

Review

Lean Management Framework in Healthcare: Insights and Achievements on Hazardous Medical Waste

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Abstract: Hazardous medical waste (HMW) presents significant environmental and public health challenges, particularly in the context of rising healthcare demands and the global push for sustainable resource management. This study investigates the evolution of HMW management through a bibliometric and thematic analysis of 1703 articles published between 2020 and 2025, retrieved from the Web of Science database. Using VOSviewer, co-occurrence mapping and term clustering reveal six major conceptual domains, including thermal treatment technologies, operational optimization, environmental indicators, and behavioral dimensions. This study adds value by applying a dual bibliometric–thematic lens to provide new insights into the operational, technological, and sustainability dimensions of HMW. The analysis identifies a gradual shift from traditional disposal methods to circular models focused on resource valorization through pyrolysis, gasification, and sterilization. Lean management principles—such as process efficiency, waste minimization, and the promotion of recovery and reuse—emerge as complementary to circular economy goals. Additional visualizations outline international collaboration trends, highlighting established research hubs and emerging contributors. The findings emphasize the role of data-driven decision tools, sustainability assessment methods, and cross-sectoral integration in enhancing medical waste systems.

Keywords: hazardous medical waste; circular economy; lean healthcare; healthcare innovation



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1. Introduction

Environmental protection and public health have become increasingly pressing global priorities, particularly considering the growing volumes of HMW and the consequences of its inadequate management, which present significant threats to both ecosystems and human health [1,2].

According to World Health Organization (WHO), around 85% of the waste produced by healthcare activities is non-hazardous and comparable to domestic household waste.

The remaining 15%, however, falls into the hazardous category, potentially infectious, chemical, or even radioactive, requiring special attention and careful management [1]. On this matter, the United Nations Environment Programme (UNEP), in its “Global Waste Management Outlook 2024” [2], highlights a pressing concern, emphasizing that HMW is becoming an increasingly prominent component of the global waste challenge—one that demands urgent and sustained attention.

In response, the circular economy (CE) has emerged as a guiding framework for integrated resource and waste management, including HMW, aiming to reduce pollution and foster sustainability through systemic transformation. This transition requires rethinking supply chains, redesigning products, and implementing circular economy strategies to reduce critical raw material dependence and enhance sustainability [3]. Within this framework, the proper management of medical waste emerges as a crucial pillar of both environmental protection and resource efficiency [4].

HMW is considered the second most hazardous type of waste globally, following radioactive waste, due to its harmful composition and potential impacts on human well-being and the environment [5]. The treatment of such waste necessitates the use of advanced technologies capable of transforming it into valuable outputs such as biogas (methane and CO₂) [6], syngas (H₂ and CO), liquid biofuels, or even pure hydrogen. Among the advanced technologies available, plasma gasification stands out for its ability to convert HMW into syngas—a mixture primarily of hydrogen and carbon monoxide—while significantly minimizing toxic emissions and landfill dependency [7].

Implementing an effective HMW management system requires strict adherence to the waste hierarchy, prioritizing prevention, reuse, recycling, and recovery before final disposal, in line with recent EU policy developments [8]. According to the EU framework on Best Available Techniques, economic operators are mandated to minimize environmental impacts and improve industrial efficiency [9]. These techniques provide guidelines for reducing emissions and enhancing resource-use efficiency in various industrial sectors. Furthermore, the revised Industrial Emissions Directive, adopted in 2024 [10], strengthens the mandate for economic operators to implement Best Available Techniques across various sectors, including waste management, to minimize environmental impacts and enhance resource efficiency.

This study examines the technological advancements developed between 2020 and 2025 in the field of HMW treatment, assessing their environmental performance and alignment with CE principles. The analysis considers waste typologies—those requiring incineration versus those eligible for recycling—based on their composition and hazard level. Special attention is given to green technologies that enable waste valorization, highlighting their potential to reduce the volume and risk profile of hazardous materials and contribute to European sustainability targets.

In parallel with these developments, lean management has gained increasing attention as a complementary framework for improving the efficiency of healthcare and waste systems. Lean is fundamentally grounded in the principle of waste reduction, targeting all forms of inefficiency, whether material, energetic, temporal, or informational. Core lean principles—such as process flow improvement, value stream enhancement, and the continuous pursuit of value creation—are now being adapted to medical waste contexts, where operational gaps frequently translate into both environmental and safety risks. The convergence between lean thinking and CE objectives opens up new pathways for systemic innovation in hazardous waste management.

Building on this convergence, the present study combines bibliometric and thematic analyses to explore how recent scientific research addresses HMW through the lenses of circularity, technological innovation, and operational optimization. Through this research,

we aim to provide an integrated picture of the evolution of scientific research on HMW, bringing to the forefront the synergy between technological innovation and operational sustainability paradigms.

Despite the growing body of literature on HMW, most existing reviews either focus narrowly on single technologies or lack integrative approaches combining environmental and operational perspectives. Few studies have examined the convergence of lean management and the circular economy in this context, especially through data-driven bibliometric methods. This study fills that gap by identifying thematic clusters—such as thermal valorization via pyrolysis and gasification—and analyzing how these contribute to both resource recovery and lean workflows by reducing process inefficiencies, treatment time, and waste volume.

2. Literature Review on HMW Management

2.1. *Technological Advances in HMW Treatment*

The management of HMW continues to present significant environmental and public health challenges, prompting a sustained research effort to develop advanced technologies and policy frameworks that align with CE principles. As global healthcare systems generate increasing quantities of medical waste [11,12], especially in the aftermath of global health crises, the pressure to transition from linear disposal models to more sustainable and integrated systems has intensified. Within this context, the recent literature has increasingly focused on how innovation in treatment technologies, regulatory compliance, environmental assessment, and resource valorization can be harmonized under the CE paradigm.

The incorporation of sustainability assessments such as life cycle assessment (LCA) has further strengthened the scientific basis for selecting and validating treatment technologies. As a decision-making tool, LCA facilitates the comparison of environmental burdens across the entire life cycle of disposal options—from collection to treatment and final disposal—helping identify the most efficient and least harmful alternatives [13].

Concrete examples from Romania illustrate the practical application of these principles. For instance, Stericycle Romania has implemented high-temperature sterilization units that utilize hot air to disinfect medical waste while simultaneously reducing its volume [14]. These installations demonstrate the feasibility of minimizing water and energy use through internal heat recirculation mechanisms. Similarly, the Oradea sterilization station uses pressurized steam to decontaminate various medical waste categories while optimizing resource efficiency [15]. These cases underscore the potential of combining technological innovation with operational best practices to achieve CE goals at the local level.

In response to these policy shifts, significant progress has been made in the development and application of treatment technologies capable of aligning with CE objectives. Among these, high-temperature processes such as pyrolysis and gasification have received particular attention for their dual capacity to neutralize hazardous components and generate energy or valuable secondary products. Pyrolysis, for example, has been demonstrated to break down medical plastics and organic matter into useful by-products such as syngas, pyrolytic oil, and char, which may be repurposed as fuels or additives [16]. Similarly, gasification enables the conversion of carbon-rich medical waste into a combustible gas mixture, offering a cleaner energy pathway with lower emissions compared to conventional incineration.

Alongside these thermal methods, anaerobic digestion has emerged as a biological alternative. The integration of anaerobic digestion with thermal or sterilization methods can provide a complementary route to manage complex waste streams, further enhancing system resilience [17].

2.2. Operational Optimization and Lean Principles

Although lean management was originally developed for industrial optimization, its core tenet—the reduction in all non-value-adding activities—has proven highly relevant for HMW systems. In this context, waste reduction is not only a sustainability target but also a performance strategy, enabling healthcare organizations to eliminate inefficiencies in logistics, storage, treatment, and resource use. This principle functions as a conceptual connector between environmental responsibility and operational discipline, allowing lean tools to be reframed as instruments for circularity and waste valorization. Building on this perspective, the following literature review examines how recent research has addressed HMW through the combined lenses of environmental impact, technological advancement, and systemic optimization.

A common thread across recent contributions is the increasing interest in valorization strategies that enable recovered materials or energy to be reintegrated into production cycles. Such approaches aim not only to minimize waste output but also to reclassify medical waste as a resource stream, thereby advancing the circular transition in the healthcare sector.

Moreover, environmental auditing and comparative evaluations of existing treatment methods have become critical tools in the identification of improvement opportunities. Such evaluations enable institutions to identify inefficiencies at each treatment stage and adopt greener alternatives with lower ecological and financial costs. These audits also provide the empirical basis for life cycle-based policy recommendations and guide the adoption of flexible, context-appropriate technologies, especially in countries or regions with limited treatment infrastructure.

2.3. Behavioral Dimensions and Staff Engagement

The literature increasingly acknowledges that no single technology can address the multifaceted nature of HMW. Instead, hybrid treatment architectures that combine high-temperature, low-temperature, chemical, biological, and digital solutions are necessary to ensure a comprehensive coverage of diverse waste categories. Studies emphasize the importance of modularity, adaptability, and environmental compliance as design principles for future waste management systems [18].

A growing body of research also focuses on the behavioral and organizational aspects of waste management. Effective HMW systems rely not only on technology and policy but also on the awareness, training, and engagement of healthcare staff. Staff perception, compliance with guidelines, and intervention-based training programs play a significant role in the correct segregation, handling, and treatment of hazardous waste.

2.4. Policy, Regulation, and Sustainability Frameworks

One of the key directions in contemporary research is the reevaluation of the indicators used to assess the sustainability of hazardous waste treatment methods. As highlighted by Kumar et al. (2023) [18], aligning these methods with CE principles requires a shift toward strategies that emphasize environmental protection, waste prevention, and resource efficiency. In this context, sustainability assessments must capture not only the operational safety and efficiency of technologies but also their capacity to support reduction, reuse, and recycling.

Table 1 offers a comprehensive overview of recent contributions (2020–2025) addressing HMW management, reflecting the thematic richness and methodological diversity of the field. It synthesizes key innovations across a wide spectrum—from thermochemical processes such as pyrolysis, gasification, and sterilization to advanced modeling techniques, sustainability assessments, and digital integration. The studies illustrate a pronounced shift toward CE frameworks, with the emphasis on energy recovery, resource valorization, and eco-design principles. The inclusion of decision-support methods, artificial intelligence

applications, and blockchain technology further underscores the field’s growing alignment with data-driven and systems-based approaches. By mapping these contributions, the table anchors the bibliometric results in concrete research outputs, thereby bridging quantitative trends with qualitative insights.

Table 1. Key contributions to HMW management in the circular economy framework (2020–2025).

First Author	Year	Contributions	Reference
Abedeem et al.	2025	Alternative fuel recovery from syringe and bottle waste using pyrolysis in a fixed-bed reactor.	[19]
Pillai et al.	2025	Neutrosophic decision method applied to improve biomedical waste disposal under uncertainty.	[20]
Ebrahimzadehsarvestani et al.	2025	Highlights gaps in medical waste research; proposes tech, policy, and awareness strategies.	[21]
Dsouza et al.	2025	Promotes integrated sterilization, pyrolysis, composting, and digital waste platforms.	[22]
Soyler et al.	2024	Co-word analysis shows rising trends in pyrolysis and circular technologies in waste studies.	[23]
Fang et al.	2024	Ash from incinerated medical waste used to degrade antibiotics through activation of peroxydisulfate.	[24]
Bułkowska et al.	2024	Co-word analysis shows rising trends in pyrolysis and circular economy in waste studies.	[25]
Kharmawphlang et al.	2024	Links waste to energy tech to waste traits and country income; essential amid urbanization.	[26]
Zhou et al.	2024	Proposes a combined process of plasma gasification and Fischer–Tropsch synthesis to convert medical waste and biomass waste into synthetic fuels.	[27]
Shen et al.	2024	Optimizes medical waste transport using advanced route and location algorithms.	[28]
Suthagar et al.	2024	Proposes circular waste system with drone deliveries and reverse logistics.	[29]
Kumari et al.	2024	Recycles medical plastic into carbon dots for sustainable fluorescent markers.	[30]
Hu et al.	2024	Applies pyrolysis and gasification to treat infectious HMW.	[31]
Ji et al.	2024	Evaluates waste technologies for urban-scale sustainable healthcare solutions.	[32]
Liu et al.	2024	Improves waste crushing through parameter optimization in processing.	[33]
Bhandari et al.	2023	Reviews modern sterilization methods like plasma and ozone for hospitals.	[34]
Balaji et al.	2023	Uses sodium-ion supercapacitors made from recycled medical waste for sustainable energy.	[35]
Mehmood et al.	2023	Presents microbial treatment of pharmaceutical waste as a cost-effective, eco-friendly option.	[36]
Dri et al.	2023	Highlights advanced recycling like pyrolysis and bioremediation to recover hard-to-recycle waste.	[37]
Baralla et al.	2023	Introduces blockchain to improve traceability and efficiency in waste management systems.	[38]
Chandra et al.	2023	Discusses low-cost biological methods for degrading hazardous healthcare waste.	[39]
Matalkah et al.	2023	Transforms HMW ash into concrete additives to enhance durability and reduce waste impact.	[40]
Li et al.	2023	Explores plasma gasification for converting medical waste into hydrogen and methanol fuels.	[41]
Zhao et al.	2023	Combines biogas and waste valorization for zero-emission hydrogen fuel production.	[42]

Table 1. Cont.

First Author	Year	Contributions	Reference
Keleş et al.	2023	Analyzes polymer-based HMW for energy recovery through thermal treatment methods.	[43]
Alaedini et al.	2023	Analyzes waste gasification and catalyst design for hydrogen fuel and fuel cell use.	[44]
Andooz et al.	2023	Reviews pyrolysis for resource recovery; notes cost and tech barriers to implementation.	[45]
Bolan et al.	2023	Details environmental risks of toxic elements from incinerated medical waste.	[46]
Çelik et al.	2023	Applies fuzzy multi-criteria evaluation to improve hospital waste management.	[47]
Chu et al.	2023	Calls for policy support to scale green waste technologies despite high costs.	[48]
Długosz-Lisiecka et al.	2023	Assesses radioactive waste in radiotherapy using beam energy modeling.	[49]
Dong, et al.	2023	Evaluates heat recovery + gasification system for energy-efficient waste treatment.	[50]
El-Saadony et al.	2023	Warns of leachate risks; supports pyrolysis, gasification, and detox methods.	[51]
Kaur et al.	2023	Studies bacterial effects on strength and toxicity of ash-based concrete.	[52]
Krishna et al.	2023	Stresses education and infrastructure gaps in managing HMW in developing regions.	[53]
Kumar Mishra et al.	2023	Explores biochar from HMW as an eco-solution for soil and carbon capture.	[54]
Kumar et al.	2023	Highlights emission control tech for incinerated waste ash.	[55]
Lv et al.	2023	Proposes an integrated system that combines plasma gasification of medical waste, solid oxide fuel cells, supercritical carbon dioxide cycles, and desalination technologies.	[56]
Manjunath et al.	2023	Explores use of incinerated ash in concrete to improve durability and reduce waste.	[57]
Peng et al.	2023	Analyzes emission control and dioxin migration in medical waste incineration.	[58]
Qin et al.	2023	Studies technical feasibility of gasifying medical waste with converter gas.	[59]
Ramalingam et al.	2023	Uses thermal cracking to produce biofuels from plastic medical waste generated by personal protective equipment such as masks and gloves.	[60]
Sančanin et al.	2023	Recommends improved HMW storage to prevent risks from hazardous substances.	[61]
Sapkota et al.	2023	Compares disposal methods; promotes circular solutions like chemical recycling.	[62]
Tan et al.	2023	Evaluates catalytic pyrolysis of medical plastic waste for fuel and chemical recovery.	[63]
Tang et al.	2023	Applies pyrolysis and ash stabilization for sustainable plastic HMW management.	[64]
Thakur et al.	2023	Combines chemical and oxidation methods to treat toxic medical waste in low-resource settings.	[65]
Wang et al.	2023	Proposes biodegradable masks and stricter disposal regulations to address plastic pollution.	[66]
Wu et al.	2023	Compares remediation methods for endocrine-disrupting compounds; calls for regulation and monitoring.	[67]
Sepetis et al.	2022	Stresses public policy, green tech, and stakeholder collaboration for medical waste management.	[68]
Quan et al.	2022	Promotes gasification and combustion integration to support the circular economy and renewable energy.	[69]

Table 1. *Cont.*

First Author	Year	Contributions	Reference
Pokson et al.	2022	Evaluates energy efficiency of combined heat–power systems fueled by infectious medical waste.	[70]
Bharti et al.	2022	Reviews advanced sterilization like Ultraviolet-C radiation and ozone for safer medical waste disinfection.	[71]
Wawale et al.	2022	Recommends real-time tracking using sensors and fuzzy classification to manage hazardous waste.	[72]
Lemma et al.	2022	Highlights risks of poor infectious waste handling; urges standard procedures and staff training.	[73]
Govindan et al.	2022	Advocates for reverse logistics to recover and reuse protective equipment and syringes.	[74]
Erdem	2022	Proposes a logistics model to manage increased medical waste during pandemics sustainably.	[75]
Zhao et al.	2022	Supports rapid destruction and recycling technologies for emergency HMW management.	[76]
Zhao et al.	2021	Compares disposal technologies by efficiency, emissions, and costs; supports balanced solutions.	[77]
Giakoumakis et al.	2021	Reviews incineration, pyrolysis, gasification, and fermentation for valorizing HMW.	[78]
Su et al.	2021	Recommends integrated waste treatment adapted to local needs for effective management.	[79]
Soldatos et al.	2021	Highlights digital tools like Internet of Things (IoT) and blockchain for traceability and resource monitoring.	[80]
Patel et al.	2020	Describes pyrolysis as a cleaner method to convert HMW into fuel and reduce fossil use.	[81]
Alam et al.	2020	Assesses incineration vs. landfill in Chittagong using life cycle analysis for impact comparison.	[82]

Table 1 provides a structured synthesis of the most relevant contributions between 2020 and 2025 regarding HMW management under the CE paradigm. The entries in the table reveal five dominant thematic directions that reflect the evolution of the field across technological, environmental, operational, and systemic dimensions.

First, a significant body of studies focus on thermal valorization methods—notably pyrolysis and gasification—as core strategies for reducing the volume and hazardousness of medical waste while recovering energy or secondary products. Research by Abedeen et al. (2025) [19], Hu et al. (2024) [31], and Tan et al. (2023) [63] exemplifies laboratory and pilot-scale assessments of pyrolytic oil properties, calorific efficiency, and gas composition, supporting the potential of waste-to-fuel pathways. Similarly, Zhou et al. (2024) [27] and Li et al. (2023) [41] explore co-valorization and plasma gasification, often coupled with hydrogen production or Fischer–Tropsch synthesis, as part of decarbonization efforts.

Second, a growing cluster of contributions addresses resource recovery and material reuse, especially the transformation of medical plastic waste and ash into value-added products. For example, Kumari et al. (2024) [30] propose the creation of carbon dots from recycled plastics, while Matalkah et al. (2023) [40] and Kaur et al. (2023) [52] investigate the incorporation of incinerated ash into concrete mixtures, enhancing material circularity and reducing environmental impact.

A third set of studies investigate non-thermal and hybrid treatment technologies, such as advanced sterilization (e.g., gamma irradiation, pressurized steam), composting, anaerobic digestion, and biological methods including bioremediation. Dsouza et al. (2025) [22] present these techniques as alternatives or complements to incineration, especially for infectious and biodegradable waste, while Chandra et al. (2023) [39] and Mehmood et al. (2023) [36] highlight the role of microorganisms in treating pharmaceutical residues.

Fourth, the literature includes contributions focused on system design, logistics, and digital integration. Shen et al. (2024) [28] and Suthagar et al. (2024) [29] develop models for optimizing waste transport and routing using heuristic algorithms and AI (artificial intelligence), while Baralla et al. (2023) [38] and Wawale et al. (2022) [72] explore the application of blockchain and IoT technologies for real-time tracking, traceability, and transparency in waste management chains. These works suggest a strong movement toward smart, data-driven systems.

Fifth, several authors emphasize policy frameworks, stakeholder behavior, and sustainability evaluation, particularly in low- and middle-income countries. Studies such as Krishna et al. (2023) [53] and Lemma et al. (2022) [73] highlight infrastructural and educational gaps.

Collectively, these contributions indicate a shift from mono-technology disposal toward integrated waste management architectures that combine valorization, monitoring, and sustainability assessment. While high-income countries lead in technology-intensive solutions, many studies call for adaptable frameworks suitable for diverse regional contexts. This multi-dimensional evidence base sets the stage for the bibliometric mapping in the next section, which visualizes how these themes coalesce in academic discourse.

Building on the insights synthesized in Table 1, the following section presents a complementary data-driven investigation of the field. A bibliometric and thematic analysis was conducted using VOSviewer version 1.6.20, focusing on 1703 records retrieved from the Web of Science database. Through co-occurrence maps, temporal overlays, and keyword clustering, the analysis reveals the structural and conceptual dynamics of the literature, identifies major research themes, and highlights emerging directions within HMW research.

The following section outlines the methodological framework used to systematically map and analyze research trends in HMW, combining bibliometric and thematic approaches.

3. Materials and Methods

This study employed a systematic review methodology to identify, screen, and analyze the recent scientific literature focused on medical and healthcare waste management. The search was conducted using the Web of Science Core Collection database.

The search strategy was conducted using the following Boolean query terms: “medical waste” OR “healthcare waste”. The full selection process is detailed in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram (Figure 1).

Search filters were applied to include only articles and reviews published in English between 1 January 2020 and 5 April 2025. The full search was performed on 5 April 2025. Inclusion criteria consisted of publications focusing on waste in healthcare systems, while exclusion criteria eliminated articles unrelated to healthcare waste (e.g., electronic, industrial, or animal waste) and non-English texts.

Bibliometric visualizations were conducted in VOSviewer version 1.6.20. For keyword co-occurrence analysis, a minimum node occurrence threshold of 10 was set. The clustering algorithm used was the linear-logarithmic modularity optimization, with the normalization method set to association strength. Fractional counting was applied for all co-authorship and keyword network analyses to ensure a proportional representation of multilateral collaborations and term prominence. Co-authorship maps used a minimum of 5 publications per country. Overlay and density visualizations were generated using default color scaling adjusted for interpretability in the 2021–2024 window.

These settings ensured structural clarity, reproducibility, and thematic robustness across all bibliometric maps presented in Figures 2–6.

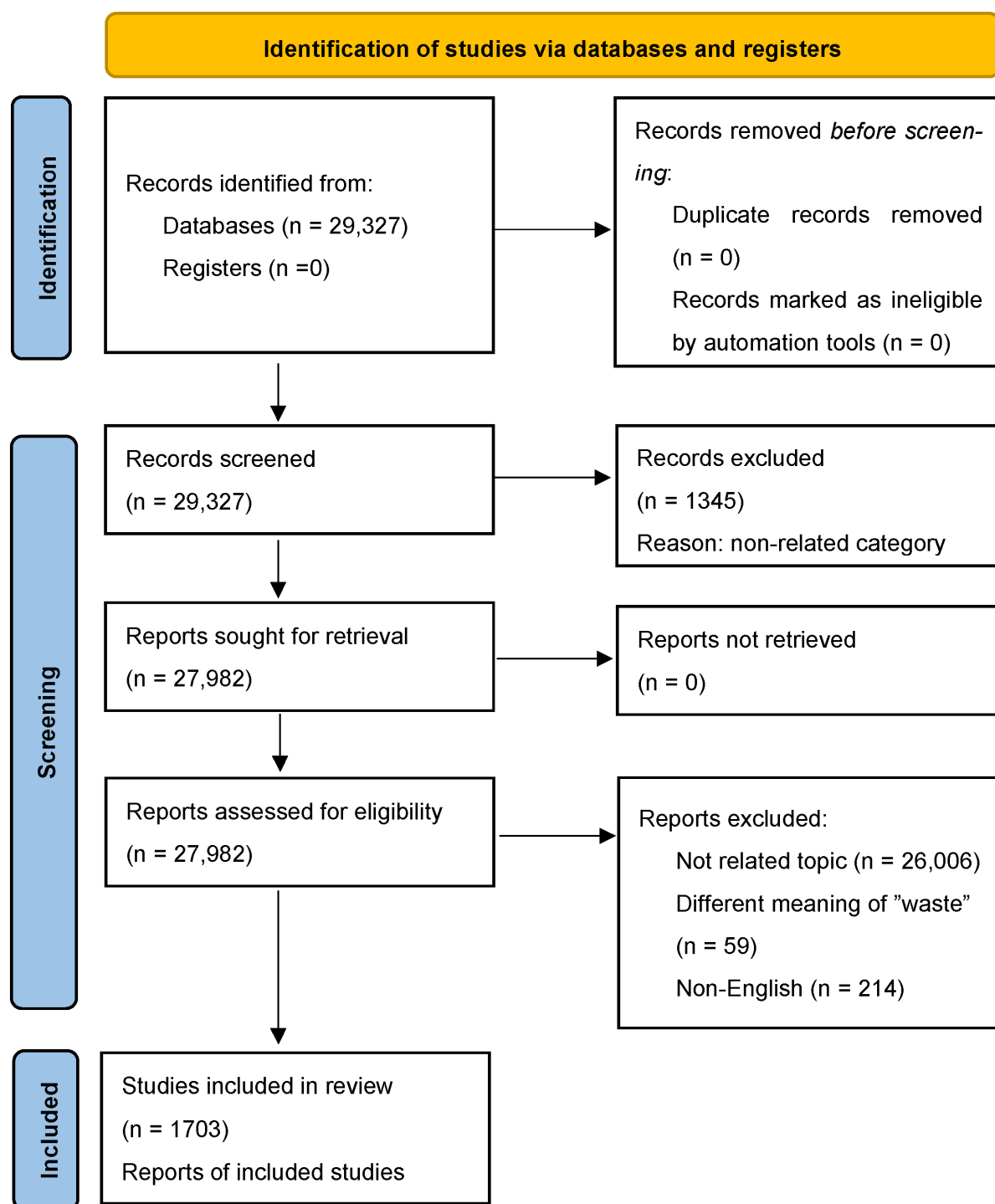


Figure 1. PRISMA flow diagram for the selection of articles in bibliometric analysis. Created by authors based on BMJ model [83].

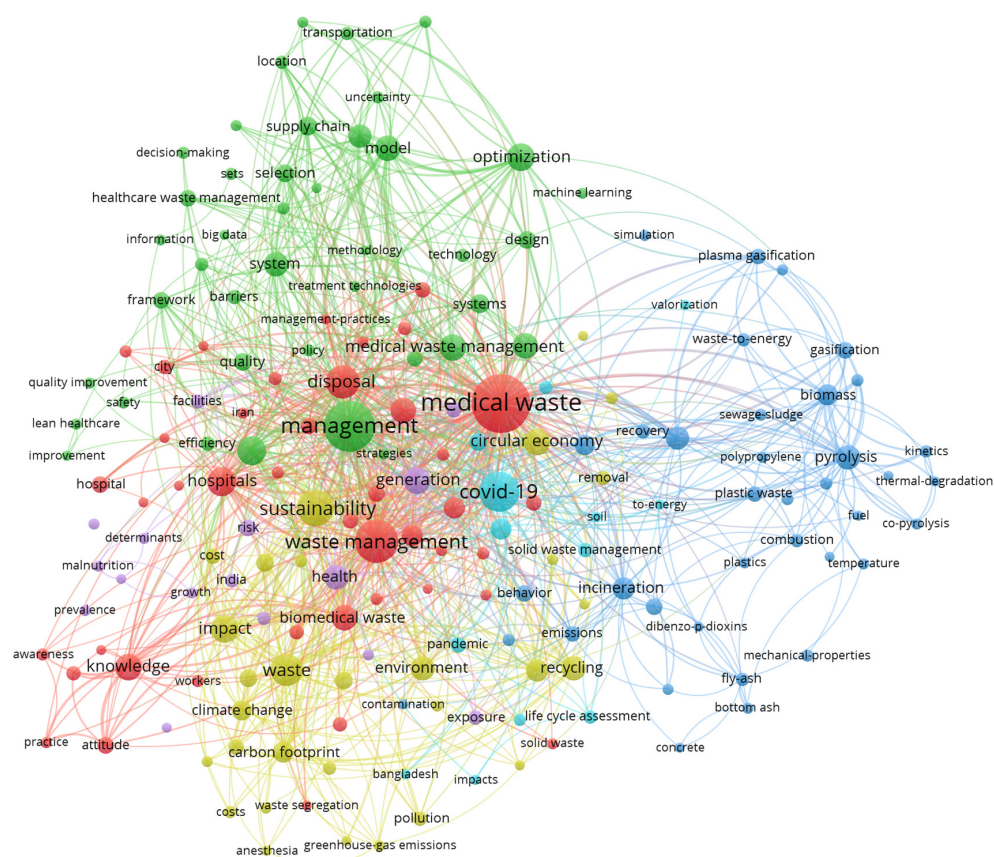


Figure 2. Co-occurrence map of keywords in HMW literature ($N = 1703$ records).

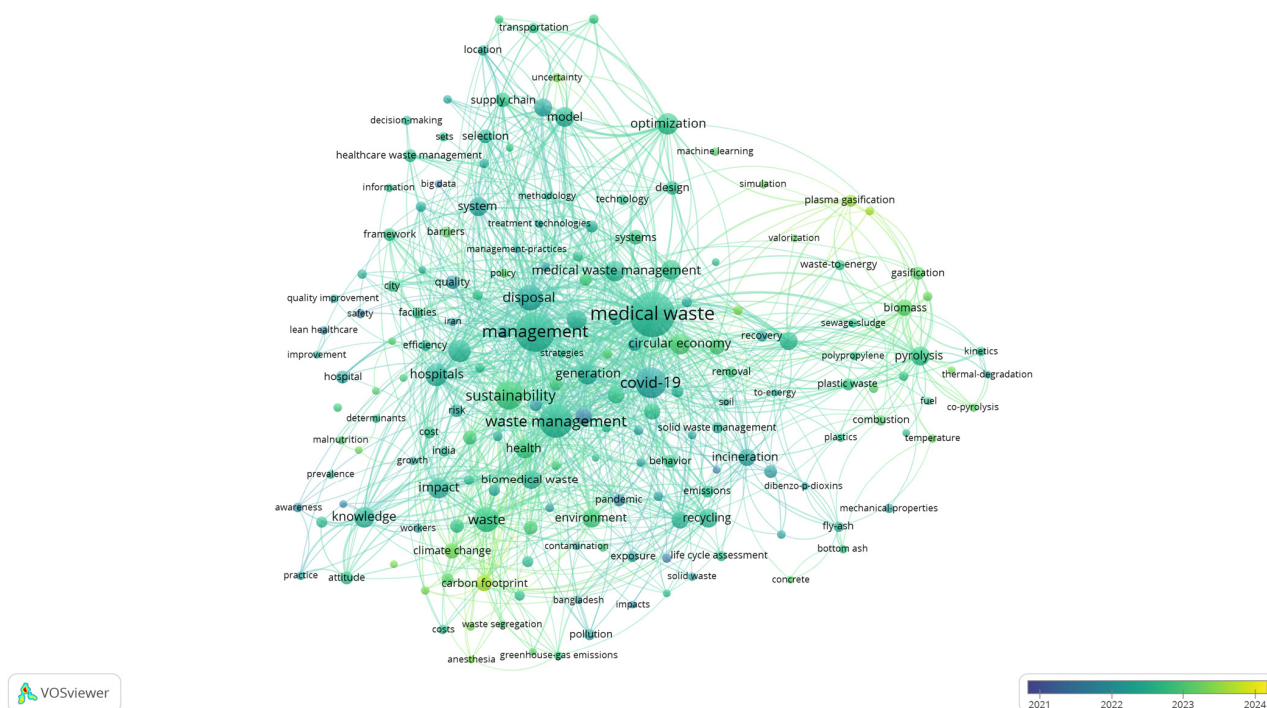


Figure 3. Temporal overlay visualization of keyword co-occurrence in HMW literature (2020–2025). Note: The color scale was adjusted to cover the interval of 2021–2024 to enhance the visual contrast between recent and earlier publications. A broader timespan would have resulted in uniform coloring, reducing interpretability.



Figure 4. Density visualization map of keyword co-occurrence in HMW literature.



Figure 5. International co-authorship network in HMW research. Note: The color scale was adjusted to cover the interval of 2021–2024 to enhance the visual contrast between recent and earlier publications. A broader timespan would have resulted in uniform coloring, reducing interpretability.

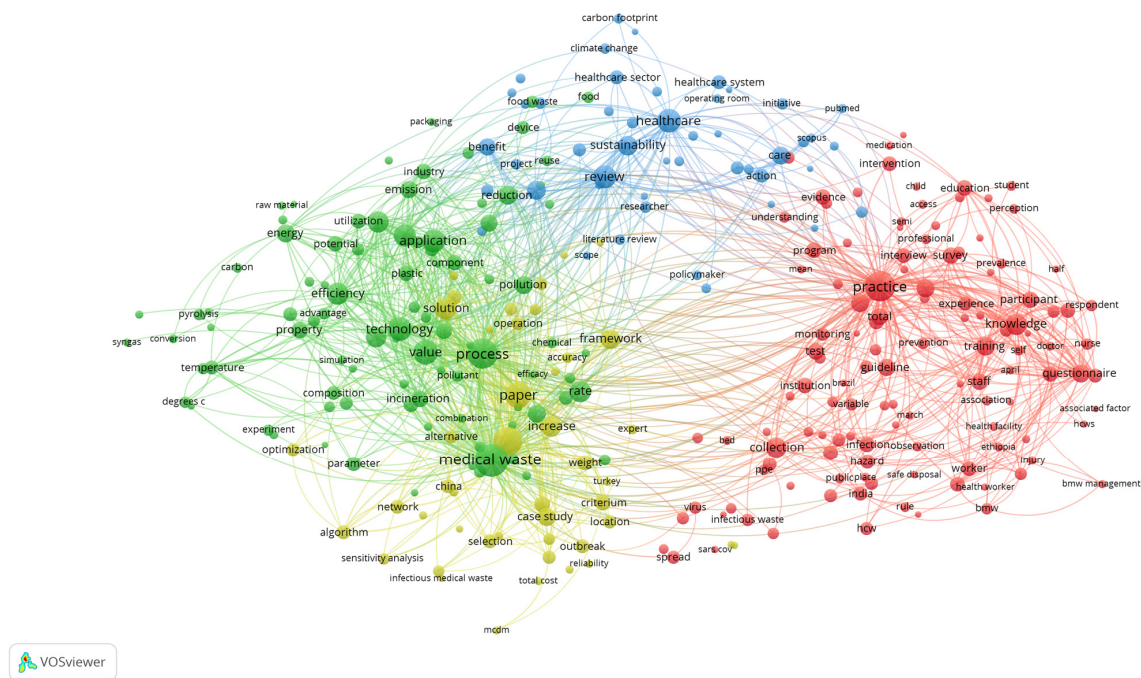


Figure 6. Thematic clustering of terms in titles and abstracts from medical waste literature.

A total of 29,327 records were initially identified through the database search. No additional records were retrieved from registers, and no duplicates were detected. After an initial screening based on titles and abstracts, 1345 records were excluded due to being assigned to unrelated categories (e.g., Zoology, Philosophy, Astronomy, Archaeology, International Relations, Food Science, Linguistics, and Mathematical Physics).

This left 27,982 articles for further eligibility assessment.

In the final stage of the screening process, each of the remaining 27,982 article titles was examined individually to assess its relevance. A total of 26,279 records were excluded based on three key criteria. First, most articles ($n = 26,006$) were unrelated to the healthcare or medical waste context, instead referring to agricultural, food, industrial, animal, or electronic waste. Second, a subset of 59 articles used the word “waste” in unrelated medical contexts (e.g., wasting disease, muscle wasting), thus falling outside the scope of this analysis. Third, 214 articles were published in languages other than English and were excluded to maintain linguistic consistency within the bibliometric review. As a result, a total of 1703 studies met the inclusion criteria and were retained for the final analysis.

The bibliometric analysis was carried out using VOSviewer, a widely used tool for the visual representation of bibliographic data. This software facilitated the development of co-occurrence maps, bibliographic coupling diagrams, and keyword co-network visualizations, allowing for the identification of dominant research themes, high-impact publications, and patterns of scholarly collaboration. Complementing this, a thematic analysis was applied to investigate recurring subjects, emerging directions, and gaps within the existing body of literature.

The resulting visualizations offer valuable insights into the structural and temporal dynamics of the research landscape. Specifically, the bibliometric maps expose clusters of thematically connected studies, while temporal overlays trace the evolution of research foci from foundational concepts to current areas of exploration.

By integrating quantitative precision with qualitative depth, this mixed-methods approach provides a comprehensive understanding of the academic discourse surrounding sustainable universities, delivering insights that are both analytically rigorous and practically relevant.

4. Results

The set of 1703 scientific records retrieved from the Web of Science database was used to create a co-occurrence map of keywords in the medical waste literature. The first analysis was performed to identify the primary conceptual clusters within the field of medical waste management (Figure 2). A total of 180 keywords met the occurrence threshold of 10 (meaning that the keywords that occurred a minimum 10 times were considered), forming a dense network of 4441 links and a total link strength of 10,317, suggesting a well-structured and highly interconnected research landscape.

The visualization revealed six major thematic clusters. The red cluster centered around medical waste, hospitals, healthcare waste, and disposal reflects the clinical and public health dimension of the topic. Closely associated terms such as COVID-19, challenges, and pandemic suggest an intensified research focus during the pandemic years, integrating issues of waste generation and infectious disease control.

The green cluster reflects the use of systems modeling and decision-making tools, with high-frequency keywords such as optimization, supply chain, technology, and methodology, underscoring the role of lean management in waste management solutions. This conceptual linkage suggests a growing emphasis on process efficiency, waste minimization, and performance measurement in medical waste operations—core aspects of lean thinking adapted to healthcare and environmental contexts.

The yellow cluster emphasizes themes like sustainability, recycling, climate change, and environment, indicating a growing body of literature addressing the ecological implications and long-term impacts of healthcare waste. The presence of terms like carbon footprint and greenhouse gas emissions at the periphery of this cluster suggests the emergence of cross-cutting environmental evaluations in recent publications.

From a technological and operational standpoint, the blue cluster includes specialized terms such as pyrolysis, gasification, biomass, and incineration, indicating a sustained focus on thermal and chemical treatment technologies.

The map also captures an overlay between red and yellow clusters, where terms like knowledge, attitude, practice, and awareness form a socio-behavioral sub-theme. These indicate a subset of research focusing on the human dimension of waste management, highlighting the importance of education, perception, and training, especially in healthcare settings.

Collectively, this mapping exercise provides a comprehensive overview of the knowledge structure in the domain, revealing both consolidated research areas and emerging directions. It also underscores the interdisciplinary nature of the topic, spanning environmental science, public health, engineering, and behavioral studies.

The overlay visualization (Figure 3) offers a temporal perspective on the development of research topics in the field of medical waste management between 2020 and 2025. The color gradient, ranging from blue (older topics) to yellow (more recent), highlights the dynamic evolution of conceptual emphases within the field.

Core terms such as medical waste, management, waste management, and sustainability appear in green–blue hues, indicating their consistent and foundational role throughout the analyzed period. Keywords associated with health system performance—such as hospitals, infection, awareness, and disposal—cluster around earlier years, reflecting the pandemic-induced intensification of research during 2020–2021.

In contrast, recent keywords—displayed in light green and yellow—include optimization, gasification, and carbon footprint, pointing to the emergence of efficiency-focused approaches and resource valorization models. The increased prominence of pyrolysis, biomass, and plastic waste suggests a growing interest in integrating thermochemical technologies and sustainability metrics into medical waste management.

Notably, terms such as lean healthcare, quality improvement, and efficiency, though still peripheral, indicate the beginning of a thematic convergence between waste treatment and lean management principles. This evolution implies a conceptual shift from static waste disposal models toward adaptive, resource-efficient, and systemic management frameworks.

Figure 4 presents the density visualization of keyword co-occurrence, offering a spatial representation of thematic intensity across the research landscape. High-density areas, shown in bright yellow, indicate core topics with frequent and highly connected appearances.

Medical waste, management, waste management, circular economy, and COVID-19 form the central nucleus of the map, reflecting the most widely studied and structurally integrated themes in the last 5 years.

Closely surrounding the core zone, concepts like sustainability, hospitals, health, and biomedical waste form secondary clusters with strong associative ties, underlining the public health dimension and the operational realities of medical institutions. These themes are essential pillars in the literature and form the interface between healthcare service delivery and environmental performance.

In contrast, the outer areas—shaded in green and blue—contain emerging or specialized topics such as pyrolysis, gasification, plastic waste, optimization, and life cycle assessment. Although less dense, these concepts are increasingly present in recent publications, as can be seen in the overlay visualization (Figure 3), and signal a gradual expansion of the research domain toward advanced technological solutions and performance evaluation frameworks.

Figure 5 displays the international co-authorship network for publications on medical waste in the last 5 years. A total of 71 countries met the minimum publication threshold (five documents per country), resulting in a network with 745 collaboration links and a total link strength of 1658. Countries are represented as nodes, whose size corresponds to the number of documents authored, while the link thickness indicates the frequency and strength of bilateral collaboration.

The most central and prolific contributors are China, India, and the USA, which also act as major hubs of international collaboration. Their strategic positioning and dense interconnections suggest a high research capacity and extensive involvement in multinational projects. These countries are often linked to others with developing or transitional healthcare systems, including Bangladesh, Pakistan, Indonesia, and Nigeria, highlighting the global dimension of medical waste issues and the need for knowledge transfer across regions.

European countries such as England, Germany, France, Romania, and the Netherlands form a moderately interconnected cluster, often acting as regional collaborators. Meanwhile, countries like South Korea, Iran, Saudi Arabia, and Australia exhibit strong ties across multiple continents, indicating their active participation in global research networks.

Several countries (Singapore, Czech Republic, Ethiopia, Ghana) appear at the periphery of the network, with fewer but potentially emerging contributions. Their presence suggests opportunities for increased integration into established research clusters, particularly in the context of global public health and sustainable development initiatives.

The average publication year overlay indicates that recent contributions (yellow) are increasingly coming from countries such as Thailand, Vietnam, Mexico, and Qatar, suggesting a diversification of interest and capacity in waste research beyond the traditional core of highly industrialized nations.

To further explore the conceptual underpinnings of medical waste research, a co-occurrence analysis of terms extracted from article titles and abstracts was conducted (Figure 6). This method allowed for the identification of recurrent expressions and their co-association patterns, resulting in a visually structured map comprising four major thematic clusters.

The green cluster highlights the technical and performance-oriented dimension of the field, with central terms including process, value, process, and technology. This cluster reflects a clear operational focus, where engineering and systems thinking intersect with resource management. The presence of terms such as value, application, and performance suggests an emerging lean-inspired vocabulary aimed at improving workflows and minimizing inefficiencies in waste treatment systems.

The red cluster captures the socio-educational and behavioral perspective, represented by terms such as practice, knowledge, participant, training, and intervention. These keywords reflect empirical and often survey-based approaches that investigate awareness, compliance, and staff engagement in waste handling, especially within clinical and community contexts. This theme is particularly significant for integrating human factors into sustainable waste strategies.

The blue cluster encompasses broader systemic and policy-driven aspects, with a focus on sustainability, climate change, carbon footprint, and the healthcare system. This group reflects growing attention to environmental impacts and the alignment of medical waste practices with CE principles and global sustainability agendas.

A fourth, yellow cluster, smaller in scale but methodologically dense, consists of terms such as algorithm, network, sensitivity analysis, and framework. This group signifies a shift toward computational modeling, data analysis, and decision-support tools, pointing to future directions in smart waste system design.

Together, these clusters offer a multi-layered view of the research landscape, where the convergence of technological, behavioral, and environmental themes suggests a fertile ground for the integration of lean management philosophies. By connecting process efficiency, system modeling, and sustainability, the literature increasingly supports a transition from reactive waste handling toward proactive, streamlined, and data-informed waste management systems.

To further explore the temporal dynamics of research themes in the medical waste literature, an overlay visualization was generated based on the co-occurrence of terms from titles and abstracts (Figure 7). This analysis provides insight into the chronological development of conceptual clusters and the emergence of new thematic directions.

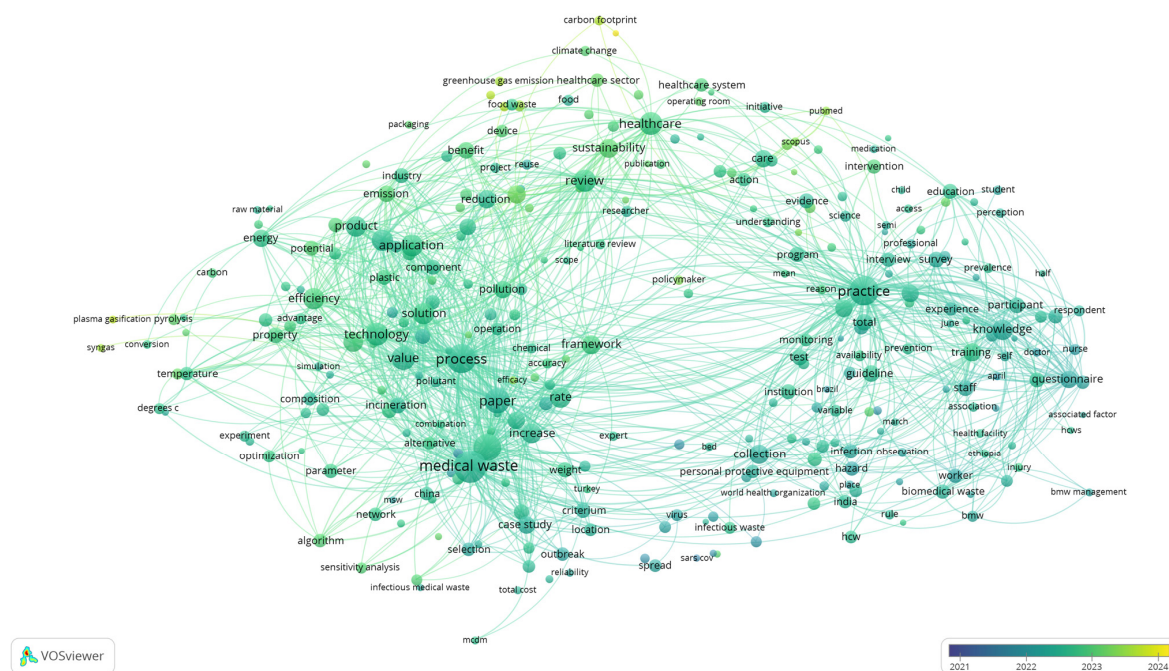


Figure 7. Temporal overlay of thematic terms from titles and abstracts.

Central and frequently occurring terms such as medical waste, process, technology, practice, and efficiency appear in green tones, suggesting they have been persistently discussed across the period analyzed. These form the backbone of the field, integrating technical, empirical, and management perspectives.

The yellow-highlighted terms (e.g., carbon footprint, syngas, and plasma gasification) mark the most recent research interests. Their peripheral position on the map reflects their status as emerging directions rather than established core concepts. These terms indicate a growing integration of sustainability assessment frameworks, environmental indicators, and decarbonization strategies into waste management discourse.

Additionally, the presence of relatively new terms such as algorithm, network, sensitivity analysis, and parameter in the lower-left quadrant highlights a shift toward more analytical and systems-based methodologies, potentially enhancing decision-making and performance evaluation in medical waste management.

The temporal layering reinforces the thematic convergence observed in previous maps: from static disposal methods toward systemic, computational, and sustainability-aware approaches. This shift aligns with the growing interest in performance optimization, value creation, and risk minimization—hallmarks of lean thinking in complex operational environments.

5. Discussions

HMW includes materials that pose substantial risks to health and the environment.

Medical waste management typically involves a standardized sequence of steps: segregation at the point of generation, collection and interim storage, transportation, appropriate treatment, and final disposal [84].

Each stage requires strict adherence to protocols and regulatory compliance to ensure the minimization of health and environmental risks. Common challenges across these stages include inadequate training of personnel, insufficient infrastructure, lack of real-time monitoring, improper segregation of hazardous and non-hazardous waste, and weak enforcement of regulations.

Recommendations widely emphasized in the literature include the need for the following:

- Strengthening segregation practices using color-coded systems [5];
- Capacity-building and ongoing training for healthcare staff [73];
- Investing in decentralized and modular treatment technologies [19,27];
- Enhancing digital traceability and compliance monitoring tools (e.g., IoT, blockchain) [22,38,80];
- Establishing robust policy frameworks and funding mechanisms to ensure long-term sustainability [21].

The COVID-19 pandemic has significantly increased the volume of hazardous waste, particularly from single-use personal protective equipment (PPE), which poses long-term environmental risks due to the release of microplastics and microfibers into ecosystems [85]. Addressing this emergent waste stream requires integrated strategies that combine material innovation (e.g., biodegradable PPE) with efficient segregation and disposal systems.

This general framework underscores the need to integrate both foundational practices and advanced innovations, ensuring that basic waste-handling protocols are not overlooked in the pursuit of high-tech solutions.

This study reveals the multi-dimensional nature of medical waste research, reflecting a convergence of technological, environmental, and operational themes. Through integrative bibliometric and thematic analysis, we mapped the conceptual structure and emerging trends of the field, highlighting the increasing alignment with sustainability goals and process optimization logics.

The results show that research on medical waste has gradually evolved beyond its traditional biomedical and regulatory focus. New directions emphasize technological

innovation (e.g., pyrolysis, gasification, plasma treatment), environmental performance (carbon footprint, emissions, circular economy), and systems-level efficiency, which is particularly evident in terms like optimization, value, and process. These trends suggest a shift toward frameworks that mirror principles of lean management, such as waste minimization, workflow improvement, and value creation.

Consistent with the recent literature on sustainable operations, our analysis identifies four dominant thematic clusters—technical systems, behavioral change, environmental metrics, and computational modeling—each contributing to a broader understanding of how medical waste can be managed more efficiently and ethically. The overlay and density visualizations further reinforce this conceptual layering, revealing that recent publications increasingly focus on data-driven methods, life cycle-based assessments, and integrated decision-making tools.

At a global scale, the co-authorship network analysis indicates that medical waste is a topic of shared international concern, with major contributions from China, India, and the USA, but also growing visibility of emerging economies. This highlights the need for knowledge-sharing platforms and international collaborations, particularly to support low-resource settings.

6. Conclusions

Following the thematic analysis, Table 2 presents a synthesis of the main implications derived from the findings, structured across the most relevant dimensions observed in the literature.

Table 2. Medical waste dimensions and implications.

Thematic Dimension	Key Findings	Implications for Research and Practice
Technological systems	Strong focus on advanced treatment methods (e.g., pyrolysis, gasification, sterilization)	Further research needed on integration of these technologies into scalable, cost-effective waste infrastructures
Environmental metrics	Emergence of <i>carbon footprint</i> , <i>LCA</i> , <i>circular economy</i> concepts in recent literature	Encourages adoption of performance-based sustainability indicators in waste policy and system design
Operational efficiency	Frequent use of <i>optimization</i> , <i>process</i> , <i>value</i> terms; alignment with lean management logic	Suggests the applicability of lean tools (Value Stream Mapping, 5S method, Kaizen) for enhancing efficiency and minimizing waste in healthcare systems
Computational modeling	New terms: algorithm, network, simulation, sensitivity analysis	Opens directions for AI- and data-driven decision support systems in smart waste management
Behavioral and policy	Clusters include training, awareness, guidelines, intervention	Highlights the need for participatory, education-based, compliance-focused strategies in waste reduction efforts
Global collaboration	Dense international co-authorship network with key hubs in China, India, USA	Reinforces the need for knowledge-sharing platforms and capacity building, especially in emerging and low-resource countries

The implications summarized in Table 2 reflect a clear transition in medical waste management research—from fragmented, reactive strategies toward integrated, systems-oriented frameworks. The identification of lean-aligned vocabulary, data-driven modeling, and sustainability assessment tools signals the potential for transdisciplinary innovation. In practice, this calls for not only technical advancement but also policy alignment, staff training, and collaborative governance models that support resource-efficient and socially responsive waste systems. Selective collection by medical waste categories, continuous investment in existing technologies, involvement of authorities in their authorization,

and state support through funding policies in this sector are key success factors in the processes of recovery and reuse of HMW. Compliance with the proximity principle—ensuring final disposal of medical waste as close as possible to the place of generation—is directly proportional to the allocation of transport logistics and human resources involved in the proper management chain of HMW.

While Table 1 highlights individual innovations, methods, and case studies from the literature—ranging from pyrolysis and gasification to blockchain-based traceability and AI-driven optimization—Table 2 extrapolates and distills these findings into six cross-cutting thematic dimensions. These dimensions reflect broader structural trends and conceptual orientations within the field, including technological systems, environmental metrics, operational efficiency, computational modeling, behavioral dynamics, and global collaboration. Together, the two tables operate in tandem: one capturing the empirical richness of current research, and the other mapping its systemic implications for both academic inquiry and practical implementation. This dual-layered approach enables a transition from case-level understanding to strategic-level synthesis, reinforcing the article’s core objective: to connect innovation with impact in the evolving landscape of HMW management.

Despite the comprehensive nature of this study, certain limitations should be acknowledged. First, the bibliometric analysis was limited to the Web of Science Core Collection, excluding publications from other databases such as Scopus or PubMed. Second, the reliance on English-language sources introduces language bias, likely excluding regional case studies and non-English contributions.

Moreover, while the VOSviewer version 1.6.20 methodology offers strong visual and structural insights, the clustering process is influenced by parameter settings (e.g., occurrence thresholds, normalization method), which may affect the interpretability of marginal themes. Third, the analysis was restricted to English-language publications, excluding potentially valuable contributions in other languages. Additionally, this study may underrepresent research from low- and middle-income countries due to disparities in publication volumes and indexing. Future research could address these limitations by incorporating multi-database triangulation, multilingual corpora, and comparative regional analyses to enrich the understanding of HMW dynamics in diverse contexts.

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References

1. World Health Organization. Health-Care Waste. WHO Fact Sheet, 2023. Available online: <https://www.who.int/news-room/fact-sheets/detail/health-care-waste?> (accessed on 30 April 2025).
2. UNEP. Global Waste Management Outlook 2024. United Nations Environment Programme, 2024. Available online: <https://www.unep.org/resources/global-waste-management-outlook-2024> (accessed on 30 April 2025).
3. Zisopoulos, F.K.; Teigiserova, D.A.; Schraven, D.; De Jong, M.; Tong, X.; Ulanowicz, R.E. Are There Limits to Robustness? Exploring Tools from Regenerative Economics for a Balanced Transition Towards a Circular EU27. *Clean. Prod. Lett.* **2022**, *3*, 100014. [CrossRef]
4. Colasante, A.; D’Adamo, I.; Morone, P.; Rosa, P. Assessing the Circularity Performance in a European Cross-Country Comparison. *Environ. Impact Assess. Rev.* **2022**, *93*, 106730. [CrossRef]

5. Miamiliotis, A.S.; Talias, M.A. Healthcare Workers' Knowledge about the Segregation Process of Infectious Medical Waste Management in a Hospital. *Healthcare* **2023**, *12*, 94. [CrossRef] [PubMed]
6. Johnson, N. Exploring Integrated Biogas Solutions for Industrial Processes: An Advanced Approach towards Renewable Energy. *Preprints* **2024**. [CrossRef]
7. Deshmukh, P.; Jagdale, T. Production of Energy from Waste Material—A Review. In *Proceedings of the International Conference on Applications of Machine Intelligence and Data Analytics (ICAMIDA 2022)*; Tamane, S., Ghosh, S., Deshmukh, S., Eds.; Advances in Computer Science Research; Atlantis Press International BV: Dordrecht, The Netherlands, 2023; Volume 105, pp. 122–129. [CrossRef]
8. European Commission. Waste Framework Directive—Targeted Revision Proposal. 2023. Available online: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en (accessed on 30 April 2025).
9. Phu, G.N. Factors Affecting the Use of Best Available Techniques and the Impact on Business Sustainability. *Int. J. Asian Bus. Inf. Manag.* **2023**, *14*, 1–18. [CrossRef]
10. European Suppliers of Waste-to-Energy Technology (ESWET). Industrial Emissions Directive: A Step Towards Enhanced Environmental Compliance. 12 March 2024. Available online: <https://eswet.eu/documents/industrial-emissions-directive-a-step-towards-enhanced-environmental-compliance/> (accessed on 12 May 2025).
11. Kaposi, A.; Nagy, A.; Gomori, G.; Kocsis, D. Analysis of Healthcare Waste and Factors Affecting the Amount of Hazardous Healthcare Waste in a University Hospital. *J. Mater. Cycles Waste Manag.* **2024**, *26*, 1169–1180. [CrossRef]
12. Attrah, M.; Elmanadely, A.; Akter, D.; Rene, E.R. A Review on Medical Waste Management: Treatment, Recycling, and Disposal Options. *Environments* **2022**, *9*, 146. [CrossRef]
13. Mushtaq, M.H.; Noor, F.; Mujtaba, M.A.; Asghar, S.; Yusuf, A.A.; Soudagar, M.E.M.; Hussain, A.; Badran, M.F.; Shahapurkar, K. Environmental Performance of Alternative Hospital Waste Management Strategies Using Life Cycle Assessment (LCA) Approach. *Sustainability* **2022**, *14*, 14942. [CrossRef]
14. National Environmental Protection Agency. Environmental Permit Issued to SC Stericycle România SRL for Activities Including the Collection and Treatment of Hazardous and Non-Hazardous Waste. Available online: https://www.anpm.ro/documents/13565/0/AG_AM+14+-+09.02.2022+Stericycle.pdf/87a7171c-d867-4810-96e8-80bac93b9868 (accessed on 10 September 2024).
15. WESSLING România SRL. Environmental Impact Presentation Report, Project “Construction of a Hall for Medical Waste Management and Office Facilities. Available online: <https://apmbh.anpm.ro/documents/14457/42977742/Memoriu+de+prezentare+Construire+Hala+deseuri+Medicale.pdf/5e303e5c-6ef2-40e7-b04e-8148b760745b> (accessed on 10 September 2024).
16. Senthil, R.; Thamizhvel, R.; Sudagar, S. A Comparative Analysis of Pyrolytic Oil from Medical Waste and Its Suitability as Fuel in a Compression Ignition Engine. *Energy Sources Part A Recovery Util. Environ. Eff.* **2024**, *46*, 2040–2058. [CrossRef]
17. Almendrala, M.C.; Valenzuela, K.A.T.; Santos, S.M.N.B.; Avena-Ardeta, L.G.S. Enhanced Biogas Production via Anaerobic Co-Digestion of Slaughterhouse and Food Waste Using Ferric Oxide as a Sustainable Conductive Material. *arXiv* **2025**, arXiv:2505.04635. [CrossRef]
18. Kumar, A.; Thakur, A.K.; Gaurav, G.K.; Singh, R.K.; Kumari, A.; Shukla, S.K.; Varjani, S. A Critical Review on Sustainable Hazardous Waste Management Strategies: A Step towards a Circular Economy. *Environ. Sci. Pollut. Res.* **2023**, *30*, 105030–105055. [CrossRef] [PubMed]
19. Abedeen, A.; Hossain, M.S.; Rahman, A.N.M.M. Characterization and Energy Recovery of Fuels from Medical Waste via Thermal Pyrolysis. *Heliyon* **2025**, *11*, e42599. [CrossRef] [PubMed]
20. Pillai, N.D.; Parthasarathy, V.; Anbalagan, K. Assessment and Optimization of Biomedical Waste Management Using Neutrosophic Multi-Criteria Decision-Making Method. *Eng. Res. Express* **2025**, *7*, 015405. [CrossRef]
21. Ebrahimzadehsarvestani, E.; Sarvestani, E.M.; Safarzadeh, H.; Enayati, M.; Di Maria, F. Implementing Circular Economy in Healthcare Waste: Technological Innovations and Process Management. *J. Solid Waste Technol. Manag.* **2025**, *51*, 14–24. [CrossRef]
22. Dsouza, M.R.; Naji, K.M.; Ramaiah, M.K.; Patil, S.J. Revolutionizing Biomedical Waste Management: Embracing Innovative Technologies for a Healthier Future. In *Solid Waste Management*; Pandey, A., Suthar, S.S., Amesho, K.T.T., Eds.; Springer Nature Switzerland: Cham, Switzerland, 2025; pp. 173–196. [CrossRef]
23. Soyler, A.; Burmaoglu, S.; Kidak, L.B. The Evolutionary Path of Medical Waste Management Research: Insights from Co-Citation and Co-Word Analysis. *Waste Manag. Res.* **2024**, in press. [CrossRef]
24. Fang, X.; Zhang, G.; Zhang, X.; He, S.; Xu, W.; Zhang, X.; Zhong, S. Resource Utilization of Medical Waste Incineration Fly Ash to Activate Peroxydisulfate for Tetracycline Degradation: Synergy between Adsorption and PDS Activation. *Environ. Res.* **2024**, *258*, 119488. [CrossRef]
25. Bułkowska, K.; Zielińska, M. Thermal Disintegration of Waste-Activated Sludge. *Energies* **2024**, *17*, 4447. [CrossRef]
26. Kharmawphlang, I.M.; Paul, J.; Doloi, S.; Hussain, N. Waste to Energy Technologies: A Sustainable Key Approach Towards Circular Economy and Energy Recycling. In *Trash or Treasure*; Singh, P., Borthakur, A., Eds.; Springer Nature Switzerland: Cham, Switzerland, 2024; pp. 143–181. [CrossRef]

27. Zhou, J.; Ayub, Y.; Shi, T.; Ren, J.; He, C. Sustainable Co-Valorization of Medical Waste and Biomass Waste: Innovative Process Design, Optimization and Assessment. *Energy* **2024**, *288*, 129803. [\[CrossRef\]](#)
28. Shen, L.; Xu, X.; Shao, F.; Shao, H.; Ge, Y. A Multi-Objective Optimization Model for Medical Waste Recycling Network Design under Uncertainties. *Transp. Res. Part E Logist. Transp. Rev.* **2024**, *184*, 103492. [\[CrossRef\]](#)
29. Suthagar, K.S.; Mishra, U. Sustainable Green Circular Economic Model with Controllable Waste and Emission in Healthcare System. *Environ. Dev. Sustain.* **2024**, *27*, 8767–8809. [\[CrossRef\]](#)
30. Kumari, M.; Chaudhary, G.R.; Chaudhary, S. Transformation of Medical Plastic Waste to Valuable Carbon Dots: A Sustainable Recycling of Medical Waste to Efficient Fluorescent Marker. *J. Mol. Liq.* **2024**, *395*, 123910. [\[CrossRef\]](#)
31. Hu, Y.; Yu, X.; Ren, J.; Zeng, Z.; Qian, Q. Waste Tire Valorization: Advanced Technologies, Process Simulation, System Optimization, and Sustainability. *Sci. Total Environ.* **2024**, *942*, 173561. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Ji, A.; Guan, J.; Zhang, S.; Ma, X.; Jing, S.; Yan, G.; Liu, Y.; Li, H.; Zhao, H. Environmental and Economic Assessments of Industry-Level Medical Waste Disposal Technologies—A Case Study of Ten Chinese Megacities. *Waste Manag.* **2024**, *174*, 203–217. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Liu, H.; Chen, S.; Huang, F.; Li, Q. Study on Characteristics and Parameter Optimization of Medical Waste Crushing Process. *Powder Technol.* **2024**, *431*, 119085. [\[CrossRef\]](#)
34. Bhandari, G.; Chaudhary, P.; Gangola, S.; Gupta, S.; Gupta, A.; Rafatullah, M.; Chen, S. A Review on Hospital Wastewater Treatment Technologies: Current Management Practices and Future Prospects. *J. Water Process Eng.* **2023**, *56*, 104516. [\[CrossRef\]](#)
35. Balaji, T.E.; Das, H.T.; Maiyalagan, T.; Das, N. Developing Potential Aqueous Na-Ion Capacitors of Al₂O₃ with Carbon Composites as Electrode Material: Recycling Medical Waste to Sustainable Energy. *J. Alloys Compd.* **2023**, *931*, 167501. [\[CrossRef\]](#)
36. Mehmood, T.; Nadeem, F.; Bilal, M.; Meer, B.; Meer, K.; Qamar, S.A. Biological Treatment of Pharmaceutical Wastes. In *Waste Management and Resource Recycling in the Developing World*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 577–600. [\[CrossRef\]](#)
37. Dri, M.; Canfora, P.; Antonopoulos, I.S.; Gaudillat, P. *Best Environmental Management Practice for the Waste Management Sector*; Publications Office of the European Union: Luxembourg, 2018. Available online: <https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/inline-files/WasteManagementBEMP.pdf> (accessed on 25 February 2025).
38. Baralla, G.; Pinna, A.; Tonelli, R.; Marchesi, M. Waste Management: A Comprehensive State of the Art about the Rise of Blockchain Technology. *Comput. Ind.* **2023**, *145*, 103812. [\[CrossRef\]](#)
39. Chandra, V.; Arpita, K.; Yadav, P.; Raghuvanshi, V.; Yadav, A.; Prajapati, S. Environmental Biotechnology for Medical Waste Management: A Review of Current Practices and Future Directions. *Environ. Earth Sci.* **2023**, preprint. [\[CrossRef\]](#)
40. Matalkah, F. Recycling of Hazardous Medical Waste Ash Toward Cleaner Utilization in Concrete Mixtures. *J. Clean. Prod.* **2023**, *400*, 136736. [\[CrossRef\]](#)
41. Li, J.; Wang, H.; Chen, H.; Wu, H.; Xu, G.; Dong, Y.; Zhao, Q.; Liu, T. Comparative Thermodynamic and Techno-Economic Analysis of Various Medical Waste-to-Hydrogen/Methanol Pathways Based on Plasma Gasification. *Appl. Therm. Eng.* **2023**, *221*, 119762. [\[CrossRef\]](#)
42. Zhao, X.; Chen, H.; Zheng, Q.; Liu, J.; Pan, P.; Xu, G.; Zhao, Q.; Jiang, X. Thermo-Economic Analysis of a Novel Hydrogen Production System Using Medical Waste and Biogas with Zero Carbon Emission. *Energy* **2023**, *265*, 126333. [\[CrossRef\]](#)
43. Keleş, H.; Önal, Y.; Akbulut, Y. Characterization of Polymeric Wastes in the Hygienic Product Factory and Energy Recovery from These Wastes. *Yüzüncü Yıl Univ. J. Inst. Sci.* **2023**, in press. [\[CrossRef\]](#)
44. Alaedini, A.H.; Tourani, H.K.; Saidi, M. A Review of Waste-to-Hydrogen Conversion Technologies for Solid Oxide Fuel Cell (SOFC) Applications: Aspect of Gasification Process and Catalyst Development. *J. Environ. Manag.* **2023**, *329*, 117077. [\[CrossRef\]](#) [\[PubMed\]](#)
45. Andooz, A.; Egbalpour, M.; Kowsari, E.; Ramakrishna, S.; Ansari Cheshmeh, Z. A Comprehensive Review on Pyrolysis from the Circular Economy Point of View and Its Environmental and Social Effects. *J. Clean. Prod.* **2023**, *388*, 136021. [\[CrossRef\]](#)
46. Bolan, S.; Padhye, L.P.; Kumar, M.; Antoniadis, V.; Sridharan, S.; Tang, Y.; Singh, N.; Hewawasam, C.; Vithanage, M.; Singh, L.; et al. Review on Distribution, Fate, and Management of Potentially Toxic Elements in Incinerated Medical Wastes. *Environ. Pollut.* **2023**, *321*, 121080. [\[CrossRef\]](#)
47. Çelik, S.; Peker, İ.; Gök-Kısa, A.C.; Büyüközkan, G. Multi-Criteria Evaluation of Medical Waste Management Process under Intuitionistic Fuzzy Environment: A Case Study on Hospitals in Turkey. *Socio-Econ. Plan. Sci.* **2023**, *86*, 101499. [\[CrossRef\]](#)
48. Chu, Y.T.; Zhou, J.; Wang, Y.; Liu, Y.; Ren, J. Current State, Development and Future Directions of Medical Waste Valorization. *Energies* **2023**, *16*, 1074. [\[CrossRef\]](#)
49. Długosz-Lisiecka, M.; Biegała, M.; Jakubowska, T. Activation of Medical Accelerator Components and Radioactive Waste Classification Based on Low Beam Energy Model Clinac 2300. *Radiat. Phys. Chem.* **2023**, *205*, 110730. [\[CrossRef\]](#)
50. Dong, Y.; Wei, L.; Wang, S.; Pan, P.; Chen, H. Design and Performance Evaluation of Integrating the Waste Heat Recovery System (WHRS) for a Silicon Arc Furnace with Plasma Gasification for Medical Waste. *Entropy* **2023**, *25*, 595. [\[CrossRef\]](#)

51. El-Saadony, M.T.; Saad, A.M.; El-Wafai, N.A.; Abou-Aly, H.E.; Salem, H.M.; Soliman, S.M.; Abd El-Mageed, T.A.; Elrys, A.S.; Selim, S.; Abd El-Hack, M.E.; et al. Hazardous Wastes and Management Strategies of Landfill Leachates: A Comprehensive Review. *Environ. Technol. Innov.* **2023**, *31*, 103150. [[CrossRef](#)]
52. Kaur, H.; Siddique, R.; Rajor, A. Effect of Bacteria on Strength Properties and Toxicity of Incinerated Biomedical Waste Ash Concrete. *Environ. Technol.* **2023**, *44*, 1705–1729. [[CrossRef](#)] [[PubMed](#)]
53. Krishna, D.; Sachan, H.K. Hazardous Biomedical Waste Management Scenario in Developing Countries. In *Waste Management and Resource Recycling in the Developing World*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 505–519. [[CrossRef](#)]
54. Mishra, R.K.; Kumar, D.J.P.; Narula, A.; Minnat Chistie, S.; Ullhas Naik, S. Production and Beneficial Impact of Biochar for Environmental Application: A Review on Types of Feedstocks, Chemical Compositions, Operating Parameters, Techno-Economic Study, and Life Cycle Assessment. *Fuel* **2023**, *343*, 127968. [[CrossRef](#)]
55. Kumar, V.; Gaurav, G.; Khan, V.; Choudhary, S.; Dangayach, G.S. Life Cycle Assessment and Its Application in Medical Waste Disposal. *Mater. Today Proc.* **2023**, in press. [[CrossRef](#)]
56. Lv, J.; Wang, Y.; Chen, H.; Li, W.; Pan, P.; Wu, L.; Xu, G.; Zhai, R. Thermodynamic and Economic Analysis of a Conceptual System Combining Medical Waste Plasma Gasification, SOFC, Sludge Gasification, Supercritical CO₂ Cycle, and Desalination. *Energy* **2023**, *282*, 128866. [[CrossRef](#)]
57. Manjunath, B.; Di Mare, M.; Ouellet-Plamondon, C.M.; Bhojaraju, C. Exploring the Potential Use of Incinerated Biomedical Waste Ash as an Eco-Friendly Solution in Concrete Composites: A Review. *Constr. Build. Mater.* **2023**, *387*, 131595. [[CrossRef](#)]
58. Peng, Y.; Ma, Y.; Lin, X.; Long, J.; Li, X. Emission Control and Phase Migration of PCDD/Fs in a Rotary Kiln Incinerator: Hazardous vs Medical Waste Incineration. *Waste Dispos. Sustain. Energy* **2023**, in press. [[CrossRef](#)]
59. Qin, L.; Zhu, S.; Xu, Z.; Zhao, B.; Chen, W.; Zhang, Q.; Han, J. Technical Feasibility and Sensitivity Analysis of Medical Waste Gasification by the Converter Gas. *Energy* **2023**, *275*, 127379. [[CrossRef](#)]
60. Ramalingam, S.; Thamizhvel, R.; Sudagar, S.; Silambarasan, R. Production of Third Generation Bio-Fuel through Thermal Cracking Process by Utilizing COVID-19 Plastic Wastes. *Mater. Today Proc.* **2023**, *72*, 1618–1623. [[CrossRef](#)]
61. Sančanin, B.; Sančanin, A. Unapređenje procedura za skladištenje medicinskog otpada. *Sanamed* **2023**, *18*, 65–72. [[CrossRef](#)]
62. Sapkota, B.; Pariatamby, A. Pharmaceutical Waste Management System—Are the Current Techniques Sustainable, Eco-Friendly and Circular? A Review. *Waste Manag.* **2023**, *168*, 83–97. [[CrossRef](#)]
63. Tan, K.Q.; Ahmad, M.A.; Oh, W.D.; Low, S.C. Valorization of Hazardous Plastic Wastes into Value-Added Resources by Catalytic Pyrolysis-Gasification: A Review of Techno-Economic Analysis. *Renew. Sustain. Energy Rev.* **2023**, *182*, 113346. [[CrossRef](#)]
64. Tang, Y.; Wang, J.; Chen, M.; Wu, Y.; Zhang, Y.; He, Z. MSW Pyrolysis Volatiles' Reforming by Incineration Fly Ash for Both Pyrolysis Products Upgrading and Fly Ash Stabilization. *Chemosphere* **2023**, *313*, 137536. [[CrossRef](#)] [[PubMed](#)]
65. Thakur, M.; Chandel, M.; Rani, A.; Sharma, A.; Pathania, D. Chemical Methods for the Treatment of Biomedical Hazardous Waste. In *Waste Management and Resource Recycling in the Developing World*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 521–541. [[CrossRef](#)]
66. Wang, L.; Wu, D.; Zhang, J.; Li, Y.; Hu, X.; Wang, Z.; Wang, H. Global Face Mask Pollution: Threats to the Environment and Wildlife, and Potential Solutions. *Sci. Total Environ.* **2023**, *887*, 164055. [[CrossRef](#)] [[PubMed](#)]
67. Wu, Y.; Zhang, H.; Chen, X.; Li, W.; Zhao, X.; Guo, Y. Physico-Chemical and Biological Remediation Techniques for the Elimination of Endocrine-Disrupting Hazardous Chemicals. *Environ. Res.* **2023**, *232*, 116363. [[CrossRef](#)]
68. Sepetis, A.; Zaza, P.N.; Rizos, F.; Bagos, P.G. Identifying and Predicting Healthcare Waste Management Costs for an Optimal Sustainable Management System: Evidence from the Greek Public Sector. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9821. [[CrossRef](#)]
69. Quan, L.M.; Zhang, Q.; Guo, H.; Xie, Z.; Chen, X.; Li, X. Review of the Application of Gasification and Combustion Technology and Waste-to-Energy Technologies in Sewage Sludge Treatment. *Fuel* **2022**, *316*, 123199. [[CrossRef](#)]
70. Pokson, C.; Chaiyat, N. Thermal Performance of a Combined Cooling, Heating, and Power (CCHP) Generation System from Infectious Medical Waste. *Case Stud. Chem. Environ. Eng.* **2022**, *6*, 100221. [[CrossRef](#)]
71. Bharti, B.; Li, H.; Ren, Z.; Zhu, R.; Zhu, Z. Recent Advances in Sterilization and Disinfection Technology: A Review. *Chemosphere* **2022**, *308*, 136404. [[CrossRef](#)]
72. Wawale, S.G.; Shabaz, M.; Mehbodniya, A.; Soni, M.; Deb, N.; Elashiri, M.A.; Naved, M. Biomedical Waste Management Using IoT Tracked and Fuzzy Classified Integrated Technique. *Hum.-Centric Comput. Inf. Sci.* **2022**, *12*, 401–414. [[CrossRef](#)]
73. Lemma, H.; Asefa, L.; Gameda, T.; Dhengesu, D. Infectious Medical Waste Management During the COVID-19 Pandemic in Public Hospitals of West Guji Zone, Southern Ethiopia. *Clin. Epidemiol. Glob. Health* **2022**, *15*, 101037. [[CrossRef](#)]
74. Govindan, K.; Nosrati-Abarghoee, S.; Nasiri, M.M.; Jolai, F. Green Reverse Logistics Network Design for Medical Waste Management: A Circular Economy Transition Through Case Approach. *J. Environ. Manag.* **2022**, *322*, 115888. [[CrossRef](#)]
75. Erdem, M. Designing a Sustainable Logistics Network for Hazardous Medical Waste Collection: A Case Study in COVID-19 Pandemic. *J. Clean. Prod.* **2022**, *376*, 134192. [[CrossRef](#)] [[PubMed](#)]

76. Zhao, H.; Liu, H.; Wei, G.; Zhang, N.; Qiao, H.; Gong, Y.; Yu, X.; Zhou, J.; Wu, Y. A Review on Emergency Disposal and Management of Medical Waste During the COVID-19 Pandemic in China. *Sci. Total Environ.* **2022**, *810*, 152302. [CrossRef] [PubMed]
77. Zhao, H.-L.; Wang, L.; Liu, F.; Liu, H.-Q.; Zhang, N.; Zhu, Y.-W. Energy, Environment and Economy Assessment of Medical Waste Disposal Technologies in China. *Sci. Total Environ.* **2021**, *796*, 148964. [CrossRef]
78. Giakoumakis, G.; Politi, D.; Sidiras, D. Medical Waste Treatment Technologies for Energy, Fuels, and Materials Production: A Review. *Energies* **2021**, *14*, 8065. [CrossRef]
79. Su, G.; Ong, H.C.; Ibrahim, S.; Fattah, I.M.R.; Mofijur, M.; Chong, C.T. Valorisation of Medical Waste Through Pyrolysis for a Cleaner Environment: Progress and Challenges. *Environ. Pollut.* **2021**, *279*, 116934. [CrossRef]
80. Soldatos, J.; Kefalakis, N.; Despotopoulou, A.M.; Bodin, U.; Musumeci, A.; Scandura, A.; Aliprandi, C.; Arabsolgar, D.; Colledani, M. A Digital Platform for Cross-Sector Collaborative Value Networks in the Circular Economy. *Procedia Manuf.* **2021**, *54*, 64–69. Available online: <http://creativecommons.org/licenses/by-nc-nd/4.0/> (accessed on 25 March 2025). [CrossRef]
81. Patel, A.; Agrawal, B.; Rawal, B.R. Pyrolysis of Biomass for Efficient Extraction of Biofuel. *Energy Sources Part A Recover. Util. Environ. Eff.* **2020**, *42*, 1649–1661. [CrossRef]
82. Alam, O.; Mosharraf, A. A Preliminary Life Cycle Assessment on Healthcare Waste Management in Chittagong City, Bangladesh. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 1753–1764. [CrossRef]
83. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 Statement: An Updated Guideline for Reporting Systematic Reviews. *BMJ* **2021**, *372*, n71. [CrossRef]
84. World Health Organization. *Safe Management of Wastes from Health-Care Activities*, 2nd ed.; Chartier, Y., Emmanuel, J., Pieper, U., Prüss, A., Rushbrook, P., Stringer, R., Townend, W., Wilburn, S., Zghondi, R., Eds.; WHO Press: Geneva, Switzerland, 2014. Available online: https://iris.who.int/bitstream/handle/10665/85349/9789241548564_eng.pdf (accessed on 12 May 2025).
85. Abbasi, S.; Khalilabad, M.A.; Shojaei, A.R. PPE pollution during COVID-19: A review of environmental challenges and sustainable solutions. *Sci. Total Environ.* **2022**, *849*, 160322.

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