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Assessment of the Main Elements for a Healthcare Waste Management System Using Analytical Hierarchical Process

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Abstract

When addressing Healthcare Waste Management (HCWM), numerous factors play a crucial role in ensuring its safety and environmentally responsible handling within institutional processes. Recognizing this imperative, this study employed the Analytical Hierarchical Process (AHP) methodology to establish a comprehensive assessment of 10 primary criteria and 66 sub-criteria concerning the governance and operational aspects of Healthcare Waste Management. This evaluation was based on the insights of 14 specialists in the field. It demonstrated innovation by prioritizing essential elements for the construction and maintenance of a comprehensive Healthcare Waste Management System. The results indicated the paramount importance of Treatment and Collection Services, which accounted for 13.4% of the overall assessment. Among the sub-criteria within this domain, the Number of Environmental Fines emerged as particularly significant, constituting 32.2% of the total assessment. Following closely, the Best Destination for Biological Waste criterion garnered

13.3% importance, while Monitoring Healthcare Waste Management Plan and Prioritization of Operational Steps ranked 12.7% and 10.9%, respectively. These insights and conclusions will guide stakeholders in developing an effective Healthcare Waste Management System that addresses critical dimensions such as biosafety, legal compliance, environmental stewardship, and financial sustainability.

Keywords

Healthcare waste management system; analytical hierarchical process; governance; operational; prioritization

1. Introduction

Waste encompasses materials, substances, or objects from human activities intended for disposal, whether in solid, semi-solid, gaseous or liquid forms [1]. The varied nature of waste generated in human endeavors necessitates integrated management approaches that account for economic, cultural, and social factors, alongside active engagement from communities and stakeholders. Such management strategies must also align with regional policies for effective coordination [2].

Healthcare Waste (HCW) demands heightened attention due to its diverse origins and associated chemical, biological, or radioactive risks. According to the World Health Organization (2014), HCW emanates from healthcare facilities, including clinical laboratories and hospitals, and waste generated during home appointments, categorized into hazardous and non-hazardous types. Approximately 85% of this waste is considered typical domestic waste, while the remaining 15% poses significant risks to both human health and the environment, needing careful management protocols [3]. However, the applicability of this statistic varies, contingent upon factors such as technical regulations, guiding legislation, and internal organizational structures within healthcare facilities. Individual analysis reveals varying proportions of hazardous waste within healthcare settings, ranging from 6.42% at a University Hospital in Hungary to 64% at a hospital in Brazil, 5% at another hospital in Brazil, and 35% at a microbiology laboratory in Greece [4-6].

In terms of quantity, the largest inhabitant-related generators of HCW *per* continent are North and South America, with 4.42 and 1.64 $kg\cdot bed^{-1}\cdot day^{-1}$, respectively. Regarding hazardous waste, the highest rate is reported in Oceania (0.77 $kg\cdot bed^{-1}\cdot day^{-1}$), while Africa presents the lowest values, not only for non-hazardous but also hazardous waste (0.19 and 0.39 $kg\cdot bed^{-1}\cdot day^{-1}$) [7]. Moreover, when assessing data within the context of the SARS-CoV-2 pandemic, only in Brazil, the rate of hazardous waste from HCW increased from 14 million tons in 2019 to 24 million tons in 2020 [8]. In Bangladesh, the amount of HCW originating from COVID-19 patients rose from 658.08 tons in March 2020 to 16,164.74 tons in April 2021, while in the USA, the rate of HCW generation surged from 0.4 million tons per month before the pandemic to 2.5 million tons per month during the pandemic [9, 10].

In a study conducted by Singh *et al*. [11], the analysis of 78 countries revealed that only an average of 38.9% of their healthcare waste (HCW) was segregated for proper management, with merely 41% of healthcare professionals trained in handling such residues. This finding underscores the urgent need for improved biosafety measures in HCW management, particularly to mitigate the risks of accidents like punctures or contamination exacerbated by inadequate segregation and storage practices [12-14]. Additionally, there is a notable occurrence of environmental dangers and accidents stemming from improper treatment and disposal methods, potentially leading to contamination and significant health hazards. In light of these challenges, it is imperative for HCW managers to commit to minimizing these issues by implementing safe and environmentally responsible Healthcare Waste Management Systems.

To establish and implement an appropriate Healthcare Waste Management System, it is essential to have laws and technical standards that guide HCW generators, delineating responsibilities and requirements for segregation, collection, storage, handling, treatment, transport, and final disposal [3, 15]. These legal frameworks must explicitly address HCW and include an inspection system to ensure law enforcement, along with specifications regarding technical registration and environmental licensing procedures for HCW [3].

In Europe, most healthcare waste is incinerated and the recognition of the significant environmental and financial costs resulting from inadequate management of Healthcare Waste (HCW) has led to the development of regulations prioritizing waste minimization, proper segregation at the point of generation, and a commitment to training and best practices. This underscores the importance of strategies such as regular internal audits [16, 17]. However, in developing Asian countries like India, Pakistan, and Bangladesh, HCW legislation is relatively recent, and despite incorporating recommendations from international organizations, it is not effectively enforced within management systems [18]. Moreover, factors such as the absence of HCW generation data registration, coupled with insufficient awareness and training, cause the management process to be inefficient, thereby increasing risks for the healthcare community and the environment [13]. Thakur & Anbanandam [19] identified that most healthcare managers in India fail to maintain records of their HCW processes and often outsource their treatment, indicative of an inefficient commitment where attention is solely focused on delivering improved healthcare services to the population.

Given the highlighted problems, the present study aims to assess and classify the essential elements of Healthcare Waste Management Systems, focusing on governance and operational criteria in accordance with current legislation and offering guidelines to be implemented in Healthcare Facilities.

2. Materials and Methods

To assess the essential governance and operational elements for a Healthcare Waste Management System, use of the Analytical Hierarchical Processes (AHP) methodology was employed. Developed by Thomas L. Saaty [20], AHP relies on the inherent human ability to make profound judgments about simple problems, facilitating the organization of perception, sensation, and experience into a structured framework that elucidates the forces influencing the final decision [20]. In AHP, the problem to be addressed is broken down into hierarchical criteria levels for analysis, decomposing it into as many levels as necessary. At each level, individuals must establish the priority of importance for one element relative to another. The methods stages used are presented in Figure 1. This priority among elements is represented by a numerical value, according to a scale developed by Saaty [20], as detailed in Table 1. The collective judgments form a square matrix, where each judgment reflects the dominance of one element over another in the row relative to the column of the matrix.

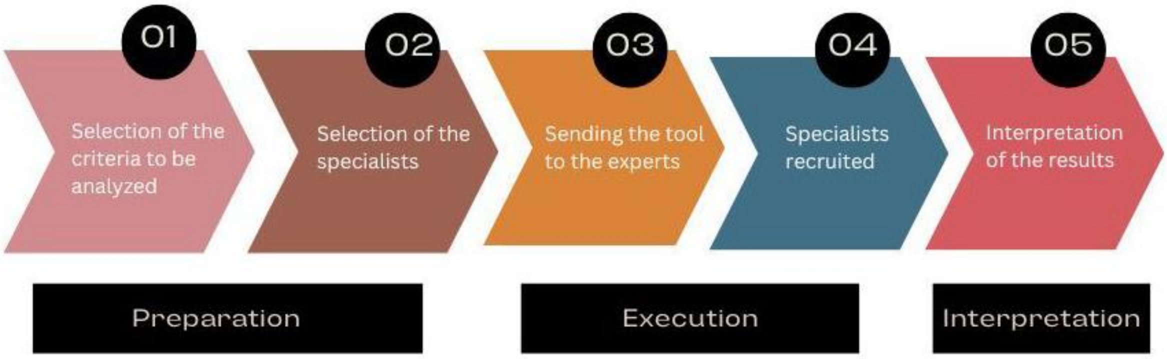

Figure 1 Flowchart of the used stage methods – adapted from [20].

Table 1 Fundamental scale of Saaty [20] for judgment done by the AHP method.

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment favour the activity
5	Strong importance	Experience and judgment strongly Favor one activity over another
7	Very strong importance or demonstrated importance	An activity is strongly favored over another, and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	For importance between the values above	Sometimes it is necessary to interpolate a judgment of commitments

This is a methodology used broadly for decision-making in problems that involve multiple criteria, such as the selection of location for final deposition of waste, management group decisions, logistics, and people management [21-24]. Confidence and fuzziness were measured by lambda, considering more than 10% to validate, as suggested by Saaty [20]. Consistency ratio and consensus were also monitored, confirming the results presented.

The AHP (Analytic Hierarchy Process) method is widely used for multi-criteria decision-making. However, there are equivalent and more recent methods, such as BWM (Best-Worst Method), LBWA (Level-Based Weight Assessment), FUCOM (Full Consistency Method), and DIBR (Defining Interrelationships Between Ranked Criteria), which aim to simplify the paired comparison process. It is worth noting that the AHP method benefits from a vast literature of case studies and comparisons, which enhances confidence in its results. Additionally, it allows for incorporating both qualitative and quantitative criteria, making it adaptable to various contexts and problem scales [23, 24].

Furthermore, the paired comparison process is intuitive and easily understandable for decision-makers. It also includes a mechanism to calculate the consistency of these comparisons. While it requires more comparisons, this can lead to a more detailed and accurate analysis, particularly in complex problems with numerous criteria and alternatives. Therefore, it is important to highlight the maturity, flexibility, transparency, and ability of the AHP method to handle complex problems, making it still highly applicable to contexts similar to those explored in this article.

For the construction of the judgment matrix, criteria and sub-criteria were identified based on the current national and regional legislation for HCW in Brazil (operational patterns) and ISO 14001 (governance patterns). Figure 2 contains the first, second, and third-level criteria selected for evaluation by specialists. These criteria and sub-criteria were organized into worksheets within the Excel software. Each judgment was assigned an integer value, indicating whether the element of the row was more important than the element of the column or the reverse value when the element of the column was more significant than the element of the row. The assigned values were quantitatively analyzed for consistency using established formulas from the AHP method. Consequently, for each criterion, the elements to be prioritized in a Healthcare Waste Management System considering governance and operational aspects were determined.

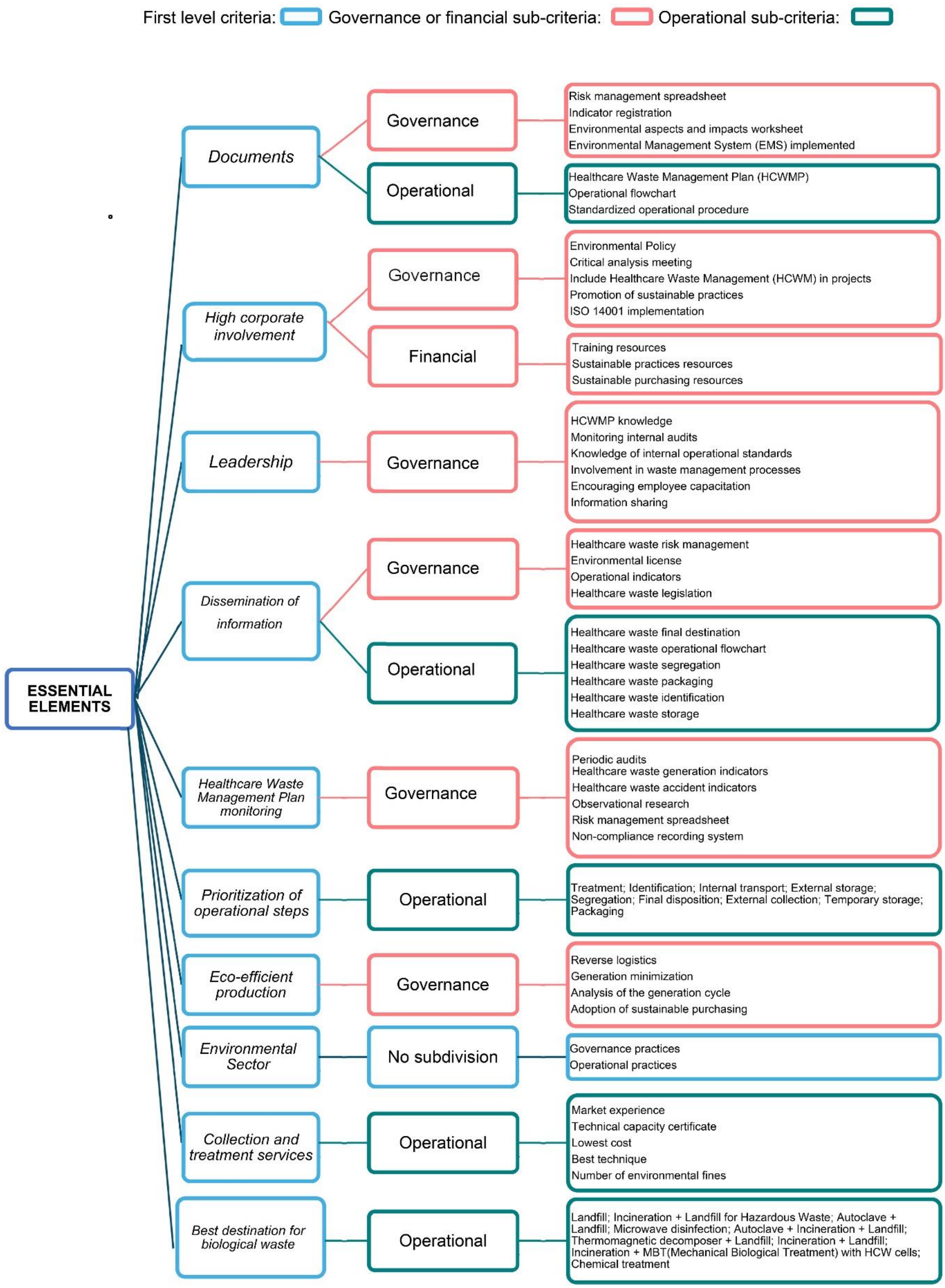

Figure 2 Criteria, sub-criteria, and elements for assessment by specialists.

To selection specialists, research was conducted among HCW managers from Brazilian public health laboratories and large-scale hospitals in Belo Horizonte (state of Minas Gerais, Brazil). Researchers in the waste management field, institutions responsible for waste management in Belo Horizonte (Minas Gerais, Brazil), members of the municipal Permanent Commission of Support in Healthcare Waste Management (COPAGRESS), and representatives of healthcare professional councils. The profiles of the interviewed specialists are detailed in Table 2.

Table 2 Profile from the experts that analyzed HCW management governance and operational criteria.

Profile	Number of Experts
Responsible for HCW management in a large hospital	4
Responsible for HCW management in public health laboratory	5
Researcher	1
Responsible for HCW management in the healthcare unit of Federal University	1
Associations/commissions representatives	2
Representative of the agency responsible for municipal HCW management	1

3. Results and Discussion

Of 24 specialists who received the criteria judgment worksheets, 14 returned their evaluations after 4 months. As there was no hierarchy among the specialists, therefore, all assessments were given equal significance. To produce a consolidated consensus of the judgments, a geometric mean of the results from the specialists for each analyzed criterion was applied, following the recommendation of Saaty [25], as shown in Figure 3. For this purpose, the tool developed by Goepel [26] was utilized, where the data is individually entered into an Excel worksheet, resulting in a consolidated summary with the weight of each assessed criterion. The results, containing the level of importance of criteria for each matrix, were compiled into a single result, applying the geometric mean as recommended by the AHP method [25].

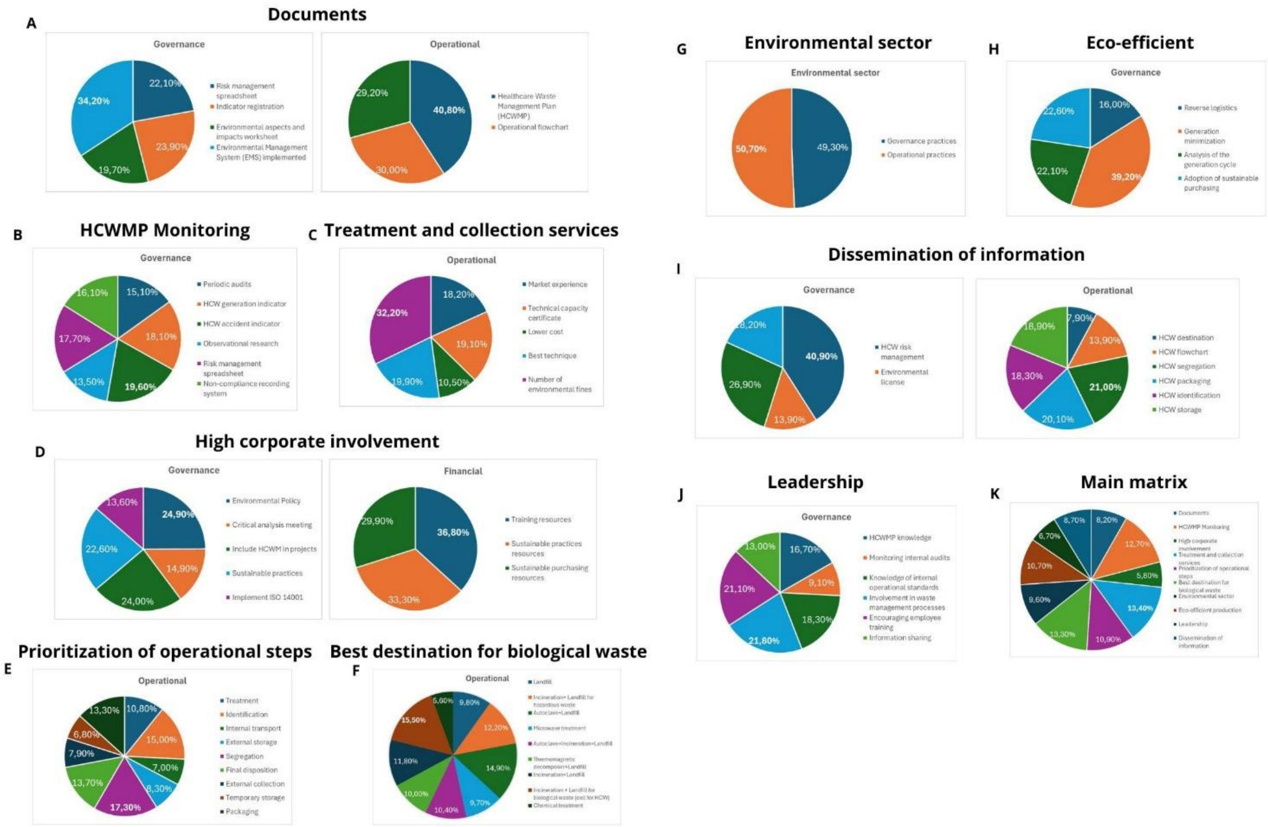

Figure 3 Consolidated expert judgment for the established criteria and sub-criteria. Legend: A – Governance: consistency of 3.0 and consensus of 74.2%; Operational: consistency of 3.0 and consensus of 81.1%. B – Governance: consistency of 6.0 and consensus of 83.4%. C – Operational: consistency of 5.0 and consensus of 67.9%. D – Governance: consistency of 5.0 and consensus of 77.0%; Financial: consistency of 3.0 and consensus of 75.9%. E – Operational: consistency of 9.0 and consensus of 83.1%. F – Operational: consistency of 9.0 and consensus of 50.0%. G – Environmental sector: consistency of 2.0 and consensus of 89.8%. H – Governance: consistency of 4.0 and consensus of 80.1%. I – Governance: consistency of 4.0 and consensus of 83.1%; Operational: consistency of 6.0 and consensus of 81.0%. J – Governance: consistency of 6.0 and consensus of 86.1%. K – Main matrix: consistency of 10.0 and consensus of 82.4%.

The first-level criterion, *"Documents"* (8.2%), assessed the importance of record-keeping that aids governance and operational processes. Results on the *"Governance"* scale indicate that an *"Environmental Management System implemented"* (34.2%) is most relevant, followed by *"Indicator registration"* (23.9%) and *"Risk management spreadsheet"* (22.1%). An Environmental Management System (EMS) is a transparent and systematic process recognized by the entire enterprise. It aims to establish and implement goals, policies, and environmental responsibilities, including regularly auditing its elements [27]. In the healthcare context, the application of an EMS promotes an integrated vision of variables from healthcare and sustainability principles. When effectively applied, this results in reduced waste production and handling costs, improved energy utilization, lower rates of hospital infections, and increased quality and credibility of the institution

[28-30]. Although HCW management is not the sole purpose of an EMS, the objective of this study is to understand the benefits of its adoption for efficient governance and operational processes of this waste category. Basic EMS criteria, such as risk descriptions, indicator registration, and environmental impact studies, can be implemented in HCW management to establish internal and/or external procedures, services, and contracts covering HCW generators [31]. In terms of certification, organizations may validate their EMS against internationally recognized standards such as ISO 14001, Eco-Management, and Audit Scheme (EMAS) [32]. The formal adoption of an EMS by healthcare facilities is often seen as a distant reality, considering challenges such as document procurement and lack of recognition by senior leadership. However, EMS implementation does not solely depend on the intention to obtain certification but also serves as a tool for implementing environmental policy, with technical formalization often occurring after activities commence, even without certification [33, 34]. Romero & Carnero [35] developed a model for better sustainability performance in hospitals to align with ISO 14001 standards, assessing factors such as hazardous waste generation, waste logistics, energy consumption, environmental compliance of suppliers, and environmental awareness of the hospital community. However, engineering solutions alone cannot sustain an EMS without support from organizational structure, appropriate culture, competent and conscientious staff, and effective information/communication systems [36].

The results regarding the *"Documents"* criterion in the *"Operational"* dimension, on the other hand, revealed that the most significant sub-criteria for specialists were the *"Healthcare Waste Management Plan (HCWMP)"* (40.8%), followed by the *"Operational flowchart"* (30.0%) and *"Standardized operational procedure"* (29.2%). The HCWMP serves as a tool that outlines and describes actions related to HCW handling that must be formulated according to the specific characteristics of each facility in compliance with current regional, national, or international regulations and standards [2, 37]. The responsibility to develop, implement, and monitor the HCWMP lies with the HCW generator [38]. From a global perspective, a study conducted by Windfeld & Brooks [39] on HCW regulatory systems in the United States, Canada, the European Union, and other developed countries highlighted standard features such as the classification and categorization of HCW, mandatory identification, storage, and quantitative recording of waste generation by facilities. Other notable considerations include limits on atmospheric emissions from incineration equipment and, notably, financial, and criminal penalties for non-compliance with regulations. Therefore, developing an HCWMP that encompasses the entire operational flowchart of HCW is essential to guide healthcare facilities in compliance with legal regulations. In addition to meeting mandatory requirements, the HCWMP aims to reduce waste generation, promote sustainable solutions such as recycling and reverse logistics, reduce costs in intra or extra-institutional processes, and mitigate environmental and health risks [40-42].

For the *"High corporate involvement"* (5.8%) criterion, the sub-criterion *"Environmental Policy"* (24.9%) was the most prominent, followed by *"Include Healthcare Waste Management in Projects"* (24.0%) and *"Sustainable Practices"* (22.6%). Analysing the Sustainable Development Goals (SDGs) and the Sustainable Development Agenda, there is a growing commitment by healthcare facilities, particularly regarding cleaner production, reducing hazardous waste generation and fostering sustainable innovation. A way to establish a starting point for collaboration on these topics is the adoption of an Institutional Environmental Policy, which aims to ensure environmental responsibility not only in internal activities but also among manufacturers, distributors, and suppliers [43, 44]. In the United States, among large healthcare companies included in financial and social development rankings, only an average of 32% is committed to publishing sustainability reports, lagging behind other economic sectors and consequently, far from achieving the SDGs [45]. The results presented by the specialists suggest that, if the high-level corporate members of an establishment commit to an Environmental Policy, there is a greater chance of implementing the commitments made.

In the *"Financial"* dimension, the specialists emphasized the importance of providing *"Training Resources"* (36.8%). A training structure should aim to enhance employee competence (technical knowledge), motivation (commitment and engagement with activities), and opportunities (periodic development of effective actions), tailored to the type of waste generated/handled in specific activities (clinical care, laboratory analysis, cleaning, transportation, etc.). This approach can cultivate an individual and collective mindset within the establishment, promoting vigilant and responsible attitudes toward HCW management. Formal training, interventions, practical demonstrations, and monitoring results are essential and are directly associated with allocating resources for the Internal Environmental Management of the facilities [46].

For *"Leadership"* (6.7%), the item *"Involvement in waste management processes"* (21.8%) was highlighted by the specialists. Leadership involvement in healthcare waste (HCW) management can provide the motivation and guidance that the rest of the staff needs. Anozie *et al*. [47] conducted research with 54 healthcare managers in Nigeria and found that only 1.9% of the facilities had head staff knowledgeable about waste management procedures and practiced proper segregation when discarding waste. Similarly, a study by Botelho [16] involving 741 healthcare establishments in Portugal demonstrated that designating responsible personnel for healthcare waste management increased the conformity rate by nine percentage points compared to units that did not implement this measure. For the *"Environmental Sector"* (9.6%), the sub-criteria *"Operational Practices"* (50.7%) were slightly ahead of *"Governance Practices"* (49.3%). This proximity suggests that governance and operational decisions must work together to establish a technical and organized HCW management system. A functional HCW committee, such as an environmental sector, is significant for the success of these practices in both public and private facilities [48-50].

Regarding the *"Prioritization of operational steps"* (10.9%), specialists identified *"segregation"* (17.3%) as the most critical step. This is an expected outcome, as proper segregation significantly reduces the volume of hazardous waste and the incidence of accidents among healthcare staff. Research by Aduan *et al*. [51] conducted in six Brazilian hospitals indicated that correct segregation processes reduced hazardous waste volume by 42%. Similarly, Rasheed and Walraven [52], through an internal audit of a facility, found that 75% of the waste destined for incineration did not have infectious characteristics. It is important to note that prioritizing one operational practice does not decrease the importance of others, as the effectiveness of one step often depends on the proper execution of another [53]. For instance, the lack of suitable containers — pedal-operated lids and adequate labeling according to the waste risk — directly affects the segregation stage. Therefore, it is crucial to validate segregation practices within different areas through internal audits, periodic verification systems, and the adoption of indicators to ensure that the segregation process aligns with the institution's Healthcare Waste Management Plan (HCWMP) [54, 55].

The *"Dissemination of information"* (8.7%) criterion in the *"Governance"* dimension highlighted that information about *"HCW risk management"* (40.9%) is particularly relevant. This suggests that disseminating knowledge about the risks associated with healthcare waste (HCW) and ways to mitigate them can positively impact those involved in the management process, from the generator to those responsible for final disposal. This approach promotes a broader understanding and active participation [32, 56]. In the *"Operational"* dimension, the dissemination of knowledge about *"HCW segregation"* (21.0%) was emphasized. This aligns with the findings from the "Prioritization of operational practices" criterion, which demonstrated the importance of segregation. Promoting periodic training and using tools for disseminating internal information within the establishment can help consolidate these concepts, thereby reducing occupational risks and improving the effectiveness of operational steps [57-59].

For the *"HCWMP Monitoring"* (12.7%) criterion, the specialists concluded that the *"HCW accident indicator"* (19.6%) must be given primary consideration, noting a reasonable balance in the weights of the criteria. Monitoring involves adopting a systematic and continuous process based on a significant and periodic set of data and information that allows measuring, understanding, and evaluating its effects [60]. By establishing the HCWMP as a guiding document for the facility's HCW management decisions, stakeholders must commit to the constant evaluation and revision of procedures. This includes considering possible changes in activities that generate HCW, or the results shown in the monitoring process. Schneider *et al*. [41] proposed using a digital data management system to improve the evaluation of an HCWMP in a university hospital. The results indicated that if the system were 100% adequate, the treatment costs for hazardous waste could be reduced by 18.4% monthly, and the average savings for chemicals could be 5.83% of the total monthly cost. Considering the occupational variable, since the *"HCW accident indicator"* was the most prioritized sub-criteria, the need for information gathering and decision-making becomes even more urgent.

Accidents involving healthcare staff can occur at all stages of HCW handling, potentially causing lacerations (in the case of sharps), contamination by pathological agents, and allergic reactions due to contact with chemical substances. An inspection study by Delevati *et al*. [61] in 28 Brazilian public hospitals indicated non-conformity in the external storage of sharps, with some establishments keeping discarded boxes on the floor, posing injury risks to staff and the hospital community. For workers responsible for the collection, treatment, transport, and final disposal of HCW, the rate of accidents is even more significant. Shiferaw *et al*. [62] reported an exposure rate of over 40% and 60% to sharps and mucous membranes, respectively, among employees in this category in Ethiopia. Such accidents often result from negligence by healthcare staff in following proper procedures when discarding HCW [63]. Given these factors, it is essential to adopt a monitoring structure that ensures all operational phases, inside and outside the facility, are performed safely for workers, the community, and the environment.

The assessment in the *"Eco-efficient production"* (10.7%) domain revealed that *"Minimization of waste generation"* (39.2%) is the most important item. Eco-efficiency measures advancement towards sustainable development by correlating environmental impacts with economic performance [64]. Waste minimization involves reducing the volume, weight, and toxicity of waste generated in the production process [65]. Using the Analytic Hierarchy Process (AHP) to identify improvement opportunities in Healthcare Waste Management (HCWM) in three hospitals in Abu Dhabi, Hussain *et al*. [66] found that minimizing waste generation was the most important alternative. This included conducting stock inventories to distinguish items that are not being used. Additionally, structuring the waste generated by the institution and exploring available options can help achieve the highest sustainable potential. Stakeholders can apply Circular Economy principles

(Figure 4) to study waste flowcharts in each generator process. A circular Economy is a regenerative system aimed at reducing raw material usage and waste generation and promoting responsible energy consumption [67]. Despite resistance to Circular Economy applicability in healthcare [68], understanding its concepts can lead to more efficient procedures with lower HCW generation. Some circular actions that can be implemented in healthcare facilities include composting organic waste, adopting reusable instruments, engaging in conscientious purchasing processes (such as rejecting more polluting equipment), adopting reverse logistics systems, and adhering to cleaner production standards. Integrating these concepts into facility culture can yield environmental and financial benefits, particularly for large and medium-sized hospitals, laboratories, biological/pharmaceutical product industries, and health research institutions [69-71].

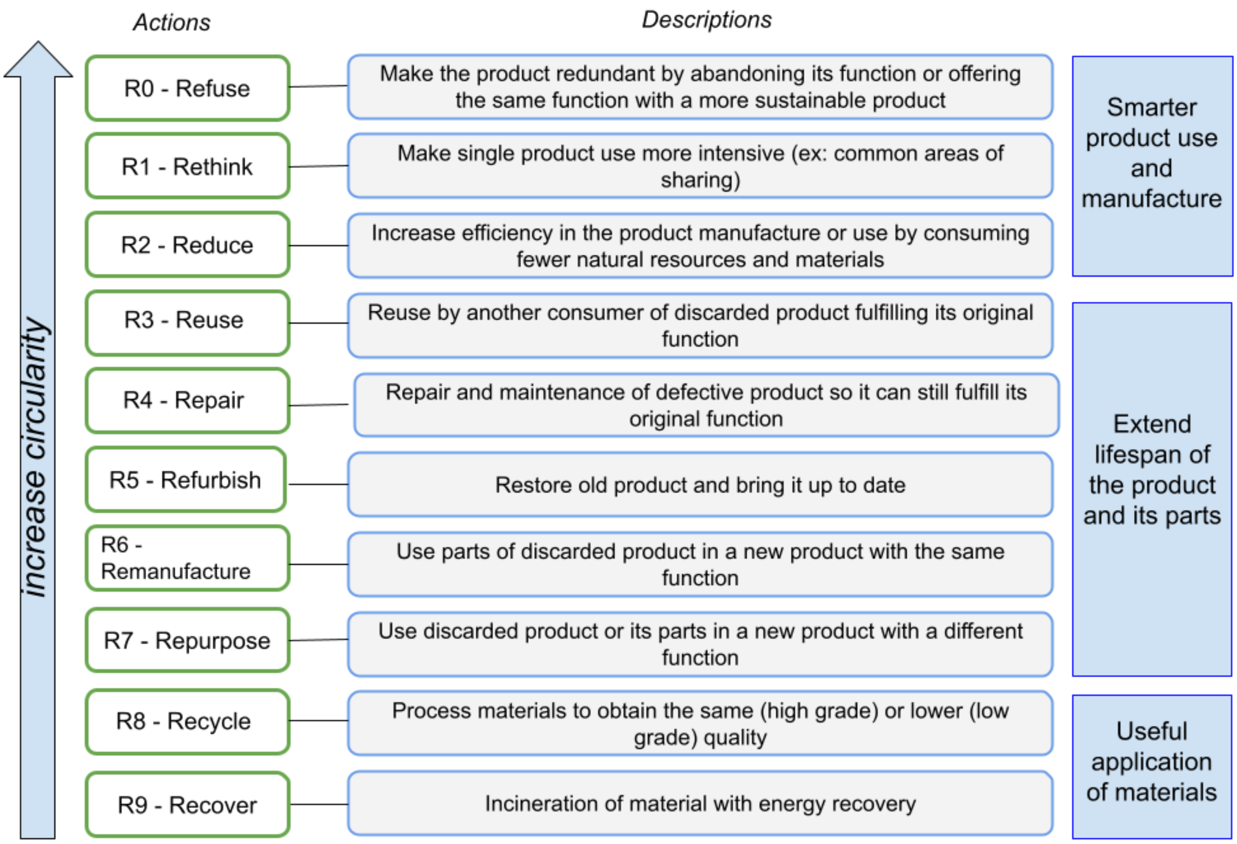

Figure 4 Principles of the Hierarchical Circular Economy – adapted from [72].

In the *"Treatment and collection services"* category (13.4% — the most highly assessed first-level criterion by specialists), the *"Number of environmental fines"* (32.2%) was the most recommended factor to consider during the hiring process. Several case studies highlight non-conformities associated with environmental service providers in the healthcare sector. These range from licensed treatment companies engaging in illegal recycling of healthcare waste (HCW) to environmental authorities admonishing or closing incinerators in Romania and the United States due to non-compliance with mandatory atmospheric emissions control systems [39, 73, 74].

When dealing with HCW, it is crucial to emphasize the importance of thorough planning when contracting an outsourced service. Maintaining constant communication and transparency between parties regarding transportation, treatment, and final disposal methods is essential to ensure both institutional and legal security for the HCW generator. Actions to validate this process include using risk evaluation tools for the company's activities, such as assessing instruments used, processing capacity, collection frequency, emergency management plans, and verifying documents like technical certificates and licenses [75]. Furthermore, literature reports show that HCW treatment companies committed to leadership and sustainable innovation are valuable allies in promoting a cultural shift towards more sustainable Healthcare Waste Management (HCWM) among their clients [76].

The final criterion, *"Best destination for biological waste"* (13.3% – the second most assessed criterion), had its sub-criteria defined by the most used technologies in Minas Gerais according to Brazilian regional regulations [77]. The option "Incineration + Landfill for biological waste (cell for HCW)" was the most highly assessed by specialists. The biological waste referred to by the specialists in the Brazilian regulation belongs to the category A4 (which is a category that does not require pre-treatment for disposal). It is important to highlight that in some countries, the necessity of treatment for biological waste before the final deposition depends on the characteristics of the infective agent present in the waste. The so-called A4 can be landfilled without treatment [78]. However, this was not the preferred method in the final results, likely due to the need to ensure the reduction of contamination potential, thereby requiring incineration before landfilling to guarantee more excellent safety. There is a wide variety of technologies available for treating hazardous healthcare waste (HCW). These can be categorized into three main groups: Chemical Procedures (utilizing alcohols, phenols, acids, bases, peroxides, anti-metabolic ozone, enzymes, etc.), Irradiation Processes (using ultraviolet rays, gamma radiation, and microwaves), and Thermal Processes (including incineration, autoclaving, gasification, pyrolysis and plasma [79].

Incineration is the most widely used HCWM treatment worldwide [80]. According to Thind *et al*. [81], in July 2020, the processing capacity of incinerators across India was strained due to increased HCW generation during the pandemic. Incineration has both advantages and disadvantages: it reduces waste volume and produces energy, but it also releases toxic and carcinogenic compounds and hazardous by-products. Therefore, minimizing the waste directed to incineration and meticulously evaluating incinerators is essential. Notable case studies include the successful reduction of chemical waste destined for incineration in a public health institution in Brazil, by a sharing and donation system for chemicals. Such an attitude benefits both the institution and university laboratories. Additionally, an assessment tool was developed to select the most suitable incinerator for healthcare facilities in Bosnia and Herzegovina, considering economic, ecological, technical, and social criteria [82].

Regarding the final destination for biological waste, the option of Incineration + Landfill for biological waste with cells for HCW was highlighted. Unlike direct landfilling, this kind of landfill may operate together with a screening and composting plant (SCP), particularly in Brazil. Therefore, biological wastes cannot be betrayed, only destined for landfills. SCP minimizes the volume and mass of buried waste by mechanically separating different factions within the waste and stabilizing the organic matter through biological processes such as anaerobic digestion or composting [83, 84]. Between 1990 and 2010, around 180 SCP plants were installed in Europe, increasing to 570 units by 2017, with a capacity of approximately 55 million tons [84]. A case study in Italy by Trulli *et al*. [85] demonstrated a 30% reduction in waste mass alongside the potential for biofuel production. In Brazil, SCP began operating in the late 1960s, with a peak in the 1990s, primarily in small cities with less than 100.000 inhabitants, driven by government incentives [86]. The specialists' preference for this system combined with incineration likely stems from the need for safe handling and final disposal of infectious HCWs. In Europe, for example, nearly all healthcare waste is incinerated in dedicated combustors, usually operating at more than 1200°C [87, 88]. Although infectious waste is not processed directly in SCP procedures, the existence of separate accommodation cells for infectious waste within these units allows for the processing of various waste types from healthcare establishments. This preference indicates a priority for enterprises that ensure caution with infectious waste and offer recycling and reuse techniques for non-hazardous waste.

According to the World Health Organization [89], selecting the best treatment technology for hazardous waste should consider minimal impacts on public health and the environment while achieving the best cost-benefit ratio. Several studies aim to build frameworks that facilitate decision-making by considering the multiple factors involved, their positive and negative aspects, uncertain information, and the pursuit of sustainability in emerging economies [90, 91].

Finally, few studies have applied the AHP methodology in the context of healthcare waste management with many variables, underscoring the significance of this study. The method proved well-suited for this application, demonstrating strong consensus validity among the participating experts. On the other hand, the AHP presents limitations: it requires numerous pairwise comparisons, which can become tedious in complex problems; it assumes independence between criteria, which does not always reflect real-world scenarios; and it is sensitive to subjectivity and inconsistencies in decision-maker responses. Additionally, it may struggle to handle many alternatives, uncertainty, or imprecise data, and it is susceptible to the "rank reversal" phenomenon [20-24, 92]. In this study, the consistency techniques outlined in the methodology helped overcome limitations and generated data validated and aligned with reality, based on the experts' perspectives, as demonstrated in the results.

4. Conclusion

The proposed objective to assess and classify the essential operational and governance elements of a Healthcare Waste Management System (HCWMS) was achieved using a methodology that included input from field specialists. No studies were found in the literature that evaluated the number and quality of criteria assessed by the specialists in this research. Generally, studies focus on specific healthcare waste management systems as individual case studies, identifying specific improvement points. Thus, the results of this study demonstrate innovation by prioritizing essential elements for the construction and maintenance of a comprehensive Healthcare Waste Management System. Among the sub-criteria within this domain, the Number of Environmental Fines emerged as particularly significant, constituting 32.2% of the total assessment. Following closely, the Best Destination for Biological Waste criterion garnered 13.3% importance, while Monitoring Healthcare Waste Management Plan and Prioritization of Operational Steps ranked 12.7% and 10.9%, respectively.

The assessment method used in this study incorporated the personal knowledge and experiences of the specialists. Consequently, healthcare waste generators examining these results for potential application in their own HCWMS should consider factors such as the type of service offered, the size of the enterprise, and its economic profile and legal responsibilities regarding waste generation, according to regional legislation and standards. It is crucial to select procedures and technologies that minimize environmental impact while complying with current laws. The guidelines presented in this research do not exhaust the topic but provide a practical guide for healthcare establishments to take the first steps toward managing healthcare waste in a safer and more efficient manner.

Author Contributions

All authors contributed to the study's conceptualization and design. Data collection and analysis were performed by F.C.L.B. The first draft of the manuscript was written by F.C.L.B. and A.C.T.A. All authors (F.C.L.B.; A.C.T.A.; M.P.G.M.; R.T.V.B.) commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

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