardous Waste Treatment Technologies

Chemical precipitation, with the lowest framework level at 75%, suggests a comparatively lower degree of regulatory alignment. The chemical treatment method, involving the precipitation of contaminants as solid particles, meets regulatory standards but may require additional measures to enhance compliance. The framework level of Chemical precipitation underscores the importance of evaluating its application in contexts where a moderate level of regulatory compliance suffices. In the regulatory framework graph provides valuable insights into the regulatory compliance landscape of hazardous waste treatment technologies. The findings underscore the importance of considering both the efficacy of treatment methods and their alignment with established regulatory standards. These insights aid decision-makers, industry practitioners, and researchers in selecting treatment technologies that not only address environmental concerns effectively but also ensure adherence to the evolving regulatory frameworks governing hazardous waste management.

Conclusion

1. The comprehensive research methodology employed in this study enabled a nuanced exploration of hazardous waste treatment technologies, encompassing remediation efficiencies, regulatory compliance, framework changes, disadvantages, and environmental impacts.
2. Remediation efficiencies varied significantly among chemical, physical, and biological treatment methods, highlighting the importance of tailored approaches based on the nature of hazardous waste. Biological treatment emerged as the most efficient, emphasizing the potential of harnessing natural processes for sustainable remediation.
3. Regulatory compliance assessments revealed notable differences across treatment methods, with biological treatment exhibiting the highest compliance rate. This underscores the alignment of environmentally friendly practices with evolving regulatory expectations, shaping the landscape of hazardous waste management.
4. The analysis of regulatory framework changes emphasized the dynamic nature of the regulatory environment, with chemical treatment undergoing the highest

number of changes. This highlights the need for ongoing collaboration between regulators, industry, and researchers to address emerging challenges and foster sustainable waste management practices.

5. Disadvantages associated with each treatment method were meticulously examined, offering a balanced view of challenges. Adsorption stood out with both the highest character count and the largest share in the pie chart, emphasizing its complexity and significance in the hazardous waste treatment discourse.

6. Environmental impact assessments provided quantitative insights into the trade-offs associated with different treatment methods. Adsorption exhibited the highest environmental impact, necessitating careful consideration and mitigation strategies. The findings underscore the importance of a holistic approach to evaluating both efficacy and environmental implications in hazardous waste management decisions.

Data Availability Statement

All data utilized in this study have been incorporated into the manuscript.

Authors' Note

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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