Review Article
Submission Date: November 17, 2025 Acceptance Date: March 13, 2026

Karaçay, G., & Göçgün, Y. (2026) Recent trends in medical waste management in hospitals: A thematic review integrating operations research, sustainability, and digitalization. Journal of Health Systems and Policies (JHESP), VIII, 29-59, DOI: 10.52675/jhesp.1824953

Recent Trends in Medical Waste Management in Hospitals: A Thematic Review Integrating Operations Research, Sustainability, and Digitalization

Gülce KARAÇAY[1*]
Yasin GÖÇGÜN[1]

ABSTRACT

Medical waste management has become a strategic priority for healthcare institutions due to volumetric increases experienced during crises, such as infectious diseases, climate change, and the COVID-19 pandemic, and has undergone significant transformations in recent years, focusing on sustainability, circular economy, and digitalization. This thematic review addresses the existing academic literature on medical waste management in hospitals, focusing on operational and managerial challenges. Findings indicate that a significant portion of the literature focuses on operational research approaches; multi-criteria decision-making methods are used for technology and location selection, while mathematical modeling and heuristic algorithms are used for cost and risk minimization in logistics network design and vehicle routing. The sustainability paradigm requires the integration of Environmental, Social, and Governance and Sustainable Development Goals frameworks into medical waste management processes. Circular economy, resource segregation, and waste-to-energy conversion technologies are emphasized. Digitalization enables optimization, whereas stakeholder engagement and training form the basis of success.

The literature review was conducted using keywords identified in the Web of Science, Scopus, PubMed, and Google Scholar databases, and relevant studies were analyzed using a thematic synthesis approach by reviewing their titles,

1 İstanbul Medipol University, Graduate School of Engineering and Natural Sciences, Istanbul, Türkiye
* Corresponding author: Gülce KARAÇAY, gulce.karacay@std.medipol.edu.tr

abstracts, and full texts. The review revealed that subjectivity in multi-criteria decision-making models, the lack of real-world validation in optimization studies, and the limited treatment of ethical and data governance dimensions of digital technologies are key research gaps. It is considered important for future studies to incorporate data-driven decision support systems, hybrid decision models, advanced optimization approaches, and validation studies with real hospital applications.

Keywords: ESG, Medical Waste Management, Operations Research, Optimization, SDGs

INTRODUCTION

In recent years, medical waste management (MWM) has undergone a significant transformation driven by approaches focusing on sustainability, circular economy, and digitalization, shaping current research trends in the field. MWM is considered a critical necessity not only for ensuring environmental sustainability but also for protecting public health. Global threats, such as increasing infectious disease risks, the pressure of climate change on healthcare systems, and antimicrobial resistance have transformed this area from an operational cost item into a strategic priority for healthcare institutions. Public health crises, particularly the COVID-19 pandemic, have tested the resilience of existing systems with sudden and uncertain increases in waste volumes, demonstrating the need for process redesign.

Academic literature provides a detailed analysis of the obstacles to an effective MWM system. Chief among these obstacles is the lack of standardized protocols and guidelines, inadequate waste separation practices, low awareness and knowledge among personnel, and a lack of financial and human resources. Given that a significant portion of medical waste is recyclable, inadequate separation practices that lead to the mixing of hazardous waste with general waste pose serious health threats to both sanitation personnel and the public. To address these complex challenges, the disciplines of operations research and decision science have found widespread application in literature. Multi-criteria decision making (MCDM) methods, such as the analytical hierarchy process (AHP), VIKOR, PROMETHEE, and analytic network process (ANP), are widely used in strategic decisions, such as facility location selection, disposal technology selection, and disposal company evaluation. MWM processes encompass complex decision-making problems involving numerous potentially conflicting criteria, such as cost, environmental impact, infection risk, regulatory compliance, and social acceptance. Therefore, MCDM methods are widely preferred in literature because they allow for the systematic and transparent evaluation of alternatives. Particularly in sustainability and governance-focused decision-making environments, the inadequacy of purely cost-based optimization approaches has led to MCDM methods becoming fundamental decision support tools in medical waste management research. At the operational level, medical waste logistics and network design play a central role. Reverse logistics network models, which aim to minimize costs, environmental impacts, and infection risks, are supported by approaches such as stochastic programming or robust optimization to manage uncertainties in waste volumes. Vehicle route planning (VRP), with the goal of cost and risk minimization, is solved using heuristic methods, such as genetic algorithms and NSGA-II.

In recent years, the perspective on MWM has evolved from technical optimization to holistic sustainability frameworks. Environmental, Social, and Governance (ESG) principles have become a fundamental component of healthcare organizations' long-term strategic planning. Similarly, waste management strategies aligned with the Sustainable Development Goals (SDGs) play a key role in improving institutions' environmental performance and corporate accountability. In this context, strategies such as circular economy principles, meticulous waste separation at source, and energy recovery through recycling and waste-to-energy (WtE) facilities are gaining prominence.

Digitalization is the most important catalyst supporting this transformation. Technologies such as artificial intelligence (AI), the Internet of Things (IoT) and blockchain are opening new horizons in process optimization. AI-based deep learning models increase the accuracy of waste classification, smart bins with IoT sensors provide real-time monitoring, and blockchain technology offers transparency and traceability. However, the success of technology is directly related to human and managerial factors. Stakeholder engagement, ongoing staff training, and practices such as Green Human Resource Management (Green HRM) are critical to achieving sustainability goals. This study aims to identify current trends, methodologies, and future research needs by systematically compiling the multidisciplinary literature in the field of waste management on a thematic basis.

Contributions

The main rationale for this study is the limited number of comprehensive synthesis studies in the medical waste management literature that address operational research approaches, sustainability frameworks, and digital transformation applications from a holistic perspective. While existing studies generally focus on specific methods or application areas, there is a noticeable lack of studies that comprehensively evaluate methodological trends, sustainability dimensions, and emerging research gaps. This study aims to contribute to the literature by bringing together approaches developed in different disciplines under a thematic structure, systematically presenting current trends in literature, identifying key research gaps, and providing a holistic roadmap for future research. In this respect, the study distinguishes itself from previous reviews in existing literature by offering a thematic classification that integrates operational research approaches with the dimensions of sustainability, ESG, circular economy, and digitalization.

Scope

The scope of this study is to comprehensively compile the academic literature in the field of MWM under specific thematic headings. The study focuses on operations research approaches used in solving MWM problems, examining MCDM methods used for strategic decisions, such as facility location, technology selection, and disposal company selection, as well as mathematical programming and optimization models developed for operational challenges, such as logistics network design and vehicle routing (VRP). The study then examines the integration of MWM processes with ESG principles and the SDG frameworks. The scope also includes circular economy principles, energy recovery disposal technologies, and WtE approaches. The role of digitalization is discussed in the context of the impact of technologies such as artificial intelligence, IoT, and blockchain on data-driven logistics and corporate governance. Finally, a holistic perspective is presented by analyzing the importance of stakeholder participation and public awareness and the role of performance measurement and decision support systems (DSS) in MWM effectiveness.

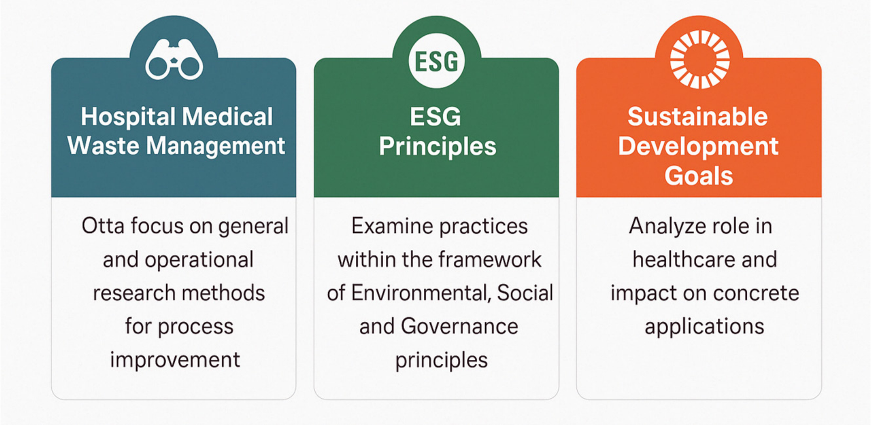

Figure 1. The scope graph of research

METHODOLOGY

This study was conducted through a comprehensive, thematic literature review to analyze current trends, methodologies, challenges, and future research directions in the field of medical waste management. Major academic databases, such as Web of Science, Scopus, PubMed, and Google Scholar, were used in the research process. The search was conducted using keywords, such as “medical waste management”, “operations research”, “ESG”, “SDGs”, “optimization”, “MCDM”, and “sustainability”.

The resulting academic articles were first screened for titles and abstracts. Then, studies directly related to the operational, strategic, sustainability, and technological dimensions of medical waste management processes were included in the full-text review. During the synthesis phase, the compiled information was grouped under seven main thematic headings. In the thematic synthesis process, studies using MCDM methods were given consideration because these approaches constitute one of the dominant methodological trends in the literature for strategic decision problems in medical waste management, such as site selection, disposal technology determination, and service provider evaluation. The inclusion of these studies in the analysis allowed for a comparative evaluation of how sustainability criteria and multidimensional performance indicators are integrated into decision models. This methodology aims to present the main research trends, the most used methods, and existing knowledge gaps in the medical waste management literature from a holistic perspective.

Figure 2 presents the flowchart of the search and screening strategy implemented in the systematic literature review and provides an overview of the reasons for exclusion.

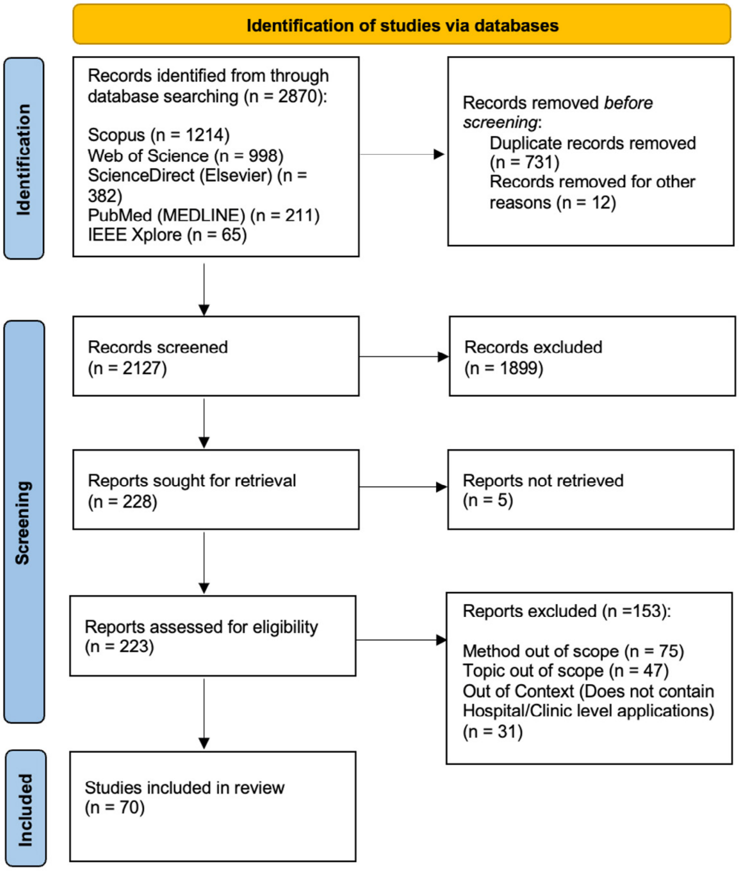

Figure 2. PRISMA flow chart for study selection

A total of 2,870 records were initially identified from the following databases: Scopus (n=1,214), Web of Science (n=998), ScienceDirect (n=382), PubMed (n=211), and IEEE Xplore (n=65). After removing 743 records (n=731 duplicates and n=12 others) before the search, a total of 2,127 studies were evaluated for title and abstract screening. After eliminating 1,899 studies through title and abstract screening, 228 studies were selected for full-text review. Because 5 of these 228 reports were not retrieved, 223 full-text articles were reviewed for eligibility assessment. Following comprehensive full-text review, an additional 153 reports (Reason 1: Method out of scope, n=75; Reason 2: Topic out of scope, n=47; Reason 3: Out of Context (Hospital/Clinic level applications), n=31) were eliminated, resulting in a final total of 70 eligible studies for inclusion in this study.

This study incorporates systematic search and selection steps, while adopting a thematic review approach in interpreting the findings. The literature review process was conducted in accordance with the principles of the PRISMA flowchart, and the study is positioned as a thematic review aiming to reveal conceptual trends and research orientations in the literature, rather than a quantitative review for meta-analysis purposes. Inclusion criteria were defined as studies focusing on medical waste management at the hospital or clinic level, being related to operational research methods, sustainability approaches, or digital technologies, and having full-text access. Exclusion criteria were defined as methodological incompatibility, subject inconsistency, and studies outside the context of hospital practice.

In the thematic synthesis process, selected studies were evaluated using a content analysis approach, and seven main thematic categories were inductively created by considering recurring research focuses, methods used, and application areas in the literature. This thematic structure was developed to encompass operational research practices, sustainability and ESG integration, circular economic approaches, digitalization and smart technologies, logistics and network optimization, decision support systems, and governance and stakeholder engagement dimensions. This approach allows for a more transparent and holistic analysis of methodological trends and research gaps in literature.

Literature Review

In this study, a bibliometric mapping analysis was conducted to visualize the intellectual structure of academic research in the fields of 'medical waste' and 'optimization' in terms of general topics. Figure 3, generated using VOSviewer software, shows the co-occurrence network of keywords in articles obtained from the Web of Science database. Each circle (node) on the map represents a keyword, and the size of the circle indicates the frequency of that word's use in the literature. The lines between the nodes indicate the frequency of these keywords' co-occurrence in articles; clusters, indicated by different colors, represent groups of keywords that are highly correlated and constitute specific research themes in the field. Figure 4 is a zoomed-in version of Figure 3. This map presents a holistic view of the dominant research topics in the medical waste optimization literature, the relationships between these topics, and potential research gaps.

Figure 3 shows that research in literature focuses particularly on concepts such as management, transfer stations, emission control, and data-driven decision-making. The keywords “management” and “station”, centrally located on the map, reveal that logistics network design, transfer station planning, and operational process management are key research focuses on medical waste management studies. Furthermore, the strong connections between concepts such as “emission”, “environmental impact”, and “SDGs” within the network indicate that environmental sustainability and performance evaluation approaches have gained increasing importance in the literature in recent years. Examining the time-based color distribution shows that studies related to sustainability and data analytics represent more current research trends.

The zoomed-in network structure presented in Figure 4 more clearly reveals the relationships between optimization methods and sustainability-based approaches. The connection between optimization techniques, such as “mixed integer programming”, “routing”, “solution”, and “NSGA-II”, and the concepts of “SDGs”, “health facility”, and “reduction” demonstrates that operational research methods are beginning to integrate with sustainable healthcare system goals. In contrast, the fact that some logistics and cost-based concepts are situated around the periphery of the network with more limited connections indicates that there is still potential for development in integrated and interdisciplinary studies in these areas. These findings reveal that the medical waste management literature is evolving from traditional optimization approaches towards sustainability, digitalization, and data-driven decision support systems.

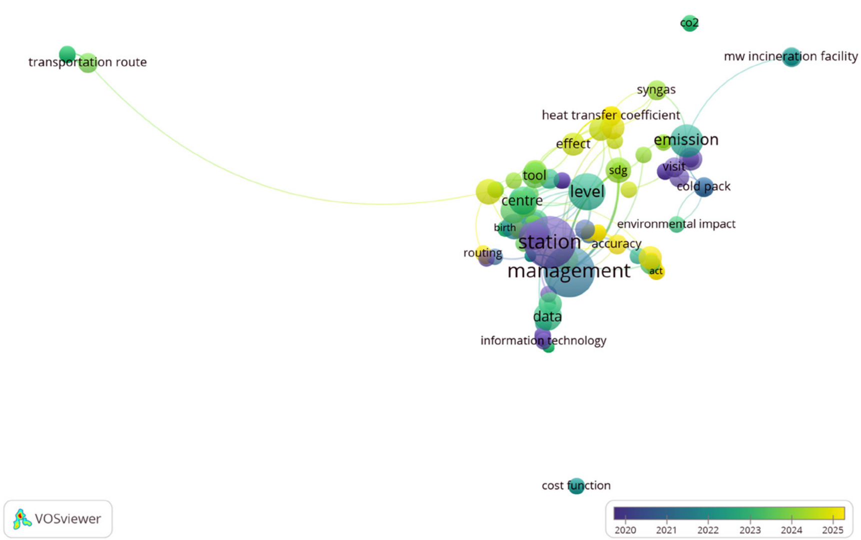

Figure 3. Medical waste and optimization literature keyword co-occurrence network (VOSviewer)

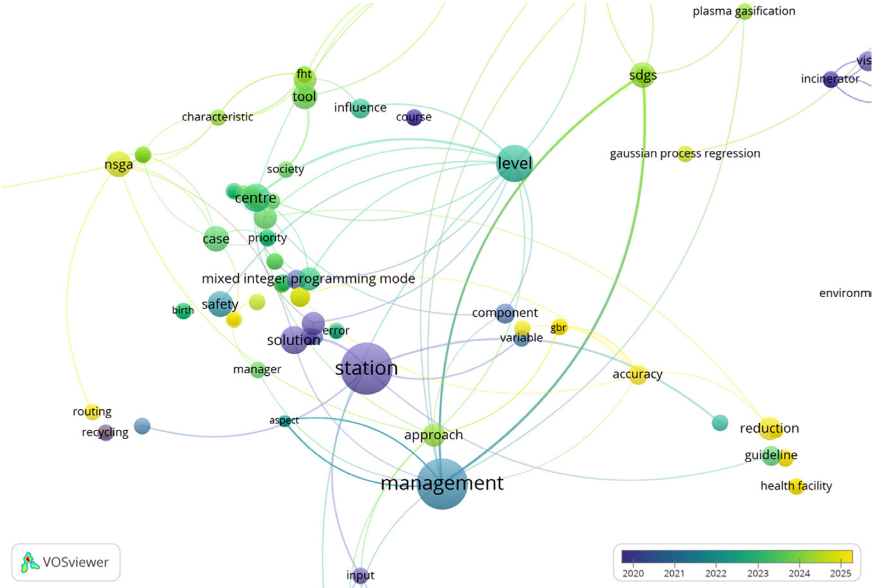

Figure 4. Detailed view of the cluster in Figure 3

Medical Waste Management in Hospitals and Operations Research Approaches

MWM has become a strategic priority for healthcare institutions due to factors such as increasing infectious disease risks, climate change, and drug resistance (Lee & Lee, 2022). It is considered a critical necessity not only for ensuring environmental sustainability but also for protecting public health (Quttainah & Singh, 2024). A significant portion of academic studies has focused on analyzing the barriers and success factors for medical waste management processes. A study based on hospital personnel data and using the AHP method found that the most significant factor affecting medical waste management was the "medical waste management" category itself, with a weight of 26.6%. This was followed by "operational management issues", "training", "awareness", and "environmental assessment" factors (Lee & Lee, 2022). In general, the main barriers to medical waste management in the literature are identified as the lack of standard guidelines, inadequate waste separation, low staff awareness, and financing problems (Quttainah & Singh, 2024). Inadequate separation practices are a serious problem, especially considering that approximately 85% of medical waste is recyclable (Lee & Lee, 2022). A case study in Pakistan showed that mixing of hazardous waste with general waste poses serious health threats to sanitation personnel and waste collectors (Ali et al., 2016).

MCDM methods have been widely used to support decision-making processes, particularly in strategic areas, such as facility location and disposal technology selection. In a study on the siting of a central incineration plant in Kenya, eight potential sites identified through geospatial analysis were evaluated using AHP, VIKOR, and PROMETHEE II methods, and the most suitable alternative was determined (Hariz et al., 2017). In selecting the disposal firm, the ANP method, which considers the interdependencies between criteria and alternatives, was used. To reduce the risk of dependence on a single source, multiple supply models were developed through which waste was distributed to firms (e.g., 500, 500, and 1000 kg/day, respectively) (Chauhan & Singh, 2021). In a study on disposal technology selection, a hybrid fuzzy method called F-DBM was applied. In this analysis, the "social dimension" was the criterion with the highest weight with 32.17%, followed by the "economic" (30.08%) and "technological" (24.59%) dimensions; "disinfection effectiveness" stood out as a critical sub-criterion in terms of inactivation of microorganisms (Demir & Moslem, 2024b).

Medical waste logistics and network designs have been extensively studied to manage increasing and uncertain waste volumes, especially during times of crisis such as the COVID-19 pandemic (Govindan et al., 2024; Yu et al., 2020). Studies in this area have generally focused on modeling reverse logistics networks aiming to minimize costs, environmental impacts, and/or risks. Scenario-based stochastic mixed integer linear programming (MILP) models (Govindan et al., 2024) or robust optimization approaches (Homayouni & Pishvaee, 2020) have been used to address uncertainties in waste quantities and facility capacities. Strategies such as establishing new collection centers, utilizing overtime, and third-party logistics (3PL) collaboration have been integrated into these models to increase resilience (Govindan et al., 2024). A multi-loop and multi-objective emergency logistics network model developed using the Wuhan outbreak example was solved with the MOPSO-NSGA2 hybrid algorithm. This study showed that the multi-cycle model more effectively reduced both the economic cost (110.139 million CNY in the optimal solution) and the infection risk (5137.88 in the optimal solution) compared to the single-cycle model (Liu et al., 2021).

VRP, an operational sub-branch of network design, has been frequently addressed in the MWM literature with the objective of minimizing cost and risk. Multi-center, two-objective route optimization models have been developed that aim to simultaneously minimize transportation cost and maximum infection risk (Wang et al., 2023). Infection risk has been defined in different ways, such as the VanUlden and S-I models, factors such as leakage amount, surrounding population density, transportation time, and wind speed (Hu et al., 2024), or storage risks at transit points in addition to transportation risk (Zhang et al., 2025). In a model focusing on COVID-19 waste, the total cost is combined as the sum of transportation costs, low-temperature sterilization costs, and various risk costs weighted by AHP (Xue et al., 2023b). Various optimization techniques have been proposed to solve these complex VRPs, such as the epsilon-constraint method (Wang et al., 2023), specialized genetic algorithms (GA) (Xue et al., 2023a), improved NSGA-II (Zhang et al., 2025), and the adaptive hybrid artificial fish swarm algorithm (AH-NSAFSA) (Hu et al., 2024).

In recent years, models for the use of electric vehicles (EVs) in medical waste collection processes have been developed in line with "green governance" (Zhao et al., 2023) and sustainability goals. Models have been designed for heterogeneous EV fleets (Erdem, 2022) or combining facility location, charging station visits, and routes (Lin et al., 2024). These models aim to minimize energy costs, charging costs, and infection risk (associated with severity and probability depending on the type of waste). Advanced algorithms, such as E-ALNS/D (Lin et al., 2024) and hybrid ALNS (Erdem, 2022), have been used for this solution. These studies have shown that fast chargers increase overall performance and that a significant portion (66%) of total energy costs arise from initial charging costs.

Technology integration is also considered as a critical element in improving the effectiveness of management processes. Advanced online monitoring technologies and real-time tracking systems (e.g., the COVID-19 BMW application in India) ensure an accurate data collection throughout the waste's lifecycle, supporting effective policy development and management planning (Bagwan, 2023).

Medical Waste Management within the Environmental, Social and Governance (ESG) Framework

Today, companies' responsibilities extend beyond profit maximization to encompass social and environmental aspects; ESG practices are seen as a fundamental tool for long-term sustainability and financial performance (Singhania & Saini, 2022). This approach is critical for the healthcare sector due to the threats posed by climate change. ESG principles have become a core component in the long-term strategic planning of large operational units, such as hospitals (van Schie, 2024) and pharmaceutical companies (Jia et al., 2022). Adopting ESG principles in healthcare organizations allows them to manage environmental and social risks, promote health equity, contribute to community well-being, and strengthen their reputation (Jia et al., 2022).

This framework is also being integrated into specific operational challenges such as medical waste management. In a study evaluating alternatives for the recovery of medical waste within the scope of ESG, MCDM methods, such as DFS-WINGS and DFS-CODAS were integrated (Chu et al., 2025). DFS-WINGS findings revealed that criteria, such as supply chain traceability, risk monitoring index, acidifying emissions, transparency and accountability, and renewable energy use were decisive in the assessment process. DFS-CODAS analysis, on the other hand, showed that the most suitable alternative within the ESG framework is the rotary kiln combustion method with heat recovery and flue gas treatment.

The success of such sustainability practices depends on factors such as management knowledge, commitment of healthcare professionals, use of technology (van Schie, 2024), and stakeholder engagement (Yu et al., 2024). Green HRM practices, which integrate environmental management with human resources, play a significant role in enhancing organizational sustainable performance (Khan & Muktar, 2024). Research shows that Green HRM practices, such as green recruitment, training, and performance evaluation, have a positive impact on sustainable performance, and this relationship is strengthened by "green employee empowerment". Employee participation in environmental decision-making processes, such as waste management and energy efficiency, directly strengthens sustainable performance in hospitals.

The integration of technology and AI is another critical element in achieving ESG goals. AI applications reduce waste by optimizing resource use in the environmental dimension; analyze occupational safety and diversity in the social dimension; and strengthen transparency and risk management in the governance dimension (Rane et al., 2024). In healthcare logistics and pharmaceutical supply chains, AI-based predictive analytics provide demand forecasting and inventory optimization, reducing the risks of waste and overstocking (Alemde, 2025). Given the high R&D costs of "green" or "double-carbon" products, advanced technologies, such as AI, digital twins, and blockchain, are becoming essential to increase operational efficiency, transparency, and profitability across the supply chain (Alemde, 2025; Yang, 2023).

Measuring and reporting ESG performance is critical for all stakeholders. To this end, integrated MCDM frameworks (Yu et al., 2024) or advanced data analytics models using deep learning techniques and prescriptive methodologies are recommended. For example, a model tested on Fortune 500 companies that used quartile scores instead of traditional weighted averages achieved nearly 99% accuracy in classifying ESG performance groups (Sariyer et al., 2024). Green employment, a tangible outcome of successful ESG strategies, demonstrates companies' environmental and social commitments and directly correlates with Sustainable Development Goals, such as SDGs 7, 8, 12, and 13 (Figuerola-Ferretti et al., 2025).

However, some limitations and challenges are also noted in literature. One limitation is that the medical waste management model is based only on qualitative data from experts in Hong Kong and has not yet been validated in the real world (Chu et al., 2025). Similarly, MCDM methods may rely on subjective differences in qualitative assessments and single expert opinion (Yu et al., 2024). Data privacy, algorithmic bias, and ethical issues are challenges that need to be considered when using AI (Rane et al., 2024). Future studies are recommended to integrate dynamic decision support tools and data-driven optimization models (Chu et al., 2025), support group decisions and quantitative data (Yu et al., 2024) and detail the long-term impacts and lifecycle sustainability of ESG criteria. Furthermore, policy makers need to support inter-hospital information sharing infrastructures and financial investments for environmental sustainability (van Schie, 2024).

Medical Waste Management Within the Framework of Sustainable Development Goals (SDGs)

Global health threats, such as infectious diseases, climate change, and antimicrobial resistance, have made MWM a strategic priority for healthcare institutions (Lee & Lee, 2022). Public health crises such as COVID-19 have further complicated these challenges, leading to sudden increases and uncertainties in the amount of medical waste (Barouki et al., 2021; Govindan et al., 2024) and placing significant pressure on healthcare systems. Correct classification of medical waste and implementation of environmentally friendly disposal methods are critical for establishing a healthcare environment aligned with the SDGs (Lee & Lee, 2022).

Literature identifies the obstacles to an effective MWM system as the lack of standardized protocols, inadequate waste separation practices, low awareness and knowledge among staff, and a lack of financial and human resources (Quttainah & Singh, 2024). Inadequacies in MWM practices can lead to waste rates exceeding World Health Organization (WHO) recommendations. In fact, a study conducted in training hospitals in Kermanshah reported that the total daily waste amount was 6279 kg and the medical waste rate was equal to the general waste rate (Alighardashi et al., 2024). For successful sustainability practices, management knowledge, involvement of managers in the process, commitment of healthcare professionals and use of technology stand out as key factors (van Schie, 2024).

Various management strategies and operational models have been developed to overcome these challenges and achieve the SDGs targets. At the operational level, optimizing single-use products through inventory management and expiration tracking (Lee & Lee, 2022) or adopting management strategies such as circular economy (CE) and plan-do-check-act (PDCA) have been found to be effective in reducing waste (Alighardashi et al., 2024). The design of logistics networks also plays a central role in optimizing MWM. Multi-loop and multi-purpose emergency medical waste disposal logistics network models have been developed that aim to simultaneously optimize economic cost and infection risk by considering uncertainties in waste generation and population density (Liu et al., 2021). These multi-loop analyses have been found to yield more advantageous results in terms of cost and risk compared to single-loop analyses. Reverse logistics network designs that include measures, such as overtime, the use of 3PL, and the establishment of new collection centers are also recommended to increase network resilience during crises (Govindan et al., 2024).

In the context of reducing environmental impact, strategies such as separating and recycling waste at source are gaining prominence as an alternative to traditional incineration methods. Life cycle assessment (LCA) studies show that switching from hazardous waste incineration to general waste management and plastic recycling strategies reduces global warming impact by 79.7% (Cho et al., 2024).

In addition to operational improvements, managerial and human factors also directly impact sustainability performance. Integrated management systems (IMS), which integrate standards such as ISO 9001 (Quality) and ISO 14001 (Environment) simultaneously improve clinical quality and environmental sustainability, providing measurable improvements in waste management, resource efficiency, patient satisfaction, and staff engagement (Simion Ludușanu et al., 2025). In terms of human resources, the adoption of Green HRM practices (recruitment, training, performance evaluation) and the empowerment of employees in environmental initiatives (Green Employee Empowerment) directly and positively impact the environmental performance of organizations (Khan & Muktar, 2024).

Finally, MWM performance is seen as an integral part of the overall sustainability performance of institutions. Measuring environmental performance is a fundamental requirement for hospital managers to develop strategies, monitor targets, and ensure institutional accountability (Dolcini et al., 2025). To this end, advanced data analytics-based models that evaluate Environmental, Social, and Governance (ESG) components across quartiles (Sariyer et al., 2024) and holistic assessment frameworks that enable benchmarking across healthcare institutions have been proposed (Yu et al., 2024). Tracking indicators such as green employment is considered as concrete evidence of institutions' commitment to goals, particularly SDG 8 (Decent Work and Economic Growth) and SDG 13 (Climate Action) (Figuerola-Ferretti et al., 2025).

Future studies should consider the integration of Industry 4.0 technologies, such as the IoT (Tirkolaee et al., 2024), RFID-tagged waste bags, EVs (Govindan et al., 2024), and AI (Simion Ludușanu et al., 2025), for the optimization of MWM processes. The use of meta-heuristic algorithms for large-scale problems and the development of domain-specific multidisciplinary approaches (Barouki et al., 2021; Quttainah & Singh, 2024) are suggested.

Circular Economy, Energy, and Technology-Based Disposal Strategies

The inadequacy of current hospital waste management practices necessitates the development of new disposal strategies based on energy and technology, in line with CE principles (Ali et al., 2016; Alighardashi et al., 2024). A study conducted in hospitals in Kermanshah found that the total daily waste amount was 6279 kg, and the proportion of medical waste exceeded the WHO recommendations (Alighardashi et al., 2024). This suggests that national waste management guidelines should be revised to include environmental and economic aspects. Effective strategies require careful separation of waste at source. A study based on Portuguese legislation revealed that by meticulously separating only those wastes that must be incinerated, the amount of waste to be incinerated could be reduced by 80% (Alvim-Ferraz & Afonso, 2005). This separation can achieve dramatic reductions in emissions, such as 98% for particulate matter (PM), 99.5% for dioxins, and 93% for SO_2 and NOx. LCC studies also confirm that switching from hazardous waste incineration to separation and plastic recycling strategies results in significant reductions in environmental impacts. For example, landfilling general waste reduces global warming impacts by 79.7%, while plastic recycling contributes an additional 11.8% (Cho et al., 2024).

Energy recovery is at the core of technology-based approaches. WtE facilities not only provide disposal but also serve as a climate-friendly alternative to fossil fuels for energy and metal recovery (Lausselet et al., 2016). Thermal disposal systems with heat recovery installed within hospitals can be both energy efficient and economically attractive, with average overall efficiencies of up to 73% and a capital payback period of 3.1 years (Bujak, 2015). The success of these systems depends on the need for facilities capable of consuming the recovered energy (typically 95.8% of which is hot water). Integrated systems such as chemical disinfection or thermal friction sterilization, developed as alternatives to incineration systems, can reduce the load on incineration by 33% to 70%, resulting in economic savings of 43% to 61%, particularly from transportation costs (Jia et al., 2022).

AI and optimization play a critical role in achieving circular economy goals. AI technologies such as machine learning and computer vision have the potential to reduce environmental burdens by optimizing waste classification, recycling, and collection processes (Snoun et al., 2025). This is particularly important for overcoming classification barriers and implementing underutilized strategies, such as "redesign" and "reduce" in the management of plastics in the healthcare sector (Cano et al., 2025). In the logistics and supply chain dimension, multi-objective optimization models developed for reverse logistics and closed-loop supply chains are gaining importance (Elliazidi & Dkhissi, 2024; Torkayesh et al., 2021). These models support network design, inventory management, and transportation decisions by optimizing economic (cost), environmental (CO_2 emissions), and social criteria together.

Tools such as life cycle osting (LCC) are used for holistic evaluation of these strategies. LCC models allow for the calculation of environmental LCC and societal LCC by transparently analyzing budget, transfer, and externality costs (Martinez-Sanchez et al., 2015). Analyses show that practices that require additional costs, such as organic waste decomposition, provide significant environmental gains in categories such as toxicity and eutrophication. However, some studies lack environmental cost-benefit analyses (Jia et al., 2022) or are limited to greenhouse gas emissions (Ali et al., 2016), suggesting the need to expand the scope of research in this area.

Digitalization, Data-Driven Logistics, and Corporate Governance – Resilience

Digitalization and data-driven logistics approaches play a critical role in optimizing community temporary storage areas and disposal routes (Zhao et al., 2023). Especially in the management of infectious medical waste, managing risks in transportation and storage processes is vital for system resilience (Zhang et al., 2025). These approaches also increase institutional resilience by providing a proactive roadmap to reduce resource waste in medical supply chains during disasters (Bastani et al., 2021). From a corporate governance perspective, operational decisions in these processes should be based on criteria of feasibility, controllability, and efficiency.

AI applications play a central role in optimizing resource use by supporting circular economy models in waste management (Snoun et al., 2025). When integrated with ESG criteria, AI supports environmental sustainability by optimizing resource use, reducing waste, and minimizing carbon footprint (Rane et al., 2024). Technologies such as machine learning and computer vision are improving waste classification and collection processes (Snoun et al., 2025). For example, deep learning-based methods such as 'Deep MWM' can visually classify medical waste with high accuracy, reducing waste volume, costs, and environmental risks (Zhou et al., 2022). Similarly, predictive analytics and IoT-based systems allow municipalities to predict waste generation patterns and reduce operational costs by up to 30% (Bello & Odiete, 2022).

The integration of specific technologies provides tangible improvements in logistics processes. Smart bins equipped with IoT sensors provide real-time monitoring of biomedical waste management with response times ranging from 3 to 16 minutes to overflow alarms (Ishaq et al., 2025). Blockchain-based management frameworks, when combined with IoT sensors and smart contracts, can offer significant gains compared to traditional methods, such as 100% traceability accuracy, a 30% reduction in disposal time, and a 90% increase in regulatory compliance (Lakshmanan et al., 2025).

Route optimization problems in medical waste reverse logistics are addressed with multi-objective models that integrate cost and risk factors. During epidemic periods such as the COVID-19 pandemic, models that consider transportation, sterilization, and multiple risk costs have been developed (Xue et al., 2023b; Yu et al., 2020). In these models, risk weights are estimated using the AHP, while customized genetic algorithms, improved NSGA-II (Zhang et al., 2025), or interactive fuzzy methods are used for the solution. Case studies show that these methods significantly reduce total cost and transportation time (Xue et al., 2023a; Xue et al., 2023b). A two-stage solution method reduced solution time by an average of 26.6%, providing effective plans for situations requiring rapid decision-making (Zhang et al., 2025).

In decision support processes, methods such as MCDM help determine optimal solutions based on cost and other criteria among different disposal technologies, such as autoclaves and incinerators (Ciplak, 2015).

However, the full integration of AI and data-driven systems also presents challenges such as data accessibility, algorithmic bias, and ethical issues. Successful implementation, especially in developing countries, requires developing strategies tailored to local socioeconomic and infrastructural conditions (Bello & Odiete, 2022) and establishing strong AI governance frameworks (Alemde, 2025). Future work is recommended to integrate dynamic patterns of waste generation and real-time data into route optimization models (Xue et al., 2023b), model more complex scenarios (Zhang et al., 2025) and utilize advanced methods such as stochastic programming to manage uncertainty (Yu et al., 2020).

Stakeholder Participation and Social Awareness

Stakeholder participation and public awareness play a critical role in ensuring sustainable and safe waste disposal processes in healthcare institutions. Waste management effectiveness is directly related to the participation of key stakeholders, such as administrators, healthcare personnel, and environmental health authorities, in decision-making processes (Azami-Aghdash et al., 2023). This participation increases interaction among different actors (Alighardashi et al., 2024), increasing information sharing and general awareness (Chauhan & Singh, 2021), thereby strengthening the effectiveness of practices, such as waste reduction and source separation.

Stakeholder theory emphasizes the importance of integrating both top-down perspectives from managers and bottom-up input from healthcare professionals in policy development processes (van Schie, 2024). Indeed, as seen in the example of the medical waste management program implemented in primary health care centers in Saudi Arabia, top-down approaches based solely on top-management decisions limit the participation of practitioners in the process, reduce their sense of responsibility, and lead to inconsistency in policy objectives (Almubarak et al., 2024). Therefore, ensuring effective collaboration and coordination among stakeholders in policy design and implementation is essential for sustainability.

Stakeholder engagement is fundamental to training programs that increase staff knowledge, attitudes, and skills. Continuing education, consulting, and awareness-raising strategies are decisive in achieving goals such as zero-waste by encouraging staff's active participation in processes (Alanazi et al., 2024). Supporting training programs with guidance materials, workshops, hands-on monitoring activities (Azami-Aghdash et al., 2023) and visual aids, such as color-coded bags and labeling systems, increase awareness and process safety. Furthermore, establishing information-sharing infrastructures among hospitals and making financial investments in environmental sustainability strengthen the awareness of both staff and the public (van Schie, 2024).

Participatory approaches provide tangible benefits at different operational stages of waste management. The success of strategies such as adopting green procurement practices (Nsowah et al., 2024) and reducing inventory waste depends directly on the active participation of managers and staff. Analytical tools such as the ABC-VEN matrix prevent waste by providing decision-making support to stakeholders in the management of high-cost and critical inventory (Alanazi et al., 2024). When selecting disposal companies, stakeholders can create cost advantages and operational efficiencies by conducting risk and performance assessments (Chauhan & Singh, 2021) or by using game theory-based collaboration models (e.g., Shapley value) (Eryganov et al., 2020). Technological integrations also support participation; in emergency hospitals, technologies such as BIM, artificial intelligence, and IoT facilitate interdisciplinary coordination and shared decision-making (Chen et al., 2022). Furthermore, tools such as the hospital-stakeholder collaboration (HSC) and the hospital performance factor (HPF) systematically collect the opinions of external stakeholders, such as patients, physicians, and insurance companies, and integrate them into service improvement processes (Purwaningsih et al., 2023).

Despite all these requirements, significant shortcomings are observed in current practices. Studies conducted in some training hospitals show that the amount of medical waste produced is equal to the general waste rate and above the WHO recommendations, indicating that current management practices and stakeholder participation are inadequate (Alighardashi et al., 2024).

Performance Measurement and Decision Support Systems

The effectiveness of medical waste management in healthcare institutions is directly related to the integrated use of performance measurement and DSS (Chu et al., 2025). DDS is considered as a fundamental tool in processes such as selecting waste disposal companies, planning logistics processes and optimizing strategic decisions. Public health crises such as COVID-19 have increased the importance of robust and effective DSS frameworks in the face of increasing waste volumes (Govindan et al., 2024). The literature demonstrates that different methodologies are utilized in the development of these systems. Methods such as the ANP increase the accuracy of decision processes by considering interactions between criteria such as the disposal company's experience or technology (Chauhan & Singh, 2021), while MCDM allows for the evaluation of different disposal and process options on a regional basis (Ciplak, 2015). To increase operational efficiency, multiple performance objectives, such as cost, risk, emissions, and employment, are simultaneously optimized using stochastic

MILP models that consider uncertainties (Govindan et al., 2024), multi-objective mathematical models (Tirkolaee et al., 2024; Torkayesh et al., 2021), and robust optimization approaches (Homayouni & Pishvaee, 2020). These models provide managers with pareto-based solution alternatives, allowing them to jointly improve operational and environmental performance.

In recent years, performance measurement has become strongly integrated with ESG indicators. Corporate sustainability depends not only on financial returns but also on fulfilling environmental and social responsibilities. In this context, ESG criteria, such as supply chain traceability, transparency, accountability, and renewable energy use (Chu et al., 2025) have become critical performance metrics for DSS (Yu et al., 2024). The integration of ESG principles in supply chains in the pharmaceutical sector (Yang, 2023) or in the overall assessment of corporate performance (Sariyer et al., 2024) increases the effectiveness of systems. Similarly, the implementation of IMS provides a comprehensive decision support framework that improves compliance with ESG goals, resource efficiency and waste management in healthcare institutions (Simion Ludușanu et al., 2025).

In specific application areas, DSS is used in medical waste logistics for optimizing electric vehicles (Lin et al., 2024) or reverse logistics networks (Qi et al., 2023). A hybrid DSS model used in the selection of disposal methods revealed that the social dimension (32.17%) is of the highest importance, followed by the economic (30.08%), technological (24.59%), and environmental (13.16%) dimensions (Demir & Moslem, 2024b). Regional analyses indicate that solutions combined with autoclave technology may be more optimal than complete incineration due to high costs (Ciplak, 2015).

The main limitations of existing studies are the subjectivity of expert opinions and the lack of data (Yu et al., 2024). Future studies recommend the integration of AI (Alemde, 2025; Chu et al., 2025), IoT applications (Tirkolaee et al., 2024), big data analytics (Sariyer et al., 2024), and metaheuristic algorithms (Homayouni & Pishvaee, 2020; Torkayesh et al., 2021) to measure performance and improve the effectiveness of DSS. AI-assisted predictive optimization and the use of real-time data such as electronic health records (EHR) have the potential to increase the accuracy and sustainability of decision processes.

Holistic Thematic Synthesis and Comparative Literature Review

When the literature examined in this study is evaluated holistically, it is seen that research on medical waste management in hospitals is clustered around three main research axes: operational research and optimization approaches, sustainability and governance frameworks (ESG-SDGs), and digitalization and data-driven decision support systems. Operational research-based studies mainly focus on minimizing cost and infection risk in facility location selection, logistics network design, and vehicle routing problems, while sustainability-focused studies expand these technical goals to include environmental performance, social responsibility, and corporate governance dimensions. The digitalization literature emerges as a complementary transformation area that enables the real-time monitoring and management of these multi-dimensional performance goals through artificial intelligence, IoT, and blockchain technologies.

Comparative analysis between studies shows that MCDM methods are dominant in strategic decision problems, while network design and VRP-based optimization models stand out at the operational level. This situation demonstrates that MCDM approaches are positioned as fundamental decision support tools in the literature, given that medical waste management decisions involve multiple and often conflicting criteria, such as cost, environmental impact, infection risk, and social acceptance. However, the definition of the risk concept, the integration of sustainability indicators into the model, and performance measurement approaches show significant differences between studies, limiting the direct comparability of the results. It has been observed that, although many optimization models utilize advanced meta-heuristic algorithms, issues such as validation with real hospital data, scalability, and applicability in dynamic decision-making environments are limited.

While studies within the ESG and SDGs frameworks expand sustainability performance, environmental indicators are seen to be more dominant compared to social and governance dimensions; stakeholder engagement, human factors, and corporate governance mechanisms are often considered separately from technical modeling studies. Similarly, although digital technologies offer high operational potential, socio-technical challenges, such as data accessibility, system integration, ethical risks, and AI governance, have not yet been addressed in an integrated manner in the literature.

The cross-theme assessment points to a fundamental transformative trend in the literature: Medical waste management research is evolving from technical optimization to sustainability-based governance and data-driven intelligent systems. However, a significant portion of current studies focus on specific methods or individual application contexts, and studies that simultaneously integrate operational research models, sustainability performance, digital infrastructures, and stakeholder engagement remain limited. Therefore, developing interdisciplinary approaches that integrate data-driven dynamic decision support systems, real-time monitoring technologies, and sustainability indicators is critical for future research.

This holistic thematic synthesis goes beyond summarizing individual studies, revealing methodological clusters, inter-thematic relationships, and conceptual gaps in the literature; thus, it offers a comparative and multidimensional academic framework for the field of medical waste management in hospitals.

Classification of the Literature

Table 1 provides the classification of papers on the basis of methodology used. As perceived from the table, various methodologies have been used within the context of medical waste management.

Table 1: Paper classification by methodology used

Paper	Methodology Used
Ali et al., 2016; Demir & Moslem, 2024a; Demir & Moslem, 2024b; Erdem, 2022; Govindan et al., 2024; Hariz et al., 2017; Homayouni & Pishvaee, 2020; Hu et al., 2024; Lee & Lee, 2022; Lin et al., 2024; Liu et al., 2021; Quttainah & Singh, 2024; Wang et al., 2023; Xue et al., 2023a; Xue et al., 2023b; Yu et al., 2020; Zhang et al., 2025; Zhao et al., 2023	Operations Research
Alemde, 2025; Chu et al., 2025; Figuerola-Ferretti et al., 2025; Jia et al., 2022; Khan & Muktar, 2024; Rane et al., 2024; Sariyer et al., 2024; Singhania & Saini, 2022; van Schie, 2024; Yang, 2023; Yu et al., 2024	The ESG Framework
Alighardashi et al., 2024; Barouki et al., 2021; Cho et al., 2024; Dolcini et al., 2025; Figuerola-Ferretti et al., 2025; Govindan et al., 2024; Khan & Muktar, 2024; Lee & Lee, 2022; Liu et al., 2021; Quttainah & Singh, 2024; Simion Luduşanu et al., 2025; van Schie, 2024	The SDGs Framework
Ali et al., 2016; Alighardashi et al., 2024; Alvim-Ferraz & Afonso, 2005; Bujak, 2015; Cano et al., 2025; Cho et al., 2024; Elliazidi & Dkhissi, 2024; Jia et al., 2022; Lausselet et al., 2016; Martinez-Sanchez et al., 2015; Snoun et al., 2025; Torkayesh et al., 2021	Technology-Based Disposal Strategies
Alemde, 2025; Bastani et al., 2021; Bello & Odiete, 2022; Ciplak, 2015; Ishaq et al., 2025; Lakshmanan et al., 2025; Rane et al., 2024; Snoun et al., 2025; Xue et al., 2023a; Xue et al., 2023b; Yu et al., 2020; Zhang et al., 2025; Zhao et al., 2023; Zhou et al., 2022	Digitalization, Data-Driven Logistics, and Corporate Governance
Alanazi et al., 2024; Alighardashi et al., 2024; Almubarak et al., 2024; Azami-Aghdash et al., 2023; Chauhan & Singh, 2021; Chen et al., 2022; Eryganov et al., 2020; Nsowah et al., 2024; Purwaningsih et al., 2023; van Schie, 2024	Stakeholder Participation and Social Awareness
Alemde, 2025; Chauhan & Singh, 2021; Chu et al., 2025; Ciplak, 2015; Demir & Moslem, 2024a; Demir & Moslem, 2024b; Govindan et al., 2024; Homayouni & Pishvaee, 2020; Lin et al., 2024; Qi et al., 2023; Sariyer et al., 2024; Simion Luduşanu et al., 2025; Tirkolaee et al., 2024; Torkayesh et al., 2021; Yang, 2023; Yu et al., 2024	Performance Measurement and Decision Support Systems

Research Gap

The literature review indicates that, while significant progress has been made in the field of medical waste management, significant research gaps persist in certain areas.

First, decision support systems and MCDM models face significant issues of subjectivity and data limitations. Many studies rely on the qualitative opinions of a single expert or a small group of experts for criteria weighting and alternative evaluation. This limits the generalizability and objectivity of the results and highlights the need for hybrid models based on quantitative data or that more effectively integrate group decisions.

It is observed that mathematical models developed in operations research and optimization (e.g., VRP or network design models) are largely theoretical and lack validation with real-world data. The number of case studies testing the applicability of models to large-scale, dynamic, and uncertain real-world hospital operations is insufficient.

While the integration of digitalization and Industry 4.0 technologies (AI, IoT, Blockchain) is rapidly increasing, the ethical dimensions of these technologies, including data privacy, algorithmic bias, and cybersecurity risks, have not been adequately addressed in the context of AI. The lack of strong AI governance frameworks and ethical guidelines is a significant gap.

Cost-benefit analyses and LCA studies are often limited in scope. Many analyses focus solely on greenhouse gas emissions or direct economic costs, while holistic LCAs that include other environmental externalities, such as toxicity and eutrophication, or social impacts, are lacking.

Finally, while studies on stakeholder engagement and management models exist, there is a gap in integrated governance and collaboration models that balance the conflicting objectives of different stakeholders (management, staff, patients, regulators) and encourage bottom-up participation.

When these research gaps are considered together with the thematic structure identified in the study, it shows that the deficiencies in the literature stem not only from methodological limitations but also from a lack of inter-thematic integration. While operational research models mostly focus on technical optimization performance, ESG and SDGs-based studies address sustainability indicators independently of operational decision-making mechanisms. Similarly, although digitalization and Industry 4.0 technologies offer significant opportunities, studies examining the integrated use of these technologies with optimization models, governance structures, and circular economy strategies remain limited. This situation reveals a conceptual disconnect between thematic areas in medical waste management research and highlights the need for integrated analytical frameworks.

Future Limitations

These limitations, when evaluated within the thematic framework presented in this study, demonstrate that the existing literature largely relies on one-dimensional research approaches. In particular, the fact that operational research, sustainability (ESG-SDGs), circular economy, and digitalization are often treated as separate research streams limits the development of integrated decision support systems.

While this review aims to provide a comprehensive overview of the medical waste management literature, it has several limitations. As a review, it is limited by the databases and keywords selected; there is a possibility that certain studies were overlooked (publication bias) because a systematic review or meta-analysis protocol was not followed. Furthermore, because the analysis relied on a synthesis of existing literature, the practical applicability or effectiveness of the proposed models was not directly tested.

Considering these limitations and the identified research gaps, the following recommendations for future research have been developed:

- **Advanced Modeling and Optimization:** Future studies should utilize advanced methods, such as stochastic programming, fuzzy logic, and robust optimization, to more effectively manage uncertainty (waste production volume, transportation times, etc.). The use and comparative analysis of metaheuristic algorithms (e.g., ALNS, Enhanced NSGA-II) should be encouraged, especially for large-scale and complex VRP or network design problems.
- **Data-Driven and Dynamic Systems:** As an alternative to static models, dynamic decision support systems should be developed. Integrating AI-supported predictive analytics (for waste production estimation), real-time data from IoT sensors (smart boxes), and electronic health records (EHR) into route optimization models will increase system efficiency and resilience.
- **Holistic Sustainability Analysis:** When evaluating disposal technologies and logistics strategies, comprehensive LCA models that go beyond mere cost or CO_2 emissions should be applied. These models should consider environmental, economic, and social dimensions (e.g., employment, public health risk) together.
- **Quantitative and Hybrid Decision Models:** To reduce subjectivity in MCDM studies, hybrid models that combine qualitative methods based on expert opinions (such as AHP and ANP) with quantitative tools such as big data analytics or simulation are needed.

- **Real-World Validation:** Validation and piloting of proposed theoretical models and algorithms through real-world hospital case studies in regions with different socioeconomic and infrastructural conditions (especially in developing countries) is critical.
- **Governance and Policy:** Ethical guidelines, data governance frameworks, and regulatory standards should be developed for the use of AI and other digital technologies in MWM processes. Furthermore, policymakers should support inter-hospital information-sharing infrastructures and financial investments in green technologies.

CONCLUSION

This literature review clearly demonstrates that medical waste management has evolved from a simple operational obligation into a multidisciplinary and strategic area that directly impacts the resilience, sustainability, and public health security of healthcare systems. The reviewed studies demonstrate that research in medical waste management primarily focuses on operational efficiency, sustainability integration, technological adaptation, and managerial frameworks.

Operations research approaches represent a mature strand of the medical waste management literature. Multi-objective optimization models and metaheuristic algorithms (GA, NSGA-II, ALNS, etc.) have been widely used, particularly in logistics network design, VRP, and facility layout, aiming to simultaneously minimize cost and infection risk. Similarly, the use of MCDM methods, such as AHP, ANP, and VIKOR, has become standard practice in strategic decisions such as disposal technology or supplier selection.

With the paradigm shift experienced in recent years, MWM processes are now being addressed in an integrated manner within the ESG and SDGs frameworks. Research highlights the critical roles that measuring environmental performance, implementing Green HRM, and institutional transparency play in helping hospitals achieve their long-term sustainability goals. This trend has also fueled the adoption of circular economy principles. Strategies such as rigorous source separation, plastic recycling, and WtE facilities reduce environmental impact while also achieving economic and energy efficiency.

Technology integration represents the most dynamic research direction in this field. Industry 4.0 technologies, such as AI, the IoT, and blockchain, have the potential to revolutionize MWM processes. AI-powered visual classification systems, real-time route optimization with IoT-based smart waste bins, and blockchain-based traceability systems are increasing both efficiency and regulatory compliance. However, the success of these technological advances depends on human factors, such as stakeholder engagement and public awareness. Lack of training and low staff participation in decision-making can lead to the failure of even the most advanced systems.

The reviewed literature, while significant progress has been made in this area, also highlights significant limitations and future research needs. Many MCDM studies rely on subjectivity in qualitative assessments and the opinion of a single or small number of experts, limiting the generalizability of the results. Data privacy, algorithmic bias, and ethical issues remain significant challenges in the implementation of AI and data-driven systems. Furthermore, the fact that many proposed models have not yet been validated with real-world data or tested on large-scale problems is a significant limitation.

Future work should focus on filling these gaps. Dynamic decision support tools and data-driven optimization models (fed by real-time data, such as AI, IoT, and electronic health records) need to be developed. Integrating stochastic programming and robust optimization approaches, particularly for situations with high uncertainty (such as a pandemic), will increase system resilience. Hybrid MCDM models that support group decision-making and make greater use of quantitative data are needed to reduce subjectivity. Finally, policymakers' support for inter-hospital information-sharing infrastructures and financial investments for environmental sustainability are essential for translating theoretical models into practice.

The key contribution of this study is its analysis of the medical waste management literature not solely through individual methods or application areas, but under an integrated thematic perspective that reveals the interaction between operational research approaches, ESG and SDGs frameworks, circular economy strategies, and digitalization-based smart systems. The findings demonstrate that the evolution of the field is progressing from technically optimized models to a sustainability-based governance approach and data-driven adaptive systems. This thematic synthesis highlights the need for a critical research direction for future research, not only in developing new methods but also in developing interdisciplinary decision models that simultaneously integrate operational, environmental, social, and digital dimensions.

Accordingly, the thematic framework developed within the scope of this study reveals that medical waste management research should be considered not only as a methodologically focused field, but also as an integrated research area shaped by the interaction of operational optimization, sustainability governance, and digital transformation. This approach guides future research trends that integrate OR-based analytical methods into data-driven and adaptable decision support systems aligned with ESG and SDGs goals, rather than the tendency to develop fragmented models.

Ethical Approval: Ethical approval was not required for this study.

Authors' Contributions: GK undertook the responsibility of writing the entire manuscript, made necessary revisions based on the feedback of the co-author, performed extensive literature review about the topic. YG reviewed the entire manuscript and provided feedback to the corresponding author, contributed to Abstract, Introduction, and Research Gap sections, and created Table 1.

Funding and Acknowledgment: No financial support was received from any institution.

Conflict of Interest Statement: The authors have no relevant conflict of interest.

REFERENCES

Alanazi, M. Q., Alkhadhairi, E. K., Alrumi, W. H., & Alajlan, S. A. (2024). Reducing pharmaceutical and non-pharmaceutical inventory waste in tertiary hospital: Impact of ABC-VEN analysis in a zero-waste strategy over 7 years. Risk Management and Healthcare Policy, 2024(17), 2659–2675. https://doi.org/10.2147/RMHP.S467230

Alemde, V. O. (2025). Deploying strategic operational research models for AI-augmented healthcare logistics, accessibility, and cost reduction initiatives. International Research Journal of Modernization in Engineering Technology and Science, 7(2), 2353–2371. https://doi.org/10.56726/IRJMETS67609

Ali, M., Wang, W., & Chaudhry, N. (2016). Application of life cycle assessment for hospital solid waste management: A case study. Journal of the Air & Waste Management Association, 66(10), 1012–1018. https://doi.org/10.1080/10962247.2016.1196263

Alighardashi, M., Mousavi, S. A., Almasi, A., & Mohammadi, P. (2024). Hospital waste management system in Kermanshah: Challenges, future and sustainable management with circular economy. Scientific Reports, 14, 25671. https://doi.org/10.1038/s41598-024-76525-4

Almubarak, S. A. H., Almass, A. A., Dahlawi, S. M., & AlMuhanna, D. S. (2024). Waste management in primary healthcare centers in Saudi Arabia: A policy analysis. International Journal of Environmental Health Research, 34(3), 1421–1430. https://doi.org/10.1080/09603123.2023.2214508

Alvim-Ferraz, M. C. M., & Afonso, S. A. V. (2005). Incineration of healthcare wastes: Management of atmospheric emissions through waste segregation. Waste Management, 25(6), 638–648. https://doi.org/10.1016/j.wasman.2004.07.017

Azami-Aghdash, S., Sayadzadeh, M., Ashtari, A., Derakhshani, N., Sedaei, Z., & Rezapour, R. (2023). Improving the hospital waste management at the Farabi hospital in Malekan -Iran: An action research study. Heliyon, 9(7), e17695. https://doi.org/10.1016/j.heliyon.2023.e17695

Bagwan, W. A. (2023). An investigation of the bio-medical waste produced in India during the COVID-19 pandemic and Maharashtra state (pre-COVID-19 and post-COVID-19) analysis: A GIS-based approach. Research in Health Services & Regions, 2(1), 8. https://doi.org/10.1007/s43999-023-00023-9

Barouki, R., Kogevinas, M., Audouze, K., Belesova, K., Bergman, A., Birnbaum, L., Boekhold, S., Denys, S., Desseille, C., Drakvik, E., Frumkin, H., Garric, J., Destoumieux-Garzon, D., Haines, A., Huss, A., Jensen, G., Karakitsios, S., Klanova, J., Koskela, I.-M., ... HERA-COVID-19 Working Group. (2021). The COVID-19 pandemic and global environmental change: Emerging research needs. Environment International, 146, 106272. https://doi.org/10.1016/j.envint.2020.106272

Bastani, P., Sadeghkhani, O., Ravangard, R., Rezaei, R., Bikine, P., & Mehralian, G. (2021). Designing a resilience model for pharmaceutical supply chain during crises: A grounded theory approach. Journal of Pharmaceutical Policy and Practice, 14(1), 115. https://doi.org/10.1186/s40545-021-00399-4

Bello, A., & Odiete, A. O. (2022). The role of predictive analytics in enhancing urban waste management efficiency: A case study of the waste generation prediction tool in developing economies. International Journal of Computer Applications Technology and Research, 10(12), 323–334. https://doi.org/10.7753/IJCATR1012.1007

Bujak, J. W. (2015). Production of waste energy and heat in hospital facilities. Energy, 91, 350–362. https://doi.org/10.1016/j.energy.2015.08.053

Cano, N. S. D. S. L., Marino, M., Brooks, A. L., Eckelman, M. J., & Bilec, M. M. (2025). Advancing the circular economy of healthcare plastics: A systematic literature review. Resources, Conservation and Recycling, 219, 108317. https://doi.org/10.1016/j.resconrec.2025.108317

Chauhan, A., & Singh, S. P. (2021). Selection of healthcare waste disposal firms using a multi-method approach. Journal of Environmental Management, 295, 113117. https://doi.org/10.1016/j.jenvman.2021.113117

Chen, L., Zhai, C., Wang, L., Hu, X., & Huang, X. (2022). Modular structure construction progress scenario: A case study of an emergency hospital to address the COVID-19 pandemic. Sustainability, 14(18), 11243. https://doi.org/10.3390/su141811243

Cho, Y., Withana, P. A., Rhee, J. H., Lim, S. T., Lim, J. Y., Park, S. W., & Ok, Y. S. (2024). Achieving the sustainable waste management of medical plastic packaging using a life cycle assessment approach. Heliyon, 10(19), e38185. https://doi.org/10.1016/j.heliyon.2024.e38185

Chu, Y. T., Moktadir, Md. A., & Ren, J. (2025). Constructing an Environmental, Social, and Governance (ESG) metrics framework for assessing medical waste valorization alternatives: A novel integrated MCDM model under decomposed fuzzy environment. Journal of Environmental Management, 373, 123457. https://doi.org/10.1016/j.jenvman.2024.123457

Ciplak, N. (2015). Assessing future scenarios for health care waste management using a multi-criteria decision analysis tool: A case study in the Turkish West Black Sea Region. Journal of the Air & Waste Management Association, 65(8), 919–929. https://doi.org/10.1080/10962247.2015.1038398

Demir, A. T., & Moslem, S. (2024a). Evaluating the effect of the COVID-19 pandemic on medical waste disposal using preference selection index with CRADIS in a fuzzy environment. Heliyon, 10(5), e26997. https://doi.org/10.1016/j.heliyon.2024.e26997

Demir, A. T., & Moslem, S. (2024b). A novel fuzzy multi-criteria decision-making for enhancing the management of medical waste generated during the coronavirus pandemic. Engineering Applications of Artificial Intelligence, 133(Pt E), 108465. https://doi.org/10.1016/j.engappai.2024.108465

Dolcini, M., Ferrè, F., Brambilla, A., & Capolongo, S. (2025). Integrating environmental sustainability into hospitals performance management systems: A scoping review. BMC Health Services Research, 25(1), 764. https://doi.org/10.1186/s12913-025-12928-x

Elliazidi, S., & Dkhissi, B. (2024). Optimizing sustainable reverse logistic networks: A case study of medical waste using the genetic artificial bee colony algorithm. International Journal on Interactive Design and Manufacturing (IJIDeM), 18(6), 4263–4284. https://doi.org/10.1007/s12008-024-01947-3

Erdem, M. (2022). Designing a sustainable logistics network for hazardous medical waste collection a case study in COVID-19 pandemic. Journal of Cleaner Production, 376, 134192. https://doi.org/10.1016/j.jclepro.2022.134192

Eryganov, I., Šomplák, R., Nevrlý, V., Smejkalová, V., Hrabec, D., & Haugen, K. K. (2020). Application of cooperative game theory in waste management. Chemical Engineering Transactions, 81, 877–882. https://doi.org/10.3303/CET2081147

Figuerola-Ferretti, I., Lumbreras, S., Paraskevas, P., & Paraskevopoulos, I. (2025). Sustainability in action: Macro-level evidence from Europe (2008–2023) on ESG, green employment, and SDG-aligned economic performance. Sustainability, 17(20), 9103. https://doi.org/10.3390/su17209103

Govindan, K., Fard, F. S. N., Asgari, F., Sorooshian, S., & Mina, H. (2024). Designing a resilient reverse network to manage the infectious healthcare waste under uncertainty: A stochastic optimization approach. Computers & Industrial Engineering, 194, 110390. https://doi.org/10.1016/j.cie.2024.110390

Hariz, H. A., Dönmez, C. Ç., & Sennaroglu, B. (2017). Siting of a central healthcare waste incinerator using GIS-based Multi-Criteria Decision Analysis. Journal of Cleaner Production, 166, 1031–1042. https://doi.org/10.1016/j.jclepro.2017.08.091

Homayouni, Z., & Pishvaee, M. S. (2020). A bi-objective robust optimization model for hazardous hospital waste collection and disposal network design problem. Journal of Material Cycles and Waste Management, 22(6), 1965–1984. https://doi.org/10.1007/s10163-020-01081-8

Hu, J., Zhang, Y., Liu, Y., Hou, J., & Zhang, A. (2024). Optimization of household medical waste recycling logistics routes: Considering contamination risks. PLOS ONE, 19(10), e0311582. https://doi.org/10.1371/journal.pone.0311582

Ishaq, A., Mohammad, S. J., Bello, A.-A. D., Wada, S. A., Adebayo, A., & Jagun, Z. T. (2025). Smart waste bin monitoring using IoT for sustainable biomedical waste management. Environmental Science and Pollution Research, 32(32), 19434–19449. https://doi.org/10.1007/s11356-023-30240-1

Jia, J., Wang, W., Yin, L., Liu, J., Nzioka, A. M., & Yan, C. (2022). Cost–benefit analysis of introducing custom-made small thermal-frictional sterilization system to the existing hospital waste disposal system: A case study of Chinese hospital. Sustainability, 14(19), 12837. https://doi.org/10.3390/su141912837

Khan, M. H., & Muktar, S. N. (2024). Green employee empowerment: The missing linchpin between green HRM and sustainable organizational performance. Journal of Cleaner Production, 434, 139812. https://doi.org/10.1016/j.jclepro.2023.139812

Lakshmanan, M., Dhanraj, J. A., Sriramkumar, R., Mude, N. N., Mithaguru, & Godhandaraman, T. (2025). Blockchain-enabled medical waste management system for enhanced traceability, safety and environmental protection. International Journal of Advances in Soft Computing and Its Applications, 17(2), 246–268. https://doi.org/10.15849/IJASCA.250730.13

Lausselet, C., Cherubini, F., del Alamo Serrano, G., Becidan, M., & Strømman, A. H. (2016). Life-cycle assessment of a waste-to-energy plant in central Norway: Current situation and effects of changes in waste fraction composition. Waste Management, 58, 191–201. https://doi.org/10.1016/j.wasman.2016.09.014

Lee, S. M., & Lee, D. (2022). Effective medical waste management for sustainable green healthcare. International Journal of Environmental Research and Public Health, 19(22), 14820. https://doi.org/10.3390/ijerph192214820

Lin, K., Musa, S. N., Lee, H. Y., & Yap, H. J. (2024). Sustainable location-routing problem for medical waste management using electric vehicles. Sustainable Cities and Society, 112, 105598. https://doi.org/10.1016/j.scs.2024.105598

Liu, Z., Liu, T., Liu, X., Wei, A., Wang, X., Yin, Y., & Li, Y. (2021). Research on optimization of healthcare waste management system based on green governance principle in the COVID-19 pandemic. International Journal of Environmental Research and Public Health, 18(10), 5316. https://doi.org/10.3390/ijerph18105316

Martinez-Sanchez, V., Kromann, M. A., & Astrup, T. F. (2015). Life cycle costing of waste management systems: Overview, calculation principles and case studies. Waste Management, 36, 343–355. https://doi.org/10.1016/j.wasman.2014.10.033

Nsowah, J., Agyenim-Boateng, G., Amoah, S. K., & Anane, A. (2024). Green procurement practices and barriers in hospitals in the Bono region of Ghana. SN Business & Economics, 4(9), 98. https://doi.org/10.1007/s43546-024-00686-7

Purwaningsih, P., Nasronudin, N., Damayanti, N. A., Mahmudah, M., Andarini, S., Qomarudin, B., Chalidyanto, D., Yuwono, S. R., Septanto, A. N., & Zulkarnain, H. (2023). Development of a hospital-stakeholder collaboration tool using mixed methods to assess stakeholder perspectives for hospital service improvement. Ethiopian Journal of Health Sciences, 33(6), 1075–1086. https://doi.org/10.4314/ejhs.v33i6.18

Qi, P., Wang, Y., & Lin, X. (2023). Optimization of reverse logistics network for medical waste recycling. Journal of Data, Information and Management, 5, 71–88. https://doi.org/10.1007/s42488-023-00090-0

Quttainah, M. A., & Singh, P. (2024). Barriers to sustainable healthcare waste management: A grey method approach for barrier ranking. Sustainability, 16(24), 11285. https://doi.org/10.3390/su162411285

Rane, N., Choudhary, S., & Rane, J. (2024). Artificial intelligence driven approaches to strengthening Environmental, Social, and Governance (ESG) criteria in sustainable business practices: A review. SSRN, https://doi.org/10.2139/ssrn.4843215

Sariyer, G., Mangla, S. K., Chowdhury, S., Sozen, M. E., & Kazancoglu, Y. (2024). Predictive and prescriptive analytics for ESG performance evaluation: A case of Fortune 500 companies. Journal of Business Research, 181, 114742. https://doi.org/10.1016/j.jbusres.2024.114742

Simion Ludușanu, D.-G., Fertu, D.-I., Tinică, G., & Gavrilescu, M. (2025). Integrated quality and environmental management in healthcare: Impacts, implementation, and future directions toward sustainability. Sustainability, 17(11), 5156. https://doi.org/10.3390/su17115156

Singhania, M., & Saini, N. (2022). Systems approach to Environment, Social and Governance (ESG): Case of reliance industries. Sustainable Operations and Computers, 3, 103–117. https://doi.org/10.1016/j.susoc.2021.11.003

Snoun, A., Mufida, M. K., El-Cadi, A. A., & Delot, T. (2025). AI-driven innovations in waste management: Catalyzing the circular economy. Engineering Proceedings, 97(1), 12. https://doi.org/10.3390/engproc2025097012

Tirkolaee, E. B., Simic, V., Ghobakhloo, M., Foroughi, B., Asadi, S., & Iranmanesh, M. (2024). Integrated design of a sustainable waste management system with co-modal transportation network: A robust bi-level decision support system. Journal of Cleaner Production, 449, 141760. https://doi.org/10.1016/j.jclepro.2024.141760

Torkayesh, A. E., Vandchali, H. R., & Tirkolaee, E. B. (2021). Multi-objective optimization for healthcare waste management network design with sustainability perspective. Sustainability, 13(15), 8279. https://doi.org/10.3390/su13158279

Van Schie, V. (2024). Governance related factors influencing the implementation of sustainability in hospitals: A systematic literature review. Health Policy, 146, 105115. https://doi.org/10.1016/j.healthpol.2024.105115

Wang, N., Cui, W., Zhang, M., & Jiang, Q. (2023). Routing optimization for medical waste collection considering infectious risk and multiple disposal centers. Expert Systems with Applications, 234, 121035. https://doi.org/10.1016/j.eswa.2023.121035

Xue, C., Dong, Y., Liu, J., Liao, Y., & Li, L. (2023a). Design of the reverse logistics system for medical waste recycling part I: System architecture and disposal site selection algorithm. 2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC), 1741–1746. https://doi.org/10.1109/ITSC57777.2023.10422624

Xue, C., Dong, Y., Liu, J., Liao, Y., & Li, L. (2023b). Design of the reverse logistics system for medical waste recycling part II: Route optimization with case study under COVID-19 pandemic. 2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC), 4011–4017. https://doi.org/10.1109/ITSC57777.2023.10422236

Yang, L. (2023). An Environmental, Social, and Governance strategic model for managing pharmaceutical supply chains with financial obstacles. Decision Analytics Journal, 7, 100203. https://doi.org/10.1016/j.dajour.2023.100203

Yu, H., Sun, X., Solvang, W. D., & Zhao, X. (2020). Reverse logistics network design for effective management of medical waste in epidemic outbreaks: Insights from the coronavirus disease 2019 (COVID-19) outbreak in Wuhan (China). International Journal of Environmental Research and Public Health, 17(5), 1770. https://doi.org/10.3390/ijerph17051770

Yu, K., Wu, Q., Chen, X., Wang, W., & Mardani, A. (2024). An integrated MCDM framework for evaluating the Environmental, Social, and Governance (ESG) sustainable business performance. Annals of Operations Research, 342(1), 987–1018. https://doi.org/10.1007/s10479-023-05616-8

Zhang, M., Cui, W., Jiang, Q., Wang, N., & Shang, Y. (2025). Vehicle routing for infectious healthcare waste collection with transit points: A problem incorporating multiple types of risks and two solution methods from different perspectives. IEEE Access, 13, 83542–83560. https://doi.org/10.1109/ACCESS.2025.3566096

Zhao, F., Wang, X., Liu, B., Sun, W., & Liu, Z. (2023). Research on optimization of medical waste emergency disposal transportation network for public health emergencies in the context of intelligent transportation. Applied Sciences, 13(18), 10122. https://doi.org/10.3390/app131810122

Zhou, H., Yu, X., Alhaskawi, A., Dong, Y., Wang, Z., Jin, Q., Hu, X., Liu, Z., Kota, V. G., Abdulla, M. H. A. H., Ezzi, S. H. A., Qi, B., Li, J., Wang, B., Fang, J., & Lu, H. (2022). A deep learning approach for medical waste classification. Scientific Reports, 12, 2159. https://doi.org/10.1038/s41598-022-06146-2