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Original Article

Sustainable Waste Management in Healthcare: Application of Fuzzy Determination Method to Prioritize Key Influencing Factors

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Abstract
Background: Hospital wastes are a significant environmental and health hazard. With the increasing volume of healthcare wastes and heightened public awareness, sustainable management practices have become imperative. This study aimed to identify and prioritize key factors influencing sustainable healthcare waste management
Methods: Adopting a quantitative approach, the study first identified ten critical factors through literature review. Subsequently, the fuzzy DEMATEL technique was employed to analyze and prioritize these factors. Fifteen experts from health, management, and statistics domains were purposefully selected to provide insights for this analysis.
Results: The analysis categorized the factors into two groups: influential and influenced. Influential factors include fostering a green healthcare organizational culture that encourages waste recycling, promoting best practices for sustainable waste management, enhancing training programs, improving environmental awareness among healthcare workers, strategic planning for waste management, and cultivating positive attitudes toward sustainability. Influenced factors encompass establishing a supportive legal framework, developing necessary infrastructure, adopting environmentally friendly waste management technologies, and implementing environmentally conscious procurement practices.
Conclusion: The findings underscore the importance of internal organizational culture and education in driving sustainable waste management. To mitigate health-related pollution risks, it is recommended that hospitals implement educational programs to foster positive attitudes and equip staff with appropriate waste management practices. Also, governmental bodies should enforce regulatory frameworks and conduct periodic audits to ensure compliance and effectiveness in healthcare waste management.
Keywords: Sustainability, Health waste management, Hospital wastes, Fuzzy DEMATEL

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Introduction
Healthcare facilities—including hospitals, clinics, diagnostic laboratories, and dental offices—generate significant amounts of solid waste, some of which poses serious environmental and health hazards. Common risks include injuries from sharps, radiation exposure, poisoning from cytotoxic drugs, contamination of drinking water with mercury or dioxins, and air pollution resulting from improper waste disposal. Effective management of hospital waste—including its collection, storage, and disposal—is therefore critical and must adhere strictly to established health protocols. While approximately 85% of healthcare waste is non-hazardous, the remaining 15% is considered hazardous and may be infectious, toxic, or radioactive.[1]

The demand for healthcare services has been steadily increasing due to factors such as rapid urbanization, an aging population, the prevalence of chronic diseases, and the emergence of infectious diseases. This surge has led to a corresponding increase in healthcare waste generation.[2] According to the World Health Organization (WHO), the primary sources of healthcare waste include hospitals, laboratories, research centers, mortuary and autopsy centers, blood banks, and nursing homes. Globally, healthcare waste generation is rising at an estimated rate of 2%–3% annually. In China, for instance, healthcare waste was projected to reach 2.496 million tons in 2023.[3] If proper segregation and management practices are not implemented, countries like Iran could see their hospital waste production reach approximately 3.5 million tons per year by 2028, potentially exacerbating municipal waste challenges.[4]

The role of healthcare facilities in maintaining environmental health has garnered significant attention, emphasizing the importance of sustainable healthcare waste management.[5] Proper implementation of sustainable practices can effectively mitigate health hazards and environmental pollution. Identifying and enhancing key factors influencing sustainable waste management is essential for progress in this area. Conversely, unsustainable and improper waste management practices can have detrimental effects on public health and the environment.[6] Sustainable healthcare waste management involves employing effective methods and strategies to collect, process, recycle, and dispose of waste in ways that minimize negative impacts on the environment, public health, and natural resources.[7] This approach integrates considerations of environmental, social, economic, technological, and resource sustainability.[8] Effective management not only protects public health and the environment but also contributes to waste reduction.[9,10] Key focus areas include site assessment, treatment technology selection, life cycle assessment, and policy analysis.[11] For example, a study by Canale et al in a hospital in Lucca, northwestern Tuscany, demonstrated that increased staff participation and scientific planning effectively reduced waste generation. The study underlined the importance of a robust legal framework to support sustainable waste management initiatives.[12]

Moreover, many healthcare workers lack full awareness of the environmental risks associated with improper waste management. Implementing adequate training programs can enhance their awareness of sustainability principles.[13]

Cesaro and Belgiorno[14] reported that waste separation efficiency was insufficient in a four-year study conducted across five hospitals in Salerno, southern Italy. They concluded that simplifying operational procedures could improve system efficiency and reduce costs.

Since most healthcare workers are not clearly aware of the environmental risks of improper waste management, appropriate training programs can help increase awareness discussed the importance of training staff in waste management in the field of healthcare management.

According to Kokkinos et al,[15] selecting an appropriate medical waste management method under uncertainty requires a robust decision-making framework. Their study introduces an intuitionistic fuzzy MCDM approach that incorporates expert judgment across seventeen criteria, ultimately highlighting safety and risk avoidance as the most critical factor for sustainable urban health systems.

By examining the research related to healthcare waste management, it can be observed that most of the articles in this field have explained the waste rate in different hospital departments and its separation and disposal methods, and two shortcomings and research gaps are observed in these studies. First, the key factors affecting the sustainability of healthcare waste management have not been identified in most of the articles.[16] Second, none of the articles analysed the causal relationships between the factors affecting sustainability. Currently, no research has examined the key factors affecting healthcare waste management from a sustainability perspective. In the present study, first, by reviewing previous research, the key factors affecting the sustainability of healthcare waste management were identified. Then, via the fuzzy DEMATEL method, the influencing and affected factors were prioritized, and the causal relationships between these factors were identified.

Materials and Methods

Phase 1: Literature Review

To identify relevant factors, a comprehensive literature review was undertaken. This involved searching reputable online databases for scholarly articles, as well as consulting both domestic and international books pertinent to the research topic.

Phase 2: Field Research

Given that sustainable waste management is an organizational and professional activity, data from field experts is essential. In 2023, the study engaged 15 experts with over ten years of experience in sustainable waste management. These experts possess extensive methodological knowledge and practical experience, qualifying them to provide insights into sustainable waste management practices.

A questionnaire acted as the primary data collection tool. The experts were asked to evaluate the influence of various factors on one another, using a linguistic scale presented in Table 1. The responses were translated into triangular fuzzy numbers, aligning with the fuzzy DEMATEL method, which utilizes fuzzy numbers to handle uncertainty in expert judgments.

The fuzzy DEMATEL method, introduced by Fonta and Gabos in 1976, is a graph-based decision-making tool that relies on pairwise comparisons to analyze complex systems. This method is particularly effective in confirming or limiting relationships between variables in a structured manner. However, precise numerical estimation of expert opinions is challenging under uncertainty, as decision-making outcomes heavily depend on subjective judgments.[17] To address this, fuzzy logic is integrated into DEMATEL, allowing for the use of fuzzy linguistic variables, which facilitates decision-making in

Table 1. Qualitative Expressions and Equivalent Values

Triangular Fuzzy Numbers	Exact Equivalent	Linguistic Phrases
(0.25, 0, 0)	0	No effect
(0.5, 0.25, 0)	1	Very little effect
(0.75, 0.5, 0.25)	2	Low impact
(1, 0.75, 0.5)	3	High impact
(1, 1, 0.75)	4	Very high impact

uncertain environments.

Unlike other decision-making methods based on pairwise comparisons, the fuzzy DEMATEL method accommodates feedback among relationships. This means that elements within the system may influence each other reciprocally. The significance and weight of each factor are determined not only by upstream or downstream influences but also by the collective interactions within the entire system.[18] This technique employs directed graphs to visually and quantitatively represent the interdependencies among factors. By leveraging expert judgments and applying graph theory principles, the method extracts influential relationships and constructs a systematic hierarchical structure, assigning numerical scores to the intensity of these relationships.

The initial step involves assembling a group of experts with substantial knowledge and experience in the subject matter to collect pertinent data. Standard criteria are established, and five qualitative expressions are utilized to compare these criteria. The linguistic terms and their corresponding fuzzy values are detailed in Table 1. Upon gathering expert opinions, each response is converted into its fuzzy equivalent based on Table 1, resulting in the formation of the initial fuzzy direct correlation matrix.

$$Z = \left(l_{ij}, m_{ij}, u_{ij}\right) \qquad z = \begin{bmatrix} 0 & z_{12} & \cdots & z_{1n} \\ z_{21} & 0 & \cdots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n1} & z_{n2} & \cdots & 0 \end{bmatrix}$$

The normalization equations are used to convert the scales of the factors into comparable scales, where the matrix X is the fuzzy matrix of the normalized direct relationships (equation 1).

$$r = max_{1 \le i \le n} \left(\sum_{j=1}^{n} a_{ij} \right)$$

$$a_{ij} = \sum_{j=1}^{n} z_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} u_{ij} \right)$$

$$x = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \& x_{ij} = \frac{z_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r} \right) \qquad (1)$$

The T matrix reflects the total relationships between couples and is calculated as equation 2:

$$T = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{m1} & t_{m2} & \cdots & t_{mn} \end{bmatrix} \& t_{ij} = \left(l_{ij}{}^{"}, m_{ij}{}^{"}, u_{ij}{}^{"} \right) \qquad (2)$$

$$\left[m_i^{"} \right] = *\left(j - x \right)^{-1}, \quad \left[u_{ij}^{"} \right] = x_u * \left(I - x_u \right)^{-1}$$

$$\left[l_{ij}^{"} \right] = x_l * \left(I - x_l \right)^{-1}$$

The next step is to obtain the sum of rows (R) and columns (D) of the fuzzy total relations matrix. The sum of rows and columns is calculated according to the following equations 3 and 4):

$$R = \left(R_i \right)_{n*1} = \left[\sum_{i=1}^{n} T_{ij} \right]_{n*1} \qquad (3)$$

$$D = \left(d_i \right)_{1*n} = \left[\sum_{i=1}^{n} t_{ij} \right]_{1*n} \qquad (4)$$

All the obtained R+D and R-D values are fuzzy numbers that we need to dephrase to obtain the cause and effect diagram.

The locations of the factors in the final hierarchy are determined by columns (R+D) and (R-D). Therefore, (R-D) represents the position of an agent (transverse axis), and if (R-D) is positive, it is definitely a cause; if it is negative, it will have an effect. (R+D) also represents the total intensity of a factor (longitudinal axis) in terms of both cause (effect) and effect (effectiveness).

To find the relationships among the subfactors, the threshold value must be calculated. With this method, it is possible to ignore partial relationships and identify important relationships. Only relations whose values in the diffusion matrix T are greater than the threshold value are displayed in the table. After the intensity of the threshold is determined, all values of the diffusive matrix T that are smaller than the threshold are set to zero; that is, the causal relationship is not considered.

The extraction criteria have been given below (A1-A10). The extracted criteria used the research background[19-27] with the opinions of experts and 15 experts in a targeted and available manner who have an executive history and expertise in the field of waste management.

A1: Strengthen educational or educational programs for sustainable waste management

A2: Urban planning for sustainable waste management

A3: Creating a positive attitude toward sustainable waste management

A4: Application of environmentally friendly waste treatment health technologies

A5: Necessary infrastructure

A6: Improving the environmental awareness of health care workers

A7: Promoting the best sustainable waste management practices

A8: Appropriate legal framework to support sustainable waste management

A9: Green healthcare organization culture and encouraging waste recycling

A10: Preferential purchase from an environmental point of view

Results and Discussion

All 15 distributed questionnaires were completed and returned by the experts. To rank the factors via the fuzzy DEMATEL technique, the following steps were performed:

Formation of the Average Matrix

After collecting the expert responses, the opinions were aggregated using the arithmetic mean method to form the average matrix (Matrix A). Table 2 presents the average responses from the experts.

Calculation of the Normalized Direct Relations Matrix

For this purpose, in equation 5, linear scale transformation is used as a normalization formula to transform the scales of the criteria into comparable criteria.

$$\tilde{a}_{ij} = \left(\sum_{j=1}^{n} l_{ij}, \sum_{j=1}^{n} m_{ij}, \sum_{j=1}^{n} r_{ij} \right) \& r = max_{1 \le i \le n} \left(\sum_{j=1}^{n} r_{ij} \right)$$

$$\tilde{x} = \begin{bmatrix} \tilde{x}_{11} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \cdots & \tilde{x}_{2n} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \tilde{x}_{mn} \end{bmatrix} \& \tilde{x}_{ij} = \frac{\tilde{z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{r_{ij}}{r} \right) \quad (5)$$

Calculation of the Total Correlation Fuzzy Matrix

In this step, we first calculate the inverse of the normalized matrix, subtract it from the identity matrix (I), and then multiply the normalized matrix by the resulting matrix.

Defuzzification is the process of converting fuzzy numbers into crisp (definite) values. This step makes the results of fuzzy inference more understandable for users. Depending on the application, various defuzzification methods have been proposed, all aiming to convert fuzzy outcomes into precise, non-fuzzy results. In a fuzzy system, the process begins with the fuzzification of input elements. This is followed by calculations using fuzzy logic, and finally, the results must be defuzzified. By defuzzifying the outputs of a fuzzy computing system—as referenced in[26,27]—the results can be presented in a clear and interpretable manner (equation 6). Table 3 presents the total relationship matrix.

Table 2. Average Opinions of the Experts

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
	Down Medium High	Down Medium High	Down Medium High	Down Medium High	Down Medium High	Down Medium High	Down Medium High	Down Medium High	Down Medium High	Down Medium High
A1	0,0,0	0,0.25,0.5	0,0.25,0.5	0.25,0.5,0.75	0.5,0.75,1	0,0,0.5	0,0.25,0.5	0,0,0	0.25,0.25,0.75	0,0.25,0.5
A2	0,0,0.25	0,0,0	0,0,0.25	0.25,0,0.75	0,0,0	0,0,0	0,0,0.25	0,0,0.5	0.25,0.25,0.75	0,0,0
A3	0,0,0	0,0,0.5	0,0,0	0,0.75,1	0,0,0	0,0.25,0.5	0.25,0,0	0,0,0.5	0,0.75,1	0,0.25,0.5
A4	0,0,0.25	0,0,0.25	0,0,0.25	0,0,0	0.5,0.75,1	0,0,0.25	0,0,0.5	0,0,0.25	0,0,0	0,0,0.25
A5	0.25,0,0	0,0,0.25	0,0,0.5	0,0,0	0,0,0	0.5,0.75,1	0,0,0	0,0,0	0,0,0.25	0,0,0.25
A6	0,0,0	0,0.5,0.5	0,0.5,0	0,0,1	0,0,0	0,0,0	0.25,0.5,0.75	0,0,0	0.25,0.75,1	0,0.25,0.5
A7	0,0,0.5	0,0,0.5	0,0.25,0.5	0.5,0.75,0	0.5,0,0.75	0,0,0.25	0,0,0	0,0,0.25	0.5,0,0.5	0,0.5,0.5
A8	0,0,0.25	0,0,0.25	0,0.25,0.5	0,0,0.25	0,0,0.75	0,0,0.25	0,0,0	0,0,0	0,0,0.25	0.25,0.5,0.75
A9	0,0,0.75	0,0,0.25	0,0,0.25	0.25,0.25,0.75	0.5,0.75,1	0,0,0	0.25,0.5,0.75	0,0,0	0,0,0	0.25,0.5,0.75
A10	0,0,0.25	0,0,0.25	0,0,0	0.25,0.5,0.75	0.5,0.75,1	0,0,0	0,0,0	0,0,0	0,0.25,0.5	0,0,0

Table 3. Total Relationship Matrix

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
A1	0.05,0,-0.31	0,0.33,-0.22	0,0.42,-0.18	0.19,0.85,-0.33	0.44,1.5,-0.47	0.12,0.81,-0.3	0.03,0.53,-0.23	1.94,0.18,-0.28	0.16,0.7,-0.3	0.26,0.63,-0.32
A2	0.02,0,-0.04	0,0.03,-0.29	0,0.04,-0.1	0.18,0.1,-0.14	0.15,0.19,-0.51	0.04,0.11,-0.37	0.02,0.08,-0.13	1.73,0.05,0.06	0.14,0.2,-0.15	0.23,0.1,-0.28
A3	0.01,0,-0.2	0,0.19,-0.17	0,0.28,-0.33	0.05,0.91,-0.11	0.09,1.2,-0.61	0.06,0.77,-0.35	0.14,0.44,-0.29	0.53,0.22,0.01	0.04,0.87,-0.17	0.07,0.64,-0.19
A4	0.04,0,-0.12	0‹0.08,-0.13	0,0.1,-0.1	0.01,0.14,-0.41	0.29,0.66,-0.16	0.07,0.31,-0.12	0.01,0.13,-0.09	0.21,0.05,-0.11	0.02,0.18,-0.31	0.03,0.14,-0.21
A5	0.14,0,-0.18	0,0.21,-0.11	0,0.26,-0.06	0.05,0.38,-0.24	0.14,0.77,-0.46	0.3,0.83,0.07	0.05,0.34,-0.19	0.83,0.12,-0.15	0.07,0.48,-0.15	0.11,0.37,-0.16
A6	0.04,0,-0.24	0,0.55,-0.2	0,0.7,-0.33	0.11,1.01,-0.28	0.35,2.06,-0.37	0.13,1.2,-0.44	0.16,0.91,-0.09	2.34,0.32,-0.26	0.19,1.28,-0.23	0.32,0.99,-0.29
A7	0.09,0,-0.12	0,0.29,-0.2	0,0.5,-0.19	0.4,1.05,-0.53	0.68,1.43,-0.54	0.44,1.16,-0.14	0.1,0.51,-0.4	4.26,0.19,-0.2	0.34,0.76,-0.3	0.58,0.82,-0.29
A8	0.01,0,-0.14	0,0.09,-0.2	0,0.26,-0.08	0.02,0.38,-0.34	0.04,0.58,-0.34	0.01,0.37,-0.26	0,0.3,-0.17	0.03,0.08,-0.25	0,0.31,-0.3	0.13,0.5,-0.08
A9	0.12,0,-0.03	0,0.21,-0.31	0,0.34,-0.22	0.42,0.77,-0.4	0.95,1.5,-0.45	0.28,0.85,-0.44	0.17,0.66,-0.19	13.66,0.39,-0.07	0.09,0.58,-0.62	1.84,0.81,-0.21
A10	0.04,0,-0.06	0,0.12,-0.12	0,0.17,-0.16	0.14,0.53,-0.06	0.32,1.02,-0.02	0.08,0.49,-0.2	0.01,0.24,-0.22	0.23,0.11,-0.16	0.02,0.42,-0.15	0.03,0.28,-0.29

$$DF_{ij} = (u_{ij}-l_{ij}) + (m_{ij}-l_{ij})/3 + l_{ij} \quad (6)$$

A threshold matrix sets a specific threshold for the relationships between elements. This means that any relationship with an impact value below a certain limit (i.e., a weak impact) is eliminated from the analysis or, in other words, is set to zero. The average threshold value was determined to be 0.204. Table 4 presents the matrix of threshold matrix values.

Calculating the Effectiveness and Effectiveness of Factors

After the total matrix is calculated, the sum of the rows and columns of the total matrix represents the influencing factors (R-D) and the intensity of influence (R+D), respectively. In this relation, C is the sum of the row elements of the factors, and R is the sum of the column elements of the factors. Table 5 shows the prioritization of each factor and the degree of its influence and influence. If (R-D) is positive, the factor is considered causal (influencing), and if it is negative, it is considered an effect (influenced). The higher the value of (R+D), the more the factor interacts with other factors. The influencing factors are green healthcare organization culture and waste recycling encouragement, the promotion of best practices for sustainable waste management, the strengthening of sustainable waste management training programs, improvements in the environmental awareness of healthcare staff, sustainable waste management planning, and the creation of a positive attitude toward sustainable waste management. The influencing factors are as follows: a suitable legal framework to support sustainable waste management, the creation of the necessary infrastructure for waste management, environmentally friendly healthcare waste technologies, and purchasing on the basis of environmental requirements. In Table 5, each of the factors and their effectiveness have been shown.

The sixth step involves drawing a cause and effect diagram (effect and effectiveness of factors).

To draw the diagram, the values of R+D and D-R should be obtained. The R+D values are shown on the horizontal axis. Similarly, the vertical D-R axis indicates the position of an agent along the width axis. Figure 1 indicates the cause and effect diagram of the factors affecting organizational resilience.

This section identifies the most influential factors in order of importance, from highest to lowest, based on their (Ri – Di) values. A higher (Ri – Di) value indicates that a factor has a stronger influence on other factors within the system. According to the results of this study, the existence of a strong legal framework that supports sustainability is a key factor influencing the effectiveness of sustainable healthcare waste management. This is particularly important given that legal requirements for sustainable waste management systems are still in effect and continue to shape system performance.

Khalili et al[28] confirmed this result and reported that conservative strategies are prioritized in medical waste management. They emphasized that implementing waste separation programs at the source, adopting modern methods of decontamination and sterilization in medical waste-generating centers, and enforcing laws and guidelines at all stages of hazardous waste management are more effective and appealing approaches in hospital waste management. Arab et al[29] stated that with greater budget

Table 5. The Degree of Influence and Effectiveness of Factors

	R-D	R+D	Cause
Strengthening sustainable waste management training programs	2.62	1.77	Cause
Sustainable waste management planning	0.44	0.54	Cause
Creating a positive attitude towards sustainable waste management	0.92	1.81	Effect
Waste-free and environmentally friendly health technologies	-1.38	1.86	Effect
Creating the necessary infrastructure for waste management	-2.2	4.74	Cause
Improving environmental awareness of healthcare workers	1.35	5.85	Cause
Promoting best practices for sustainable waste management	2.62	4.51	Effect
Appropriate legal framework to support sustainable waste management	-8.37	9	Cause
Green healthcare organization culture and encouraging waste recycling	5.51	8.3	Effect
Purchasing based on environmental requirements	-1.25	3.13	Cause

Table 4. Threshold Matrix Values

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
A1	0	0	0	0.24	0.49	0.21	0	0.61	0	0
A2	0	0	0	0	0	0	0	0.62	0	0
A3	0	0	0	0.28	0.22	0	0	0.25	0.25	0
A4	0	0	0	0	0.26	0	0	0	0	0
A5	0	0	0	0	0	0.40	0	0.27	0	0
A6	0	0	0	0.28	0.68	0.30	0.33	0.80	0.41	0.34
A7	0	0	0	0.31	0.52	0.49	0	1.42	0.27	0.37
A8	0	0	0	0	0	0	0	0	0	0
A9	0	0	0	0.27	0.67	0.23	0.21	4.66	0	0.81
A10	0	0	0	0	0.44	0	0	0	0	0

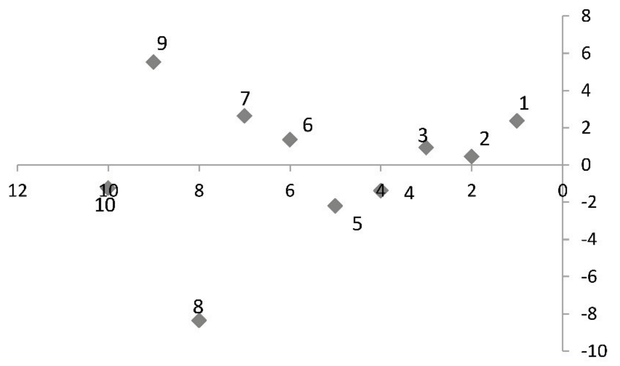

Figure 1. Cause and Effect Diagram

allocations and available capital, hospital managers have more flexibility to improve the hospital's public image by providing higher-quality services. Furthermore, legal frameworks help gradually enhance public understanding of sustainability, while inadequate regulations can result in environmental harm and public health issues due to the improper disposal of healthcare waste. The introduction of educational programs is a vital first step in waste management, as many individuals lack a deep understanding of proper practices. These programs are effective in raising awareness about the environmental and health risks associated with poor waste management. Schools play a key role in improving environmental literacy, fostering positive attitudes, and increasing public participation. Developing a positive attitude toward sustainable healthcare waste management is essential, as it is closely linked to sustainable behavior and effective waste sorting. Such attitudes also influence the environmentally responsible behavior of waste treatment workers throughout the disposal process. Advanced systems now monitor the entire waste management cycle—from collection to final disposal—including operational performance and pollutant release. Among the most influential factors are a green healthcare organizational culture and the promotion of waste recycling. A green culture boosts employee awareness of healthcare waste management, particularly regarding home waste recycling, which is a central aspect of such organizational culture. Many materials in healthcare facilities—such as blue wrap, cardboard, office paper, and plastics—can be safely and economically recycled, reducing waste and saving costs. Moreover, the promotion of sustainable management practices and urban planning for sustainable waste systems plays an important role in long-term environmental and public health outcomes. This result is consistent with the observations reported by of Aryaee and Hamidian.[30] Jayasinghe et al,[31] in a review study, noted that statistics obtained from various case studies worldwide indicate that infectious medical waste generated in healthcare facilities has experienced the most significant changes in waste generation dynamics compared with that in residential and other sectors. In other words, the waste stream in residential and other sectors has included noticeably more potentially infectious materials than it did in the past. However, owing to the complexities of collecting such data, the available information in this area is limited in terms of scientific sources. Challenges related to waste management infrastructure during the COVID-19 pandemic included a shortage of adequate systems for managing medical waste and responding to the sudden increase in infectious biomedical waste. These results accorded with those of the present study. Tseng et al[32] reported that, with respect to sustainable waste management, awareness of safety and proper waste management operating procedures in facilities and infrastructure is crucial. Waste transportation personnel should identify potential hazards at every stage of the treatment process. When workers are exposed to hazardous and infectious waste without the use of appropriate protective equipment, their health is at greater risk. In Indonesia, the control and monitoring of worker performance in waste treatment facilities has not yet been fully established. Workers do not use safe equipment, such as gloves and face masks, when handling waste. They often do not follow proper waste management guidelines and disregard relevant safety regulations, increasing the risks to their health. The lack of awareness of the importance of using protective equipment complicates effective waste management; therefore, providing workers with specific guidelines on safety hazards and operating procedures for sustainable waste management facilities is essential, and their understanding of these guidelines should be monitored and evaluated. The results of the present study are consistent with those of Tseng and colleagues' research.[32] Lee and colleagues' study aimed to identify key factors in medical waste management and treatment processes in hospitals and healthcare centres in South Korea. The results indicated that for environmental assessment, important factors included a safe medical environment from medical waste; monitoring environmental and health impacts; environmental management and education; and policy, legal, and administrative frameworks. Therefore, medical waste management is subject to strict regulations such as the Medical Services Act and environmental laws.[33] Jalali et al[34] employed the Job Hazard Analysis method to effectively assess and categorize occupational health and safety risks based on their severity. Implementing control measures, including the use of personal protective equipment, regular medical checkups, Hepatitis vaccinations, and strict adherence to safety protocols, has proven effective in mitigating these risks and preventing work-related illnesses and accidents that could result in harm. The results of the present study are consistent with those reported in the studies by Hosseinzadeh et al[35] and Hosseinzadeh et al[36] that segregation of infectious waste from hospital waste mass reduces the environmental and health risk of hospital waste and reduces the cost of waste management in private hospitals.

Conclusion

This research identified and prioritized key factors influencing sustainable waste management. These prioritized factors can serve as benchmarks for evaluating the performance of hospital managers in planning activities and allocating budgets. Promoting best practices in sustainable waste management can improve disposal processes and generate significant catalytic effects. Future development should be carefully considered in the planning of urban environments and waste management systems. Urban planning can dynamically adjust design capacities for sanitary waste generation and treatment, thereby reducing environmental pollution. To enhance the effectiveness of waste management infrastructure, managers must critically review current policies, protocols, guidelines, and operational practices. Instead of reactive approaches, policies should be formulated based on comprehensive analyses of both short- and long-term scenarios to improve the flexibility and efficiency of waste management systems. These actions include reviewing national and international biomedical waste guidelines, reassessing emergency preparedness, allocating temporary facilities to ensure continuity of operations, and strengthening safety protocols for healthcare workers. Additional essential measures include reducing reliance on single-use plastics, increasing funding for waste management initiatives, and encouraging producer responsibility. Modern technologies based on artificial intelligence—such as smart recycling bins and waste collection robots—can further optimize collection routes and minimize human contact, particularly during health crises. Moreover, regular training programs aimed at raising awareness among staff and the general public about sustainable waste management, especially regarding medical waste, can reduce unnecessary waste generation and improve system efficiency. This research faced several limitations, including financial constraints due to national economic conditions, high staff workloads and limited time for improvement projects, and the low prioritization of waste management by hospital managers and personnel. It is hoped that these limitations will diminish with improved economic conditions and the growing adoption of green culture in society. Future research could explore the impact of each of the ten identified factors in greater depth and develop targeted management policies based on these key drivers.

Authors' Contribution

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Competing Interests

No conflicts of interest have been reported by the authors.

Ethical Approval

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