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Barriers to Sustainable Healthcare Waste Management: A Grey Method Approach for Barrier Ranking

Majdi Anwar Quttainah [1,*] and Priya Singh [2]

[1] Management & Marketing Department, College of Business Administration, Kuwait University, Safat, P.O. Box 5486, Kuwait City 13055, Kuwait
[2] Supply Chain & Operations, Institute of Management Studies, Ghaziabad 201009, Uttar Pradesh, India; priyas.rs.mec15@iitbhu.ac.in
* Correspondence: majdi.quttainah@ku.edu.kw

Abstract: Healthcare Waste Management (HCWM) is critical for public health and environmental sustainability. However, healthcare facilities face significant barriers to implementing sustainable HCWM practices, particularly in developing regions. Identifying and prioritizing these barriers is essential to developing practical solutions. This study aims to identify and rank barriers to sustainable HCWM using an integrated methodology. It seeks to provide actionable insights for policymakers and healthcare administrators to improve HCWM practices. The study employed a multi-method approach, combining a comprehensive literature review, expert consultations, and Grey Relational Analysis (GRA). The literature review identified 17 potential barriers across economic, social, technical, and regulatory dimensions. Eight experts from diverse sectors evaluated these barriers based on ten criteria. GRA was used to rank the barriers, and sensitivity analysis assessed the robustness of the rankings under varying parameters. The findings revealed that the most critical barriers include the lack of standardized guidelines and protocols, ineffective waste segregation, awareness and knowledge gaps, and inadequate training. Financial constraints and disposal infrastructure also ranked highly, highlighting systemic challenges in HCWM. Sensitivity analysis demonstrated that these rankings remained stable across varying conditions, affirming the robustness of the results. Addressing the prioritized barriers—mainly through policy standardization, enhanced training programs, and improved resource allocation—can significantly improve HCWM practices. This study underscores the need for a holistic approach integrating technical, social, and regulatory interventions to enhance sustainability in healthcare waste management.

Keywords: sustainable healthcare waste management; barriers; Grey method; multi-criteria decision-making; public health; environmental protection

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1. Introduction

Waste produced by healthcare operations encompasses a wide range of items, such as dirty dressings, body parts, chemicals, medications, medical devices, radioactive materials, diagnostic samples, blood, and spent needles and syringes [1]. Various alternative terms include medical, biomedical, clinical, or health facility waste [2]. HCW is described as all sorts of waste generated from HCFs, regardless of whether it is a dangerous or innocuous material, infectious or non-infectious in nature, or a chemical [3].

Healthcare has been one of the fastest expanding global sectors in recent years [1–3], with global health spending at an all-time high and rising yearly. Healthcare waste management (HCWM) is one of the most critical aspects of the healthcare sector [4]. The most popular term used to characterize garbage generated by HCFs is healthcare waste (HCW). Healthcare waste management plays a significant role in protecting the environment and safeguarding public health [5]. On the contrary, it poses severe risks to healthcare workers, patients, the general public, and the environment if improperly managed. Healthcare

waste includes various materials, such as infectious waste, hazardous chemicals, and non-hazardous materials [6]. All these types of material waste require specific management practices to mitigate the potential harm they can cause.

Inadequate handling of medical waste can put patients, staff members handling it, the general public, and the environment at risk for contamination, harmful consequences, and injury. At the point of creation, all medical waste materials must be separated, properly handled, and disposed of safely [7]. As a by-product of healthcare, healthcare waste (HCW) includes radioactive materials, chemicals, medications, body parts, sharps and non-sharps, blood, and other items.

While people worldwide are concerned about HCWM, many healthcare facilities, especially in developing countries, struggle to implement sustainable waste management practices [8]. Several barriers hinder the adoption of sustainable HCWM practices. These barriers range from financial and infrastructural constraints to social and regulatory challenges [6]. Identifying these barriers and understanding their relative impact is essential for devising effective strategies to overcome them.

The existing literature in the research area highlights various barriers to effective HCWM practices. The most cited barriers are financial constraints, as many healthcare facilities lack adequate funding for proper waste management infrastructure and operations [9]. Because of this, proper systems exist for managing various kinds of waste, and the quantity of hazardous trash produced is continuously tracked [10]. HCW management issues are common in poorer nations, generating hundreds of tons of garbage daily. Research conducted in Ethiopia showed that 35 percent of medical facilities gather and discard needles, syringes, and other sharp objects in a way that continuously increases the danger of exposure and damage to medical staff and the general public [11]. Also, there is often a lack of awareness and training among healthcare staff regarding proper waste segregation and disposal techniques [12]. Inadequate infrastructure, including insufficient waste collection and storage facilities, further intensifies the problem [13]. Moreover, regulatory challenges, such as weak enforcement of existing laws and the absence of comprehensive policies, impede the effective management of healthcare waste [14].

Medical waste has been the subject of numerous initiatives and studies, including the Medical Wastes Act [15], treatment techniques and the state of waste management today [8], medical staff knowledge, attitudes, and practices regarding medical waste [10], and COVID-19-related medical waste, such as [16]. On the other hand, little is known about medical waste's origins, such as healthcare facilities. The efforts and activities of relevant organizations and medical professionals on the front lines of medical waste disposal are critical to environmental protection and cost reduction through medical waste reduction [8]. Moreover, planning to start a shift with healthcare professionals can lay the groundwork for establishing an environmentally friendly healthcare setting.

Given the complexity and interdependence of these barriers, tools like the Grey Relational Analysis (GRA) provide a structured approach to prioritization. The GRA is particularly suited for analyzing complex, multi-criteria problems where data may be uncertain or incomplete. However, addressing these barriers also requires a broader perspective on sustainability. Incorporating Life Cycle Assessment (LCA) into HCWM strategies can enhance decision-making by evaluating the environmental impacts of different waste management policies, such as incineration and gasification. LCA is increasingly recognized as a decision support tool that systematically compares alternatives based on their overall sustainability performance. For instance, studies on the environmental trade-offs of incineration versus recycling highlight the potential for informed policy-making in HCWM [17,18].

This study aims to bridge the knowledge gap by systematically identifying and ranking barriers to sustainable HCWM using the Grey method. By integrating expert insights and robust analytical methods, the research seeks to provide actionable recommendations for policymakers and healthcare administrators, ultimately contributing to improved HCWM practices and enhanced environmental and public health outcomes.

2. Literature Review and Methodology

The study followed a structured process to address the research questions and systematically identify the barriers to sustainable healthcare waste management (HCWM). The study process is illustrated in Figure 1, which provides a clear visual representation of the research steps.

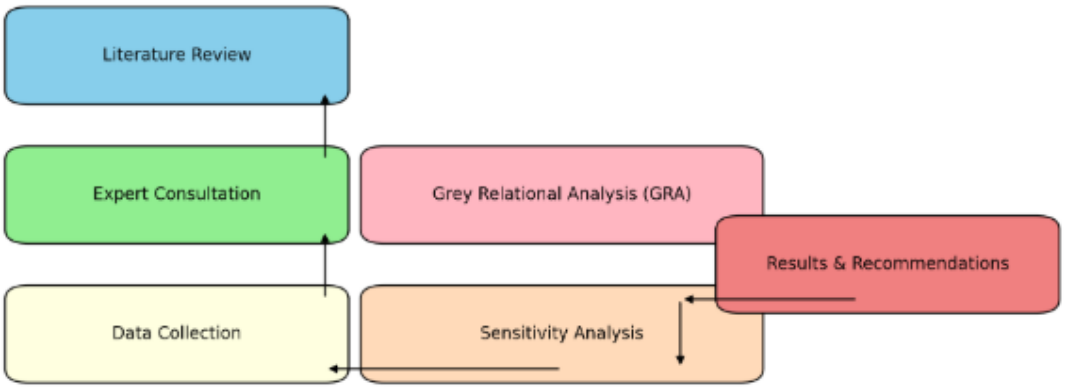


Figure 1. Outlines the research process, starting with a literature review and followed by expert consultation to gather insights. The data collected were then analyzed using Grey Relational Analysis (GRA), and a Sensitivity Analysis was conducted to assess the robustness of the results. The study concludes with presenting Results and Recommendations to inform policymakers and healthcare administrators.

2.1. Literature Review on Barriers to Sustainable Healthcare Waste Management (HCWM)

A comprehensive literature review and expert consultations were conducted to identify the barriers to sustainable Healthcare Waste Management (HCWM). The findings were categorized into four broad dimensions: economic, social, technical, and regulatory.

2.2. Economic Barriers

According to Da Silva et al., inadequate funding and government support for clinical waste management are the leading causes of poor waste management [19]. Several studies have shown that Asian countries, including Bangladesh, India, and Pakistan, lack adequate waste treatment facilities, safety protocols, and training initiatives [20].

Financial provision is required for capital and recurring expenditures, including funds for sufficient personnel, disinfectants, devices, and equipment. Funds are also needed for healthcare staff training and awareness programs. Smaller HCUs disregard waste management practices because of financial constraints [21]. This is an unappealing alternative because of the costs of reprocessing, recycling or reusing garbage. Materials loss and cross-contamination can also result from costly and ineffective recycling processes [22]. The easiest ways to dispose of HCW are usually the least expensive and least environmentally friendly, as stakeholders focus on cost minimization. This leads to stakeholders' reluctance to increase their investments [23]. Moreover, conflicts of interest between departments cause ineffective information communication and poor budgetary coordination [24]. A budgetary conflict of interest and insufficient funding for mitigating environmental damage are two factors contributing to the underfunding of infrastructure [23].

According to ref. [1] Implementing sustainable HCWM often involves substantial initial investment in infrastructure, technology, and training. The ongoing operational costs can also be high, which may deter healthcare facilities, especially those with limited budgets, from adopting these practices [23]. Many healthcare facilities operate under tight budget constraints, particularly in low- and middle-income countries. Limited financial resources restrict their ability to invest in proper waste management systems [25]. Lack of funding from government and private sectors for HCWM projects can hinder the development and maintenance of effective waste management systems. Additionally, the absence of financial

incentives for sustainable practices reduces the motivation for healthcare facilities to adopt them [26].

2.3. Social Barriers

Social barriers stem from attitudes, behaviors, and awareness among stakeholders involved in HCWM. Healthcare workers and administrators often lack sufficient knowledge about the importance of proper HCWM and its environmental and health impacts. This gap in awareness can lead to inadequate practices and compliance [27]. In some parts of the world, cultural practices and behaviors may not prioritize waste segregation and proper disposal. Overcoming these deeply rooted habits requires significant effort in education and behavior change campaigns [28]. The general public's perception of waste management practices can affect their implementation. If sustainable HCWM practices are seen as inconvenient or unnecessary, there may be resistance from both healthcare workers and the community [29].

A comprehensive training and awareness program is necessary for all healthcare personnel generating and treating waste [12]. Several studies have also shown that improper handling of medical waste puts handlers, children, scavengers, and others who come into direct contact with infectious waste at risk of contracting diseases like HIV and hepatitis [20]. In low-income nations, individuals with low socioeconomic positions frequently recycle infectious waste, particularly needles and other sharps. As a result of this recycling, they run a significant risk of getting hurt and becoming ill [30]. Infectious healthcare waste is the second most dangerous waste in the world; hence, facility personnel with the necessary training must treat it properly [6]. Raising awareness and education in this area will have a significant positive impact on the state of healthcare waste management. Developing ongoing staff education and training initiatives is also important because it will reduce the likelihood of improper healthcare waste management [31]. Numerous studies have indicated that training is critical to improving the handling of healthcare waste in healthcare facilities [6].

2.4. Technical Barriers

Under the technical barriers to sustainable healthcare waste management (HCWM), several critical issues arise in storage, transport, disposal, and recycling practices. In many developing countries, inadequate storage facilities contribute significantly to improper waste management. Facilities often lack proper sanitation, temperature control, and bio-hazard warning signs, leading to potential health hazards and environmental contamination. Moreover, some hospitals resort to open bins or improper storage methods within their premises, exacerbating the risk of waste dispersion and environmental pollution [20].

Technical barriers relate to the availability, suitability, and complexity of technologies and methods used in HCWM. Many healthcare facilities lack access to appropriate and effective waste segregation, treatment, and disposal technologies. This is especially true in resource-limited settings where advanced technologies are not readily available [32]. Proper HCWM requires well-developed infrastructure, including storage, transportation, and treatment facilities. In many regions, such infrastructure is either lacking or poorly maintained, leading to inefficient waste management [33]. The technical complexity of sustainable HCWM systems can be daunting for healthcare facilities. The need for specialized knowledge and skills to operate and maintain these systems can deter their adoption [34].

Transportation of healthcare waste also poses substantial challenges. Unlike in developed countries where sophisticated tracking systems and specialized transport routes are employed, many developing regions rely on unsafe practices. Waste is often transported by untrained personnel using inadequate equipment, such as donkey carts or improper pushcarts, exposing workers and communities to health risks [20]. These substandard transportation methods increase the risk of disease transmission and contribute to environmental contamination through leakage and accidents [35].

Regarding disposal, improper incineration techniques in developing countries further compound the technical barriers. Incineration, while widely used, often lacks proper controls for emissions and fails to meet environmental standards, releasing toxic gasses and pollutants into the air and soil [36]. Similarly, landfilling practices are often unsophisticated, leading to uncontrolled waste disposal and environmental degradation [37]. Furthermore, the unauthorized recycling of healthcare waste materials, such as contaminated plastics and sharps, poses significant health risks as these materials are repurposed into consumer goods without proper decontamination [7,38].

2.5. Regulatory Barriers

Regulatory barriers are associated with the policies, laws, and regulations governing HCWM. The WHO has divided healthcare waste into numerous categories. Developed nations, like the United States, Canada, and the United Kingdom, manage their healthcare waste by adhering to standard guidelines provided by the World Health Organization (WHO) [15]. These nations also have standard laws that are strictly and consistently enforced.

In some regions, the regulatory frameworks for HCWM are either weak or poorly enforced. However, the situation differs considerably in poor nations when managing healthcare waste. These resource-constrained nations have few regulatory organizations and only essential legislation to enforce healthcare waste management [20]. This leads to non-compliance and inadequate waste management practices [38]. The lack of standardized guidelines and protocols for HCWM across different regions and countries can create confusion and hinder the implementation of best practices [20]. Complex administrative procedures and bureaucratic red tape can slow the adoption of sustainable HCWM practices. Obtaining necessary permits and approvals can be time-consuming and discouraging for healthcare facilities [39].

3. Expert Consultations

Expert consultations were conducted to gather in-depth insights into the barriers to sustainable healthcare waste management (HCWM). These consultations involved interviews and focus groups with professionals with direct experience with HCWM practices, including healthcare providers, waste management experts, and regulatory bodies.

3.1. Expert Selection

A diverse group of eight experts was selected for consultation to ensure comprehensive insights into the barriers to sustainable healthcare waste management (HCWM). Experts were chosen based on their extensive HCWM experience and expertise in various relevant fields. The selected experts represented a range of geographical regions, including Africa, Asia, and Europe, allowing for a broad understanding of the barriers across different healthcare settings.

The geographical diversity of the experts ensured that the study captured the challenges faced by healthcare facilities in both developed and developing countries, where HCWM practices and infrastructure vary significantly. Furthermore, experts were chosen from different specialized areas:

- Healthcare professionals from hospitals and clinics with direct experience in waste management,
- Environmental health experts working with governmental or non-governmental organizations to implement waste management policies,
- Regulatory bodies involved in drafting and enforcing waste management laws and
- Academic researchers with a focus on sustainable healthcare practices and waste management systems.

3.2. Development of Semi-Structured Interview Guide

We developed a semi-structured interview guide to ensure focused and productive discussions while allowing experts the flexibility to share their unique insights. The purpose of this guide was to provide a structured consultation framework. It began with an introduction that offered a brief overview of the study and the objectives of the consultation. General questions gathered background information about the expert's experience and involvement in healthcare waste management (HCWM)—specific questions targeted identifying barriers across four dimensions: economic, social, technical, and regulatory. We also included questions to assess each identified barrier's perceived severity and impact. Finally, the guide solicited recommendations for overcoming these barriers. Sample questions included inquiries about the experts' experience with HCWM, perceived economic barriers, the influence of social and cultural factors, technical challenges encountered, regulatory issues, and suggestions for improving HCWM practices. This approach ensured comprehensive and insightful data collection to support the study's objectives.

3.3. Sample Questions

i. Can you describe your experience with healthcare waste management?
ii. What do you perceive as the significant economic barrier to sustainable HCWM?
iii. How do social and cultural factors influence waste management practices in healthcare facilities?
iv. What technical challenges have you encountered or observed in the implementation of HCWM?
v. Are there any regulatory issues that you think are particularly challenging? How can they be addressed?
vi. What recommendations do you have for improving HCWM practices?

3.4. Conducting Interviews and Focus Groups

We conducted one-on-one interviews and focus group discussions with selected experts to gather in-depth qualitative data. For the interviews, we scheduled and conducted sessions with individual experts, using video conferencing tools like Zoom or Skype for remote participants. Each interview was recorded, with the expert's consent, to ensure accurate transcription and thorough analysis. Additionally, we organized focus group discussions comprising 5–8 experts to facilitate interaction and exchange diverse ideas. A skilled facilitator guided these discussions to ensure that all participants have the opportunity to contribute. These sessions were recorded, with consent, to capture the full range of insights for detailed analysis. Combining individual interviews and group discussions provided a robust understanding of sustainable healthcare waste management barriers.

3.5. Research Objectives

The primary objective of this study is to identify and rank the barriers to sustainable healthcare waste management.

From the literature review, 17 barriers were identified, as shown in Table 1.

Table 1. List of barriers to sustainable healthcare waste management.

B1	Funding and Resource Allocation
B2	Cost minimization and investment reluctance
B3	Initial and operational costs
B4	Government and private-sector funding
B5	Awareness and knowledge gaps
B6	Cultural practices and behavioral norms

Table 1. *Cont.*

B7	Perception of waste management practices
B8	Health risks and socioeconomic factors
B9	The importance of training and education
B10	Waste segregation
B11	Inadequate storage facilities
B12	Availability and Suitability of Technologies
B13	Infrastructure deficiencies
B14	Transportation challenges
B15	Disposal methods
B16	Unauthorized recycling of healthcare waste
B17	Standardize guidelines and protocols.

3.6. Data Collection

Eight experts were selected to collect the data based on their extensive knowledge, professional experience, and contributions to the field. Experts were chosen based on their academic qualifications, expertise, and field experience. Eight experts from various sectors, including academia, the healthcare sector, and the government, were selected to ensure a comprehensive analysis.

Before the data collection, a set of evaluation criteria was developed based on a thorough literature review and expert discussions. These criteria represent the factors relevant to the barriers and serve as the foundation for quantitative analysis.

The questionnaire collected quantitative data by asking experts to rate barriers (B1 to B17) against multiple criteria. The ratings provided by the experts were on a Likert scale, ranging from zero to five, where zero indicates no impact, and five indicates a maximum or high impact. The following criteria were identified:

C1: Health Risks—The potential health hazards associated.

C2: Frequency of Occurrence—How often is the barrier expected to occur?

C3: Cost Implications—The financial impact or cost associated.

C4: Regulatory Compliance—The extent to which a barrier aligns with regulatory standards.

C5: Technical Feasibility—The practicality of implementing from a technical standpoint.

C6: Organizational Factors—The influence of organizational dynamics.

C7: Cultural and Behavioral Aspects—The impact of cultural norms and behaviors.

C8: Resource Availability—The availability of necessary resources.

C9: Stakeholder Engagement—The degree to which stakeholders are involved or impacted by the barrier.

C10: Risk of Cross-Contamination—The likelihood of cross-contamination due to the barrier.

Upon receiving the completed questionnaires, the data were carefully reviewed for completeness and consistency. Any discrepancies or missing data were addressed through follow-up communication with the experts. The final dataset was validated to reflect the experts' evaluations accurately.

3.7. Data Analysis

The first step in the data analysis was to combine data from eight experts into a single dataset. For this purpose, the average score for each rating was calculated across all the experts. This was carried out to provide a single value for each barrier-criterion pair, which can be used in the Grey Relational Analysis (GRA). The following formulae were used to calculate a barrier-criterion pair's average score.

$$x_{ij} = \frac{1}{n}\sum_{k=1}^{n} x_{ijk}$$

where

x_{ijk} Does the kth expert rate the jth barrier based on the ith criterion?

n is the total number of experts

The above formulae average score for each barrier criterion pair was calculated and the Table 2 was prepared.

Table 2. Average score for barrier criterion pair.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
B1	3.875	4.125	4.625	4.75	3.875	4.625	3.5	4.75	4.625	3.75
B2	3.25	3.5	4.625	4.625	3.75	3.875	3	3.75	3.875	3
B3	3.125	4	4.625	4.625	3.875	4	2.75	4	3.75	2.875
B4	3.875	3.625	4.625	4.75	3.875	4.5	3.375	4.75	4.625	3.75
B5	4.75	4.75	3.875	4.625	3.875	4.75	4.625	4	4.75	4.25
B6	4	4	3.5	4	3.375	4.75	4.875	3.375	4.625	3.875
B7	3.875	3.875	3.875	4.5	3.375	4.625	4.375	3.125	4.25	3.875
B8	4.75	4.75	3.875	4.75	3.5	4.125	4	4	4.125	4.875
B9	4.75	4.75	3.875	4.625	4.125	4.75	4.25	4	4.75	4.375
B10	4.875	4.75	3.875	4.75	4	4.75	4.125	4	4.75	5
B11	4.875	4.875	3.875	4.75	3.875	4.125	3.875	3.875	4.125	5
B12	4.25	4	3.875	4.75	4.75	4.25	3.625	4.125	4.125	3.25
B13	4.875	4.875	4.125	4.75	3.625	4.125	3.625	3.875	4.125	4.125
B14	4.75	4.5	3.875	4.75	3.625	4.125	3.625	3.875	4.125	5
B15	4.875	4.875	3.875	4.75	4	4.125	3.625	4	4.125	5
B16	4.875	4	3.125	4.75	3.5	4.125	3.25	3.25	4.125	5
B17	4.875	5	3.875	4.75	4.125	4.875	3.625	4.125	4.75	5

The first step in the Grey method is data normalization. This is conducted to convert the original ratings provided by the experts into a comparable scale. Since the ratings were on a Likert scale from zero to five, the data were normalized to a scale between zero and one. Before normalizing the data, it is essential to identify the criteria, such as benefit and cost criteria. Benefit Criteria are the ones where higher values are better. Cost Criteria are the ones where lower values are better. So, in this case, Regulatory Compliance, Technical Feasibility, Organizational Factors, Cultural and Behavioral Aspects, Resource Availability, and Stakeholder Engagement are benefit criteria. At the same time, Health Risks, Frequency of Occurrence, Cost Implications, and Risk of Cross-Contamination are cost criteria. The Min–Max normalization method was used to normalize the data. This method rescales the data to have a value in the range [0, 1].

Normalization was carried out using the formulas.

For benefit criteria

$$x'_{ij} = \frac{x_{ij} - \min\left(x_j\right)}{\max\left(x_j\right) - \min\left(x_j\right)}$$

For cost criteria

$$x'_{ij} = \frac{\max\left(x_j\right) - x_{ij}}{\max\left(x_j\right) - \min\left(x_j\right)} \quad (1)$$

where

x_{ij} is the original value of the ith alternative for the jth criterion.

$\min\left(x_j\right)$ is the minimum value among all alternatives for the jth criterion.

$\max\left(x_j\right)$ is the maximum value among all alternatives for the jth criterion.

Table 3 shows the normalized scores for all criteria and barrier pair.

After normalizing the value, the next step is determining the reference sequence or the ideal solution. The reference sequence or the ideal solution is generally the best value for each criterion. This could be the maximum value among alternatives and, for minimization, the minimum value.

Table 3. Normalized scores for x_{ij}.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
B1	0.57	0.58	0.00	1.00	0.36	0.75	0.35	1.00	0.88	0.59
B2	0.93	1.00	0.00	0.83	0.27	0.00	0.12	0.38	0.13	0.94
B3	1.00	0.67	0.00	0.83	0.36	0.13	0.00	0.54	0.00	1.00
B4	0.57	0.92	0.00	1.00	0.36	0.63	0.29	1.00	0.88	0.59
B5	0.07	0.17	0.50	0.83	0.36	0.88	0.88	0.54	1.00	0.35
B6	0.50	0.67	0.75	0.00	0.00	0.88	1.00	0.15	0.88	0.53
B7	0.57	0.75	0.50	0.67	0.00	0.75	0.76	0.00	0.50	0.53
B8	0.07	0.17	0.50	1.00	0.09	0.25	0.59	0.54	0.38	0.06
B9	0.07	0.17	0.50	0.83	0.55	0.88	0.71	0.54	1.00	0.29
B10	0.00	0.17	0.50	1.00	0.45	0.88	0.65	0.54	1.00	0.00
B11	0.00	0.08	0.50	1.00	0.36	0.25	0.53	0.46	0.38	0.00
B12	0.36	0.67	0.50	1.00	1.00	0.38	0.41	0.62	0.38	0.82
B13	0.00	0.08	0.33	1.00	0.18	0.25	0.41	0.46	0.38	0.41
B14	0.07	0.33	0.50	1.00	0.18	0.25	0.41	0.46	0.38	0.00
B15	0.00	0.08	0.50	1.00	0.45	0.25	0.41	0.54	0.38	0.00
B16	0.00	0.67	1.00	1.00	0.09	0.25	0.24	0.08	0.38	0.00
B17	0.00	0.00	0.50	1.00	0.55	1.00	0.41	0.62	1.00	0.00

Let the reference sequence be denoted as X_0, and the normalized alternatives as X_i, where i represents different alternatives. For benefit criteria, the value of X_0 is one, and for cost criteria, the value of X_0 is zero.

After identifying the value of X_0, the next step is to calculate the Grey Relational Coefficient (GRC). The GRC measures how close each alternative is to the ideal reference. It is calculated using the following formulae.

$$\xi_{ij} = \frac{\Delta_{min} + \zeta\Delta_{max}}{\Delta_{ij} + \zeta\Delta_{max}} \tag{2}$$

where

$\Delta_{ij} = |X_0(j) - X_i(j)|$ is the absolute difference between the reference and the alternative.

Δ_{min} is the minimum difference across all alternatives and criteria.

Δ_{max} is the maximum difference across all alternatives and criteria.

ζ is the distinguishing coefficient, typically between zero and one (commonly set at 0.5).

The value of GRC for all x_{ij} is given below in Table 4. For calculating GRC the value of ζ (distinguishing coefficient) is taken as 0.5.

After calculating the GRC values, Grey Relational Grades (GRC) are calculated for each alternative. The Grey Relational Grade is the weighted sum of the Grey Relational Coefficients for each alternative across all criteria. It is then used to rank the alternatives. The alternative with the highest Grey Relational Grade is considered the best choice. The following formulae are used to calculate the GRC

$$\Gamma_i = \sum_{j=i}^{n} w_j \xi_{ij} \tag{3}$$

where

w_j is the weight of the j-th criterion, and

ξ_{ij} is the Grey Relational Coefficient for the i-th alternative under the j-th criterion.

In the present work, the weight of all criteria is assumed equal, so the value of GRG is calculated using.

$$\Gamma_i = \sum_{j=i}^{n} \xi_{ij} \tag{4}$$

The value of GRG for the barriers is given in Table 5.

Table 4. GRC values for x_{ij}.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
B1	0.47	0.46	1.00	1.00	0.44	0.67	0.44	1.00	0.80	0.46
B2	0.35	0.33	1.00	0.75	0.41	0.33	0.36	0.45	0.36	0.35
B3	0.33	0.43	1.00	0.75	0.44	0.36	0.33	0.52	0.33	0.33
B4	0.47	0.35	1.00	1.00	0.44	0.57	0.41	1.00	0.80	0.46
B5	0.88	0.75	0.50	0.75	0.44	0.80	0.81	0.52	1.00	0.59
B6	0.50	0.43	0.40	0.33	0.33	0.80	1.00	0.37	0.80	0.49
B7	0.47	0.40	0.50	0.60	0.33	0.67	0.68	0.33	0.50	0.49
B8	0.88	0.75	0.50	1.00	0.35	0.40	0.55	0.52	0.44	0.89
B9	0.88	0.75	0.50	0.75	0.52	0.80	0.63	0.52	1.00	0.63
B10	1.00	0.75	0.50	1.00	0.48	0.80	0.59	0.52	1.00	1.00
B11	1.00	0.86	0.50	1.00	0.44	0.40	0.52	0.48	0.44	1.00
B12	0.58	0.43	0.50	1.00	1.00	0.44	0.46	0.57	0.44	0.38
B13	1.00	0.86	0.60	1.00	0.38	0.40	0.46	0.48	0.44	0.55
B14	0.88	0.60	0.50	1.00	0.38	0.40	0.46	0.48	0.44	1.00
B15	1.00	0.86	0.50	1.00	0.48	0.40	0.46	0.52	0.44	1.00
B16	1.00	0.43	0.33	1.00	0.35	0.40	0.40	0.35	0.44	1.00
B17	1.00	1.00	0.50	1.00	0.52	1.00	0.46	0.57	1.00	1.00

Table 5. GRG values for Barriers.

	Barriers	**GRG**
B1	Funding and resource allocation	0.673023
B2	Cost minimization and investment reluctance	0.469463
B3	Initial and operational costs	0.483554
B4	Government and private-sector funding	0.650513
B5	Awareness and knowledge gaps	0.703073
B6	Cultural practices and behavioral norms	0.545238
B7	Perception of waste management practices	0.496571
B8	Health risks and socio-economic factors	0.628741
B9	The importance of training and education	0.697807
B10	Waste segregation	0.763447
B11	Inadequate storage facilities	0.663822
B12	Availability and Suitability of Technologies	0.580325
B13	Infrastructure deficiencies	0.617023
B14	Transportation challenges	0.61397
B15	Disposal methods	0.665931
B16	Unauthorized recycling of healthcare waste	0.570789
B17	Standardize guidelines and protocols	0.804849

Based on these GRG values, the barriers are ranked. A higher GRG value indicates a higher rank, suggesting a higher priority of the barrier. Table 6 shows the rank of the obstacles.

Table 6. Rank for Barriers.

	Barriers	**GRG**	**Rank**
B17	Standardize guidelines and protocols	0.804849	1
B10	Waste segregation	0.763447	2
B5	Awareness and knowledge gaps	0.703073	3
B9	The importance of training and education	0.697807	4
B1	Funding and resource allocation	0.673023	5
B15	Disposal methods	0.665931	6
B11	Inadequate storage facilities	0.663822	7
B4	Government and private-sector funding	0.650513	8

Table 6. *Cont.*

	Barriers	GRG	Rank
B8	Health risks and socioeconomic factors	0.628741	9
B13	Infrastructure deficiencies	0.617023	10
B14	Transportation challenges	0.61397	11
B12	Availability and Suitability of Technologies	0.580325	12
B16	Unauthorized recycling of healthcare waste	0.570789	13
B6	Cultural practices and behavioral norms	0.545238	14
B7	Perception of waste management practices	0.496571	15
B3	Initial and operational costs	0.483554	16
B2	Cost minimization and investment reluctance	0.469463	17

4. Results

(RQ1): What are the critical barriers to Healthcare Waste Management (HCWM)? The analysis identified 17 critical barriers to sustainable HCWM, categorized into four dimensions: economic, social, technical, and regulatory. Grey Relational Analysis (GRA) ranked these barriers based on their impact and significance. The top five barriers were:

- Lack of standardized guidelines and protocols (Rank 1, GRG = 0.804849): This emerged as the most significant barrier, highlighting the absence of cohesive policies and uniform practices across healthcare facilities.
- Ineffective waste segregation (Rank 2, GRG = 0.763447): A fundamental issue impeding proper waste management and increasing the risk of contamination.
- Awareness and knowledge gaps (Rank 3, GRG = 0.703073): Reflects the insufficient understanding of HCWM's importance among healthcare workers.
- Importance of training and education (Rank 4, GRG = 0.697807): Highlights the need for continuous professional development in HCWM practices.
- Funding and resource allocation (Rank 5, GRG = 0.673023): Financial constraints are a significant obstacle to implementing sustainable HCWM systems.

Other notable barriers include disposal methods, inadequate storage facilities, and government-private sector funding collaborations. A complete ranking is shown in Table 6, and the top five barriers are visualized in Figure 2.

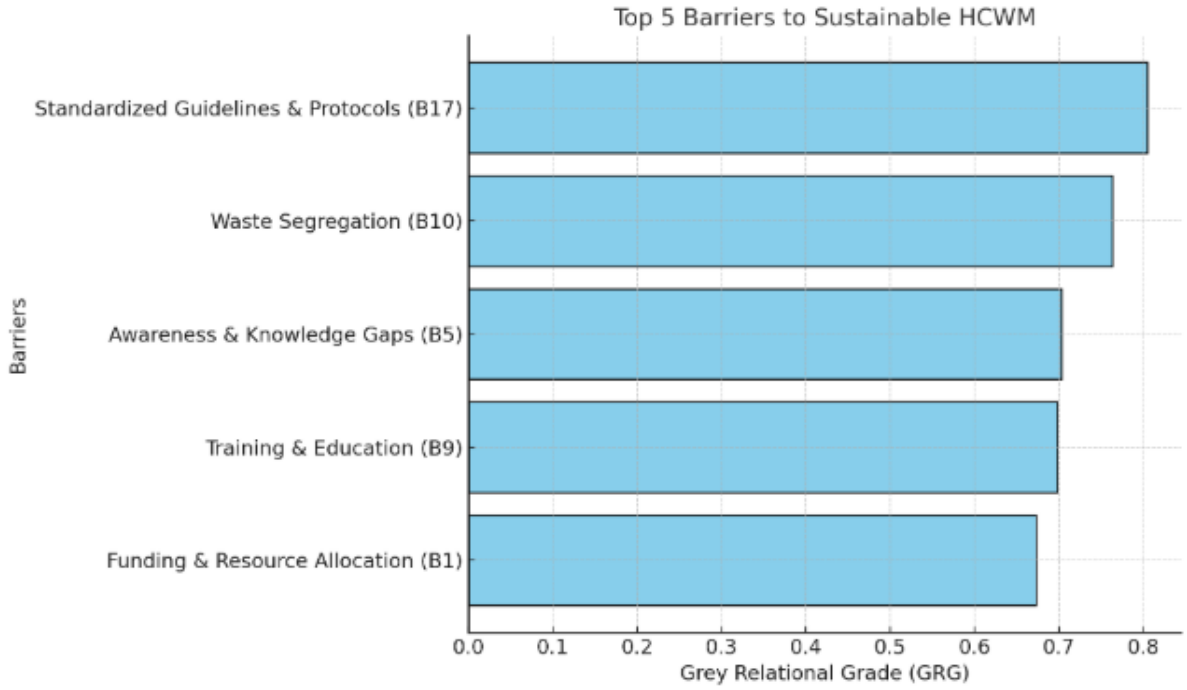


Figure 2. A bar chart showing the top five barriers' Grey Relational Grades (GRG).

(RQ2): How do these barriers vary across different dimensions (economic, social, technical, and regulatory)?

- The results revealed that the barriers span diverse dimensions, often overlapping in their impact:
- Economic Barriers: Funding and resource allocation (Rank 5) and cost minimization (Rank 17) were the most and least significant barriers in this dimension.
- Social Barriers: Awareness and knowledge gaps (Rank 3) and cultural practices (Rank 14) demonstrated the role of stakeholder behavior in HCWM.
- Technical Barriers: Ineffective waste segregation (Rank 2) and inadequate storage facilities (Rank 7) underscored the challenges in infrastructure and operations.
- Regulatory Barriers: Lack of standardized guidelines (Rank 1) highlighted the need for more robust policy frameworks.

(RQ3): What implications do these findings have for improving HCWM practices? The findings emphasize actionable strategies:

- Developing standardized policies and guidelines tailored to healthcare settings.
- Enhancing waste segregation protocols through training and awareness programs.
- Allocating adequate resources for infrastructure and financial sustainability.

Introducing continuous education programs targeting HCWM compliance and practices. Figure 3 depicts the four enablers to sustainable HCWM.

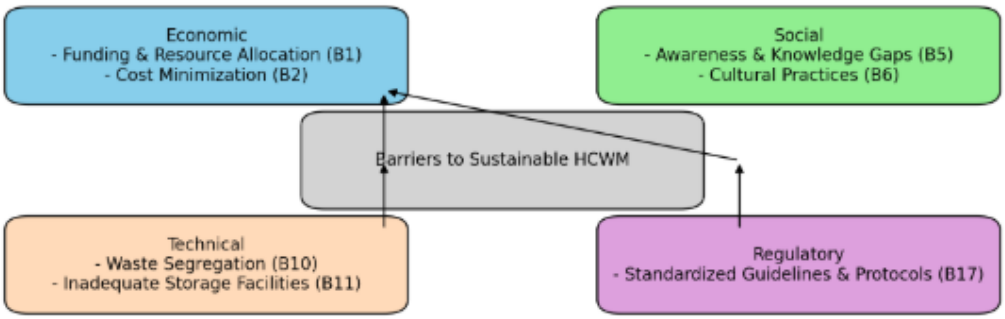


Figure 3. Flowchart categorizing barriers to sustainable healthcare waste management into Economic, Social, Technical, and Regulatory dimensions.

The remaining barriers include disposal methods (B15), inadequate storage facilities (B11), and government and private-sector funding (B4), which ranked sixth, seventh, and eighth, respectively, indicating significant structural and financial impediments in healthcare waste management. Other critical barriers, like health risks and socio-economic factors (B8) and infrastructure deficiencies (B13), ranked ninth and tenth, respectively, showing the interconnectedness between health risks, socio-economic factors, and infrastructural shortcomings in healthcare facilities.

Interestingly, unauthorized recycling of healthcare waste (B16) and cultural practices and behavioral norms (B6) ranked lower, with GRG values of 0.570789 and 0.545238, respectively. These indicate more localized or contextual issues that might not be as universal as the higher-ranked barriers. Cost minimization and investment reluctance (B2) ranked last with a GRG of 0.469463, suggesting that while cost is an issue, it is not perceived as severe as other barriers.

4.1. Sensitivity Analysis

Sensitivity analysis in the context of Grey Relational Analysis (GRA) is used to evaluate the robustness of the results when the distinguishing coefficient (ζ) is varied. The distinguishing coefficient, ζ, is crucial in calculating the Grey Relational Coefficient (GRC), influencing the Grey Relational Grade (GRG) and the final ranking of alternatives. By adjusting ζ, we can assess how sensitive the ranking of barriers is to changes in this parameter.

The distinguishing coefficient ζ determines the weight given to the minimum and maximum differences between the alternatives and the reference (ideal) sequence. It balances the influence of deviations in the data, and typically, ζ is chosen within the range of zero to one.

ζ = 0.5: This standard value is used in most GRA applications. It assigns equal weight to both the minimum and maximum deviations.

ζ < 0.5: A lower value of ζ (such as 0.3) gives more importance to minor deviations, meaning the method will focus more on reducing minor differences between the alternatives and the ideal reference.

ζ > 0.5: A higher value of ζ (0.7 or 0.9) gives more weight to larger deviations, emphasizing the significant differences between alternatives and the ideal.

To assess the robustness of the results, sensitivity analysis is performed by changing the distinguishing coefficient ζ to 0.3, 0.7, and 0.9. This was carried out to evaluate how it affects the ranking of alternatives. The results of the sensitivity analysis are given in Table 7.

Table 7. Results of sensitivity analysis.

	Barriers	**ζ = 0.5**	**ζ = 0.3**	**ζ = 0.7**	**ζ = 0.9**
B1	Funding and resource allocation	5	5	6	6
B2	Cost minimization and investment reluctance	17	17	17	17
B3	Initial and operational costs	16	15	16	16
B4	Government and private-sector funding	8	8	8	9
B5	Awareness and knowledge gaps	3	3	3	3
B6	Cultural practices and behavioral norms	14	14	14	14
B7	Perception of waste management practices	15	16	15	15
B8	Health risks and socio-economic factors	9	9	10	10
B9	The importance of training and education	4	4	4	4
B10	Waste segregation	2	1	1	1
B11	Inadequate storage facilities	7	6	7	7
B12	Availability and Suitability of Technologies	12	13	13	13
B13	Infrastructure deficiencies	10	11	11	11
B14	Transportation challenges	11	10	9	8
B15	Disposal methods	6	7	5	5
B16	Unauthorized recycling of healthcare waste	13	12	12	12
B17	Standardize guidelines and protocols	1	2	2	2

Table 7 shows the sensitivity analysis results with ζ values of 0.3, 0.5, 0.7, and 0.9. The goal is to see how the ranking of barriers changes as ζ varies.

4.2. Stable Barriers

Several barriers showed consistent rankings across all ζ values, indicating they are less sensitive to changes in ζ and are likely to remain essential barriers under various conditions:

B2 (Cost minimization and investment reluctance): Consistently ranked last (17) for all ζ values, implying it is not a priority concern compared to other barriers, regardless of the weight given to deviations.

B5 (Awareness and knowledge gaps): Ranked third across all values of ζ, indicating that this barrier is universally considered critical to healthcare waste management.

B9 (Importance of training and education): This barrier maintained a stable ranking of four, reinforcing its consistent importance.

B6 (Cultural practices and behavioral norms): Ranked 14th consistently, reflecting the persistent challenge of behavioral norms regardless of ζ changes.

4.3. Moderately Sensitive Barriers

Some barriers showed slight shifts in rankings as ζ changed, demonstrating moderate sensitivity:

B10 (Waste segregation): While ranked second under ζ = 0.5, it moved up to the first position for ζ = 0.3 and remained first for ζ = 0.7 and 0.9. This suggests that waste segregation becomes more critical as more minor deviations are emphasized.

B17 (Standardized guidelines and protocols): Ranked first under ζ = 0.5 but moved to second for ζ = 0.3, 0.7, and 0.9. This minor shift implies that standardization is slightly less sensitive when more significant deviations are weighted more heavily.

B15 (Disposal methods): Its ranking shifted from sixth under ζ = 0.5 to seventh (ζ = 0.3) and fifth (ζ = 0.7, 0.9), suggesting its importance increases as more significant deviations are considered more impactful.

4.4. Highly Sensitive Barriers

A few barriers showed more significant ranking changes, indicating high sensitivity to ζ: B1 (Funding and resource allocation): Ranked fifth under ζ = 0.5 and ζ = 0.3 but shifted to sixth for ζ = 0.7 and 0.9, indicating that when larger differences are emphasized, funding becomes slightly less critical.

B3 (Initial and operational costs): This barrier fluctuated between the 15th and 16th, indicating that its significance is affected by the weighting of more significant deviations.

B14 (Transportation challenges): Ranked eleventh under ζ = 0.5, it improved to ninth and eighth as ζ increased to 0.7 and 0.9, suggesting that transportation challenges are more prominent when prioritizing significant deviations.

5. Discussion

The primary objective of this study was to identify and rank the barriers to sustainable healthcare waste management (HCWM) and to propose actionable recommendations for overcoming these barriers. The study's findings directly address the research questions by categorizing the barriers across four key dimensions: economic, social, technical, and regulatory. The most significant barriers identified include the lack of standardized guidelines and protocols, ineffective waste segregation, awareness and knowledge gaps, and insufficient funding and resource allocation. These findings align closely with the global challenges healthcare facilities face and confirm the need for a multifaceted approach to improving HCWM.

Furthermore, this study emphasizes the importance of training and education in overcoming these barriers, particularly in the social and technical dimensions. The results show that healthcare workers cannot implement effective waste segregation practices without proper training, which exacerbates the waste management crisis. A critical regulatory barrier was the lack of standardized guidelines across healthcare settings. These findings reinforce the notion that improving HCWM requires technical interventions and significant regulatory and educational reforms. The findings of this study corroborate many of the challenges reported in existing literature on HCWM. Studies in Ethiopia and Uganda have similarly highlighted the lack of waste segregation and insufficient training as significant barriers [10,11]. In line with our study, both identified financial constraints and limited resources as fundamental obstacles to improving HCWM practices.

Moreover, the challenge of regulatory enforcement found in previous research also resonates with our results. Several studies have highlighted the need for more robust regulatory frameworks to support HCWM [29]. Our study reinforces this by ranking the lack of standardized protocols as the highest barrier, highlighting the importance of a cohesive and enforceable policy framework to guide healthcare facilities' waste management practices. While cultural norms were ranked lower in our study, they remain a crucial issue in certain regions, as suggested by previous research, where cultural practices can affect the implementation of waste segregation and disposal methods.

This study also adds to the literature by addressing the regional variation in HCWM barriers. While previous studies focused primarily on individual countries or regions, this study's geographical diversity in expert selection allowed for a broader understanding of the global nature of HCWM barriers and their varied impacts across settings.

5.1. Practical Implications

The findings from this study have several practical implications for hospitals, healthcare administrators, and policymakers. To address the barriers identified, the following actions are recommended:

5.2. Developing Standardized Guidelines and Protocols

One of the most pressing barriers is the lack of standardized guidelines across healthcare facilities. To overcome this, healthcare systems must develop and implement uniform HCWM protocols that can be adapted to local contexts. This should be a priority for policymakers to ensure that healthcare facilities follow best practices for waste segregation and disposal. Hospitals in different regions can benefit from adapting internationally recognized HCWM guidelines tailored to the local infrastructure and regulatory environments.

5.3. Enhancing Training Programs

Awareness and knowledge gaps were identified as significant impediments to effective HCWM. To address this, hospitals should implement comprehensive training programs for healthcare staff, focusing on waste segregation, safe disposal practices, and the environmental and health risks of improper waste management. These programs should be regularly updated to incorporate new technologies and regulatory changes.

5.4. Resource Allocation and Funding

Financial constraints were consistently identified as a barrier to effective HCWM. Policymakers must prioritize healthcare waste management in budgets, both at the governmental and institutional levels. Hospitals, especially in resource-limited settings, should also explore alternative financing methods, such as waste-to-energy projects or collaborations with private partners to improve waste management infrastructure.

5.5. Cultural Sensitivity and Behavioral Change

Targeted education campaigns must be developed in regions where cultural norms affect waste management practices. These programs should involve community leaders, healthcare workers, and the public to encourage the adoption of proper waste segregation practices. Cultural sensitivity should be integrated into training and educational materials to ensure they are effective and well received in local contexts.

5.6. Implementation of Monitoring and Evaluation Systems

To ensure the effectiveness of HCWM policies, hospitals and policymakers should establish robust monitoring and evaluation systems. These systems would track the progress of waste management practices, assess compliance with protocols, and identify areas needing improvement. Regular audits and feedback loops can help ensure that HCWM practices are consistently applied and adapted to meet evolving needs.

5.7. Limitations and Future Work

The present work offers valuable insights into healthcare waste management barriers. However, there are some limitations to the present analysis. The Grey Relational Analysis (GRA) results are sensitive to the selection of the distinguishing coefficient, ζ. Although sensitivity analysis was conducted with different values of ζ (0.3, 0.5, 0.7, and 0.9), the ranking of specific barriers shifted, highlighting a limitation in the method. The final rankings depend on how much weight is assigned to minor or major deviations. This variability may lead to different conclusions depending on the value chosen, affecting

decision-making. Also, The GRA method used in the analysis assumes equal weighting of all criteria (barriers). However, in practice, some barriers may be more critical than others based on the context, such as regional variations in healthcare infrastructure or waste management practices. The absence of subjective or expert-driven weighting reduces the ability of the method to fully reflect real-world complexities in the prioritization of barriers.

The analysis in the present work is based on a static dataset, and the results may not be generalizable across different regions, healthcare facilities, or countries. Healthcare waste management is affected by numerous external factors, including policy, cultural norms, and socioeconomic conditions, which are not captured in this analysis. Moreover, the data do not account for dynamic changes in healthcare systems or emerging technologies that may influence waste management practices.

Each barrier is represented as a single factor. However, many barriers (e.g., funding and resource allocation, awareness gaps) are multi-faceted and involve a combination of organizational, social, and financial challenges. The Grey method simplifies these into a single metric, which may not fully capture the complexity of these issues. Also, the analysis assumes that the data used to assess the barriers is accurate and free of bias. However, data collection in healthcare waste management may be subject to reporting biases, especially regarding the perceived importance of specific barriers. Differences in organizational transparency and the quality of available data may also affect the results.

All these limitations provide future opportunities for further research, which can enhance the findings' robustness, context specificity, and practical applicability. Future studies should explore the inclusion of expert judgment or stakeholder input to assign weights to different barriers based on their perceived importance. This would allow for a more nuanced and context-specific analysis, helping to prioritize more critical barriers in specific regions or facilities. Future research could also incorporate dynamic data that track changes in healthcare waste management practices over time. This would allow the analysis to account for technological advancements, policy changes, and evolving healthcare practices that could impact the prioritization of barriers.

Also, Comparing the GRA method with other MCDM methods, such as the Analytic Hierarchy Process (AHP) or Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), could provide additional insights. Such a comparison would help assess the robustness of the ranking results and offer different perspectives on prioritizing healthcare waste management barriers.

The studies can further focus on region-specific analyses to account for variations in healthcare infrastructure, waste management practices, and cultural factors. Including geographical and cultural diversity could lead to a better understanding of how these barriers manifest in different settings and provide more tailored recommendations for improvement.

Policy and regulatory frameworks play a significant role in shaping healthcare waste management practices. Future research could focus on analyzing the impact of government regulations, public–private partnerships, and international guidelines on the identified barriers, particularly those related to standardization, resource allocation, and funding.

Based on the prioritized barriers, future work should focus on developing and testing targeted intervention strategies. These strategies could range from policy reforms to on-the-ground training programs designed to address the top barriers identified, such as the need for standardized protocols, waste segregation, and better funding allocation.

While this study provides valuable insights into the barriers to sustainable healthcare waste management (HCWM), some limitations must be acknowledged. One such limitation is the regional differences in HCWM practices, which may affect the generalizability of the findings. Healthcare waste management systems vary significantly across regions, particularly between developed and developing countries, due to infrastructure, regulatory frameworks, and resource availability differences. For instance, the barriers identified in high-income countries, where there may be more vigorous regulatory enforcement and better infrastructure, may not be directly applicable to low- and middle-income countries

that face challenges such as inadequate funding, limited technical expertise, and weak enforcement of policies. Therefore, while the findings provide valuable insights, they may not be universally applicable without modification to suit specific regional contexts. Future research should aim to explore these regional variations further by conducting studies in diverse geographical areas to determine how local factors influence the barriers to HCWM and to develop context-specific solutions.

In addition, the Grey Relational Analysis (GRA) used in this study assumes equal weighting of all barriers, which might not reflect the real-world priorities in different regions. Future studies could incorporate region-specific expert input to assign differential weights to the barriers based on their perceived importance in different healthcare settings.

6. Conclusions

Healthcare waste management (HCWM) is essential to public health and environmental sustainability, yet numerous barriers impede its effective implementation. This study identified and ranked the critical barriers to sustainable HCWM, including the lack of standardized guidelines and protocols, ineffective waste segregation, awareness and knowledge gaps, and insufficient funding and resource allocation. These findings highlight the need for a comprehensive, multi-dimensional approach to overcoming HCWM challenges, which involves addressing technical and regulatory barriers while improving training and resource allocation.

The study's results emphasize the importance of training programs, regulatory frameworks, and financial investment to improve HCWM practices. Identifying these barriers provides a clear roadmap for hospitals, policymakers, and healthcare administrators to prioritize actions that will enhance HCWM, reduce environmental impact, and protect public health.

However, several avenues for future research could further enhance the effectiveness of HCWM strategies. First, region-specific analyses are needed to understand better the unique challenges and opportunities faced by healthcare facilities in different geographical settings. Such studies would help develop localized solutions considering regional infrastructure, regulatory frameworks, and cultural practices. Additionally, future research could explore integrating emerging technologies in HCWM, such as automated waste segregation systems, waste-to-energy solutions, and data-driven management tools. These technologies could significantly address some of the key barriers identified in this study, particularly issues related to waste segregation and resource constraints while offering scalable and sustainable solutions for healthcare facilities worldwide.

Future studies can contribute to more effective and context-specific HCWM strategies by focusing on these areas, improving the sustainability and safety of healthcare waste management practices globally.

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References

1. Andeobu, L. Medical Waste and Its Management. In *The Palgrave Handbook of Global Sustainability*; Springer International Publishing: Cham, Switzerland, 2023; pp. 761–789.
2. Yazie, T.D.; Tebeje, M.G.; Chufa, K.A. Healthcare Waste Management Current Status and Potential Challenges in Ethiopia: A Systematic Review. *BMC Res. Notes* **2019**, *12*, 285. [CrossRef] [PubMed]
3. Hasan, M.M.; Rahman, M.H. Assessment of Healthcare Waste Management Paradigms and Its Suitable Treatment Alternative: A Case Study. *J. Environ. Public Health* **2018**, *2018*, 6879751. [CrossRef] [PubMed]
4. Debnath, B.; Bari, A.B.M.M.; Ali, S.M.; Ahmed, T.; Ali, I.; Kabir, G. Modelling the Barriers to Sustainable Waste Management in the Plastic-Manufacturing Industry: An Emerging Economy Perspective. *Sustain. Anal. Model.* **2023**, *3*, 100017. [CrossRef]
5. Thakur, V.; Anbanandam, R. Healthcare Waste Management: An Interpretive Structural Modeling Approach. *Int. J. Health Care Qual. Assur.* **2016**, *29*, 559–581. [CrossRef] [PubMed]
6. Janik-Karpinska, E.; Brancaleoni, R.; Niemcewicz, M.; Wojtas, W.; Foco, M.; Podogrocki, M.; Bijak, M. Healthcare Waste—A Serious Problem for Global Health. *Healthcare* **2023**, *11*, 242. [CrossRef]
7. WHO Healthcare Waste. Available online: https://www.who.int/news-room/fact-sheets/detail/health-care-waste (accessed on 1 July 2024).
8. Lee, S.M.; Lee, D. Effective Medical Waste Management for Sustainable Green Healthcare. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14820. [CrossRef]
9. Williams, P.A.; Narra, S.; Antwi, E.; Quaye, W.; Hagan, E.; Asare, R.; Owusu-Arthur, J.; Ekanthalu, V.S. Review of Barriers to Effective Implementation of Waste and Energy Management Policies in Ghana: Implications for the Promotion of Waste-to-Energy Technologies. *Waste* **2023**, *1*, 313–332. [CrossRef]
10. Kwikiriza, S.; Stewart, A.G.; Mutahunga, B.; Dobson, A.E.; Wilkinson, E. A Whole Systems Approach to Hospital Waste Management in Rural Uganda. *Front. Public Health* **2019**, *7*, 136. [CrossRef]
11. Meleko, A.; Tesfaye, T.; Henok, A. Assessment of Healthcare Waste Generation Rate and Its Management System in Health Centers of Bench Maji Zone. *Ethiop. J. Health Sci.* **2018**, *28*, 125. [CrossRef]
12. Letho, Z.; Yangdon, T.; Lhamo, C.; Limbu, C.B.; Yoezer, S.; Jamtsho, T.; Chhetri, P.; Tshering, D. Awareness and Practice of Medical Waste Management among Healthcare Providers in National Referral Hospital. *PLoS ONE* **2021**, *16*, e0243817. [CrossRef]
13. Ferronato, N.; Torretta, V. Waste Mismanagement in Developing Countries: A Review of Global Issues. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1060. [CrossRef] [PubMed]
14. Tushar, S.R.; Alam, M.F.; Bari, A.M.; Karmaker, C.L. Assessing the Challenges to Medical Waste Management during the COVID-19 Pandemic: Implications for the Environmental Sustainability in the Emerging Economies. *Socio-Econ. Plan. Sci.* **2023**, *87*, 101513. [CrossRef]
15. Windfeld, E.S.; Brooks, M.S.-L. Medical Waste Management—A Review. *J. Environ. Manag.* **2015**, *163*, 98–108. [CrossRef]
16. Peng, Y.; Wu, P.; Schartup, A.T.; Zhang, Y. Plastic Waste Release Caused by COVID-19 and Its Fate in the Global Ocean. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2111530118. [CrossRef]
17. Castagnoli, A.; Salem, A.M.; Desideri, U.; Pecorini, I. Environmental Assessment of Gasification and Green Hydrogen Potential Role in Waste Management Decarbonization. *J. Clean. Prod.* **2024**, *482*, 144174. [CrossRef]
18. Dihan, M.R.; Abu Nayeem, S.M.; Roy, H.; Islam, M.S.; Islam, A.; Alsukaibi, A.K.D.; Awual, M.R. Healthcare Waste in Bangladesh: Current Status, the Impact of COVID-19 and Sustainable Management with Life Cycle and Circular Economy Framework. *Sci. Total Environ.* **2023**, *871*, 162083. [CrossRef]
19. Da Silva, C.E.; Hoppe, A.E.; Ravanello, M.M.; Mello, N. Medical Wastes Management in the South of Brazil. *Waste Manag.* **2005**, *25*, 600–605. [CrossRef]
20. Khan, B.A.; Cheng, L.; Khan, A.A.; Ahmed, H. Healthcare Waste Management in Asian Developing Countries: A Mini Review. *Waste Manag. Res.* **2019**, *37*, 863–875. [CrossRef]
21. Muduli, K.; Barve, A. Barriers to Green Practices in Health Care Waste Sector: An Indian Perspective. *Int. J. Environ. Sci. Dev.* **2012**, *3*, 393–399. [CrossRef]
22. Kumar, P.; Singh, R.K.; Kumar, V. Managing Supply Chains for Sustainable Operations in the Era of Industry 4.0 and Circular Economy: Analysis of Barriers. *Resour. Conserv. Recycl.* **2021**, *164*, 105215. [CrossRef]
23. Devi, A.; Ravindra, K.; Kaur, M.; Kumar, R. Evaluation of Biomedical Waste Management Practices in Public and Private Sector of Health Care Facilities in India. *Environ. Sci. Pollut. Res.* **2019**, *26*, 26082–26089. [CrossRef] [PubMed]
24. Cynarski, W.; Gajdzik, B. (Eds.) *Transitioning to Sustainable Industry, Innovation and Infrastructure*; MDPI: Basel, Switzerland, 2023; ISBN 978-3-03897-869-5.
25. Caniato, M.; Tudor, T.; Vaccari, M. International Governance Structures for Healthcare Waste Management: A Systematic Review of Scientific Literature. *J. Environ. Manag.* **2015**, *153*, 93–107. [CrossRef] [PubMed]
26. Taghipour, H.; Mosaferi, M. The Challenge of Medical Waste Management: A Case Study in Northwest Iran-Tabriz. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2009**, *27*, 328–335. [CrossRef]
27. Udayanga, L.; Sahana, L.; Perera, A.; Ranasinghe, K.; Ranathunge, T. Knowledge, Perceptions and Practices on Healthcare Waste Management and Associated Occupational Health Hazards among Healthcare Professionals in the Colombo District, Sri Lanka: A Cross-Sectional Study. *Front. Public Health* **2023**, *11*, 1215648. [CrossRef]

28. Moeini, B.; Ayubi, E.; Barati, M.; Bashirian, S.; Tapak, L.; Ezzati-Rastgar, K.; Hashemian, M. Effect of Household Interventions on Promoting Waste Segregation Behavior at Source: A Systematic Review. *Sustainability* **2023**, *15*, 16546. [CrossRef]
29. Kenny, C.; Priyadarshini, A. Review of Current Healthcare Waste Management Methods and Their Effect on Global Health. *Healthcare* **2021**, *9*, 284. [CrossRef]
30. Nema, A.; Pathak, A.; Bajaj, P.; Singh, H.; Kumar, S. A Case Study: Biomedical Waste Management Practices at City Hospital in Himachal Pradesh. *Waste Manag. Res. J. Sustain. Circ. Econ.* **2011**, *29*, 669–673. [CrossRef]
31. Wafula, S.T.; Musiime, J.; Oporia, F. Health Care Waste Management among Health Workers and Associated Factors in Primary Health Care Facilities in Kampala City, Uganda: A Cross-Sectional Study. *BMC Public Health* **2019**, *19*, 203. [CrossRef]
32. Khalil, Z.T.; Rahman, S. Leveraging Technology to Enhance Access to Healthcare and Manage Medical Waste: Practices from Emerging Countries. In *Fostering Sustainable Businesses in Emerging Economies*; Emerald Publishing Limited: Bingley, UK, 2023; pp. 187–206.
33. Lino, F.A.M.; Ismail, K.A.R.; Castañeda-Ayarza, J.A. Municipal Solid Waste Treatment in Brazil: A Comprehensive Review. *Energy Nexus* **2023**, *11*, 100232. [CrossRef]
34. Raji, M.O.; Adeogun, A.G. Healthcare Waste Management: An Overview. *ABUAD J. Eng. Res. Dev.* **2024**, *7*, 14–27. [CrossRef]
35. Bokhoree, C.; Beeharry, Y.; Makoondlall-Chadee, T.; Doobah, T.; Soomary, N. Assessment of Environmental and Health Risks Associated with the Management of Medical Waste in Mauritius. *APCBEE Procedia* **2014**, *9*, 36–41. [CrossRef]
36. Tait, P.W.; Brew, J.; Che, A.; Costanzo, A.; Danyluk, A.; Davis, M.; Khalaf, A.; McMahon, K.; Watson, A.; Rowcliff, K.; et al. The Health Impacts of Waste Incineration: A Systematic Review. *Aust. N. Z. J. Public Health* **2020**, *44*, 40–48. [CrossRef] [PubMed]
37. Abubakar, I.R.; Maniruzzaman, K.M.; Dano, U.L.; AlShihri, F.S.; AlShammari, M.S.; Ahmed, S.M.S.; Al-Gehlani, W.A.G.; Alrawaf, T.I. Environmental Sustainability Impacts of Solid Waste Management Practices in the Global South. *Int. J. Environ. Res. Public Health* **2022**, *19*, 12717. [CrossRef] [PubMed]
38. Chuks, N.; Anayo, F.; Ugbogu, O.C. Health Care Waste Management—Public Health Benefits, and the Need for Effective Environmental Regulatory Surveillance in Federal Republic of Nigeria. In *Current Topics in Public Health*; InTech: Gandhinagar, India, 2013.
39. Afesi-Dei, C.; Appiah-Brempong, M.; Awuah, E. Healthcare Waste Management Practices: The Case of Ho Teaching Hospital in Ghana. *Heliyon* **2023**, *9*, e15514. [CrossRef]

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