Sustainable biomedical waste management in healthcare: exploring composting through Fuzzy DEMATEL-ANP analysis

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ABSTRACT – REZUMAT

Sustainable biomedical waste management in healthcare: exploring composting through Fuzzy DEMATEL-ANP analysis

Effective biomedical waste management is critical for ensuring health safety, environmental sustainability, and regulatory compliance in healthcare settings. This study introduces an integrated decision-making framework that combines the Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) with the Analytic Network Process (ANP) to evaluate and prioritise sustainable waste management practices, with a focus on composting and recycling. The framework incorporates fuzzy logic to handle uncertainties in expert-driven evaluations, ensuring robust and adaptive assessments. Using criteria such as environmental impact, health safety, cost-efficiency, social equity, and regulatory adherence, the DEMATEL analysis highlights key causal relationships, providing targeted prioritisation of strategies. Results indicate that composting achieves superior performance, with higher scores in environmental sustainability (0.85) and health impact (0.88), making it the preferred approach for fostering circular economy practices. The objective of this study is to support data-driven decision-making by integrating expert opinions and system interdependencies. This study underscores the importance of multi-criteria, data-driven methods like Fuzzy DEMATEL-ANP in advancing sustainable biomedical waste management systems, promoting resource optimisation and sustainable development within healthcare facilities.

Keywords: *biomedical waste management, Fuzzy DEMATEL-ANP, healthcare waste optimisation, multi-criteria decision-making, sustainable development*

Gestionarea durabilă a deșeurilor biomedicale în domeniul sănătății: explorarea compostării prin analiza Fuzzy DEMATEL-ANP

Gestionarea eficientă a deșeurilor biomedicale este esențială pentru asigurarea siguranței sănătății, a durabilității mediului și a conformității cu reglementările în unitățile medicale. Acest studiu introduce un cadru integrat de luare a deciziilor care combină Laboratorul de evaluare și testare a luării deciziilor de tip fuzzy (DEMATEL) cu Procesul analitic de rețea (ANP) pentru a evalua și prioritiza practicile durabile de gestionare a deșeurilor, concentrându-se pe compostare și reciclare. Cadrul încorporează logica de tip fuzzy pentru a gestiona incertitudinile din evaluările efectuate de experți, asigurând evaluări robuste și adaptabile. Folosind criterii precum impactul asupra mediului, siguranța sănătății, eficiența costurilor, echitatea socială și respectarea reglementărilor, analiza DEMATEL evidențiază relațiile cauzale cheie, oferind o prioritizare țintită a strategiilor. Rezultatele indică faptul că performanțele compostării sunt superioare, cu scoruri mai mari în ceea ce privește durabilitatea mediului (0,85) și impactul asupra sănătății (0,88), ceea ce o face abordarea preferată pentru promovarea practicilor economiei circulare. Obiectivul acestui studiu este de a sprijini luarea deciziilor bazate pe date prin integrarea opiniilor experților și a interdependențelor sistemului. Acest studiu subliniază importanța metodelor multicriteriale, bazate pe date, precum Fuzzy DEMATEL-ANP, în promovarea sistemelor durabile de gestionare a deșeurilor biomedicale, promovând optimizarea resurselor și dezvoltarea durabilă în cadrul unităților medicale.

Cuvinte-cheie*: gestionarea deșeurilor biomedicale, Fuzzy DEMATEL-ANP, optimizarea deșeurilor din domeniul sănătății, luarea deciziilor pe baza mai multor criterii, dezvoltare durabilă*

INTRODUCTION

A Smart Biomedical Management System (SBMS) utilises cutting-edge technologies, including cloud computing, big data analytics, artificial intelligence (AI), and the Internet of Things (IoT), to optimise patient care, medical equipment, and device management. This system enables the easy monitoring of biomedical equipment in labs, clinics, and hospitals in real-time. Continuous data on the condition usage and operational effectiveness of medical equipment is provided by IoT sensors integrated into the device. By preventing device malfunctions or downtime, which could otherwise impair vital operations and patient outcomes, this empowers healthcare providers to employ predictive maintenance strategies. AI algorithms also examine sensor data to find trends that point to equipment wear or malfunctions, assisting hospital administration in making prompt decisions about equipment replacements or repairs. Using barcoding and radio-frequency identification

(RFID) technologies, SBMS also makes it easier to track assets accurately, reducing losses and guaranteeing that vital equipment is available in an emergency.

A cutting-edge strategy for managing sustainable biomedical waste is represented by this study. Management through the evaluation and integration of fuzzy DEMATEL and ANP methods gives priority to eco-friendly activities, especially composting. It makes use of fuzzy logic as well and offers a solid, flexible and data-driven approach to expert judgment uncertainties construction through examining how various criteria, like environmental, are interdependent. The model finds that composting has the greatest impact on health safety, cost-effectiveness, and a sustainable approach that successfully advances the objectives of the circular economy. This new hybrid methodology for making decisions improves the accuracy and applicability of sustainability evaluations for the management of medical waste.

Furthermore, SBMS ensures compliance with regulatory standards by maintaining digital records of calibration, testing, and maintenance, reducing the burden of manual documentation. In patient care, wearable devices connected to SBMS platforms monitor vital signs, sending alerts to healthcare providers if abnormalities are detected, enabling proactive interventions. Such systems are pivotal in enhancing patient safety, operational efficiency, and cost management, making healthcare delivery more responsive and sustainable (figure 1). As healthcare becomes increasingly data-driven, the adoption of smart biomedical management systems is expected to grow, leading to more resilient and adaptive healthcare infrastructures in the future.

Both medical waste (MW) and biomedical waste (BMW) management have become important worldwide concerns that are inextricably linked to environmental preservation, public health and socioeconomic prosperity. The increasing production of these wastes, especially in light of recent COVID-19 pandemic events, has increased the need for efficient and long-term management plans. Using a variety of recent studies that emphasise definitions, sources classification, potential hazards management procedures, the impact of global health crises, the critical role of disposal method and site selection and the use of advanced decision-making tools to address the complexities inherent in this field, this literature survey seeks to provide a thorough overview of the key aspects of BMW and MW management. Waste produced in healthcare facilities and associated industries is generally referred to by the terms BMW and MW. This covers waste from medical labs, blood banks, mortuaries, research and training facilities, biotechnology establishments, clinics, nursing homes, hospitals and animal shelters, among other healthcare-related operations.

The division of waste into hazardous and non-hazardous categories is a basic component of BMW management. Radiologically active and infectious waste are included in hazardous BMW, which necessitates strict management procedures to reduce risks. Whereas the remainder is usually hazardous, including both infectious and non-infectious hazardous waste, ordinary medical waste, which makes up a sizable portion in some contexts, such as Vietnam, consists of general waste from everyday activities within healthcare facilities. The first and most important stage in efficient management is the correct separation of waste at the source, which is frequently accomplished with standard colour-coded disposal bags. Collection and storage come next, followed by appropriate treatment, transportation in vehicles with biohazard symbols and disposal at the end.

Thorough training in these protocols is required for healthcare personnel with a focus on safety precautions and the appropriate language or medium of instruction. The ultimate objective of good BMW/MW management is to avoid detrimental effects on the environment and human health. Resources such as water, air and land can become contaminated as a result of poor management. Regulations like the Biomedical Waste Management Rules of 2016 highlight that healthcare providers have a legal and social responsibility to manage in a responsible and sustainable manner. In order to supervise these procedures, reduce waste production and communicate with the appropriate municipal and pollution control authorities, every healthcare facility should ideally set up a special waste management committee.

The difficulties with medical waste management have been brought to light by the recent COVID-19 pandemic. A record amount of infectious medical waste was produced worldwide as a result of the increase in healthcare activities and preventive measures. This put tremendous strain on treatment facilities already in place and increased the risk of contact infection if improperly managed. In developing nations with possibly weaker waste management systems, this situation has been especially problematic, underscoring the urgent need for efficient methods to manage large volumes of medical waste quickly to avert environmental and public health emergencies.

The pandemic has therefore increased attention to finding and putting into practice efficient methods for disposing of medical waste. Studies are assessing techniques like pyrolysis, microwave incineration, autoclave, chemical techniques, dry heat, ozone, ultraviolet light and vaporised hydrogen peroxide. Interestingly, ozone is a potentially appropriate method that fits with the circular economy's tenets for medical waste. Choosing suitable disposal techniques and sites for BMW/MW is a difficult decision-making process with many competing factors and options. When assessing these options, local governments and healthcare organisations must apply strong methodologies because they face a great deal of uncertainty.

Techniques known as Multi-Criteria Decision Making (MCDM) have grown in popularity as a means of tackling these issues because they provide organised frameworks for taking into account a variety of elements such as technical, economic, social and environmental considerations. In recent studies, different MCDM techniques have been used to address particular BMW/MW management issues. Hospital medical waste management effectiveness, for example, has been assessed using intuitionistic fuzzy multi-criteria decision-making techniques, taking into account factors like waste control infrastructure and qualified staff. Autoclaving was found to be a promising option in one study.

Similar to this, hesitant fuzzy MCDM methods have been proposed for choosing the best BMW disposal treatment method, evaluating alternatives based on social acceptance technology, operation environmental protection cost, noise and health risk. Additionally, to account for the inherent uncertainty in decision-making processes, fuzzy MCDM methodologies have been developed in single and interval-valued spherical fuzzy environments. These methodologies include the Weighted Aggregated Sum Product Assessment for ranking alternatives and the Criteria Importance Through Intercriteria Correlation for objective criterion weighting. The best healthcare waste recycling technologies that adhere to the circular economy's tenets have also been investigated through the integration of the Analytical Hierarchy Process with Weighted Aggregated Sum Product Assessment in a fuzzy environment. The practical implementation of these integrated approaches is demonstrated by case studies such as the Red2Green technology's selection as Tripura, India's top healthcare waste recycling option.

As evidenced by a study conducted for Istanbul, studies have used interval-valued neutrosophic fuzzy EDAS methods to assess possible sites based on hierarchical criteria when choosing locations for waste disposal facilities. These factors include infrastructure disaster risks, costs, social acceptance, environmental impacts and distance to settlement areas. As demonstrated in a case study conducted in Thailand, the fuzzy analytical hierarchy process in conjunction with goal programming has also been used to identify appropriate sites for infectious waste disposal centres, taking into account infrastructure, geological, social and environmental factors.

Additionally, models based on analysis network processes have been created to create risk assessment techniques for medical waste treatment facilities with the goal of determining the best treatment sites. This is especially important during infectious disease outbreaks like the one that occurred in Wuhan during COVID-19.

As demonstrated in a study conducted in Bilaspur, India, quality function deployment-based models coupled with geographic information systems have also been used to assess possible BMW disposal locations, taking into account both subjective and objective criteria. The shift to a circular economy is having a greater impact on healthcare waste management since it highlights the necessity of lowering waste production and encouraging material and product reuse and recycling. Choosing and implementing suitable healthcare waste recycling technologies is necessary due to this paradigm shift. Multi-Criteria Decision Making techniques have been used to address this issue in fuzzy environments, taking into account different recycling options and selection criteria based on expert opinions. In order to support resource efficiency and environmental sustainability, the objective is to identify practical methods for reusing disposable medical waste.

Effective medical waste management is still hampered by a number of issues, especially in developing nations, despite improvements in techniques and technology. Progress is still hampered by problems with insufficient infrastructure, limited funding, a lack of knowledge and training and ineffective shipping and disposal methods. Specific challenges in the third-party logistics management of biomedical waste have been brought to light by studies that concentrate on nations like Vietnam and India, highlighting the necessity of addressing limitations related to disposal and transportation. Additionally, some hospitals' selection of infectious medical waste contractors relies heavily on subjective evaluations and experience, which emphasises the need for more accurate and objective evaluation techniques like fuzzy Multi-Criteria Decision Making models.

Biomedical and medical waste effectively is a complex task that calls for an all-encompassing and coordinated strategy. Strong classification, safe handling practices, suitable treatment and disposal techniques and thoughtful site selection for waste management facilities are all vitally needed according to the literature. The growing use of advanced multi-criteria decision-making techniques, which enable the methodical evaluation of various and frequently incompatible criteria, shows an increasing understanding of the complexity involved in these decisions. The need for robust and flexible waste management systems has been underlined by the effects of international health emergencies like the COVID-19 pandemic. Going forward, the safe and sustainable management of biomedical and medical waste will be essential to protecting human health and the environment. This will be achieved through sustained research and development efforts, the adoption of circular economy principles and focused interventions to address the unique challenges in various contexts, especially in developing countries.

This study sets itself apart by combining Fuzzy DEMATEL and ANP, especially for biomedical waste management, which is frequently dominated by conventional single-criterion or crisp MCDM approaches to prioritise recycling and composting. This hybrid model provides a dynamic and realistic assessment by capturing interdependencies and causal relationships among criteria, in contrast to traditional approaches that treat criteria as independent. Additionally, using fuzzy logic improves how ambiguity in expert input is handled, leading to more complex and trustworthy decision-making, especially in complex healthcare settings.

Its main goal is to create a fuzzy logic-based multi-criteria decision-making framework for assessing sustainable biomedical waste disposal practices. This study offers a comparative advantage in evaluating interdependent sustainability parameters like environmental and health impacts, cost-efficiency, and compliance because it holistically integrates fuzzy DEMATEL and ANP in contrast to earlier research that concentrated on single-criteria evaluation or isolated technologies. The suggested Fuzzy DEMATEL-ANP model has drawbacks despite having a strong analytical basis. The calibre and objectivity of expert opinions, which can introduce bias, are crucial to the reliability of the results' dependability.

Additionally, its applicability in low-resource settings where computational capabilities are limited may be limited by the complexity of matrix computations and fuzzy logic conversions. The model's long-term validity and responsiveness in changing healthcare environments may be impacted by its failure to take into consideration dynamic temporal changes in waste generation or technology adoption.

MATERIALS AND METHODS

Biomedical waste management systems are evaluated using the Analytic Network Process (ANP) method in the study. It acknowledges important evaluation factors like cost-effectiveness, sustainability initiatives, technological viability, environmental impact, segregation practices, regulatory compliance, health and safety concerns and stakeholder involvement. The following options are evaluated: chemical treatment, landfilling, recycling, autoclaving, incineration and microwaves. Subjective evaluations are quantified using the fuzzy ANP method according to predetermined standards. Each alternative's distance from an ideal solution is measured by the proximity coefficients. A sensitivity analysis ensures reproducibility and reliability. Peer review and case studies are used to validate the findings. This approach provides helpful viewpoints for developing sustainable biomedical waste management procedures.

Selection of parameters

A systematic literature review and expert interviews were used to determine the parameters chosen for this study, which include environmental impact, segregation practices, regulatory compliance, health and safety, technological feasibility, cost-effectiveness, sustainability practices and stakeholder engagement. These metrics, which are in line with international guidelines suggested by the WHO, EPA and CPCB, are widely acknowledged as essential elements in assessing biomedical waste management systems. Their incorporation guarantees a comprehensive and contextually appropriate assessment of the available options. Because they offer a reliable way to measure subjective evaluations in situations involving multiple criteria for decision-making, fuzzy linguistic scales and triangular fuzzy numbers were employed to represent the degree of uncertainty in expert opinions.

Effect criteria analysis

A methodical framework for assessing and ranking composting techniques in biomedical waste management is the fuzzy DEMATEL-based Analytic Network Process (ANP). This method deals with subjectivity and ambiguity in expert opinions on factors like cost-effectiveness, environmental impact and regulatory compliance. Through the identification of causal relationships between these criteria, the DEMATEL

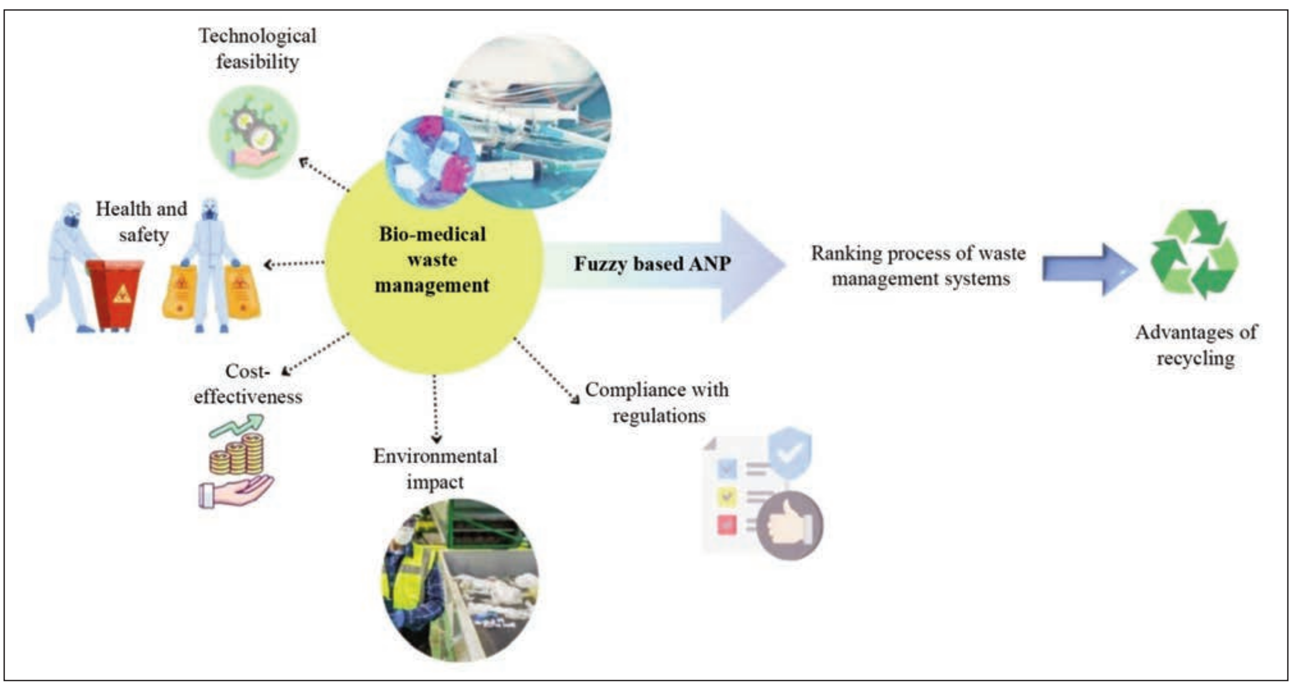

Fig. 1. Bio-medical waste management using Fuzzy-based ANP

method assists stakeholders in making well-informed decisions regarding effective and sustainable composting techniques. Through the creation of nutrient-rich compost and the safe disposal of biomedical waste, this strategy promotes the circular economy concepts in healthcare environments. The DEMATEL method addresses decision-making uncertainties in recycling by integrating the assessment of multiple factors influencing waste recycling processes.

Figure 1 illustrates how the DEMATEL approach ranks attributes that have a major impact on waste management outcomes by establishing links between criteria and determining cause-and-effect relationships.

The Fuzzy DEMATEL-Based ANP (Analytic Network Process) approach used in this study incorporates multiple iterative matrix calculations, pairwise comparisons, normalisation steps, and weight derivations involving Triangular Fuzzy Numbers (TFNs). The computational complexity primarily depends on the number of criteria (n) and alternatives (m). The DEMATEL portion involves $O(n^2)$ operations for generating and normalising direct-relation matrices, while the ANP supermatrix formation and limit matrix calculations typically exhibit $O(n^3)$ complexity. Considering the fuzzification process, each linguistic input requires three separate values (L, M, U), tripling the input size and slightly increasing computation. However, the structured methodology supports parallel processing and matrix-based optimisation, making it suitable for real-time decision support in moderate-scale real-world biomedical waste scenarios where criteria and alternative numbers are reasonably bounded.

Proposed Fuzzy DEMATEL-based ANP approach

The Fuzzy Decision-Making Trial and Evaluation Laboratory (Fuzzy DEMATEL) combined with the Analytic Network Process (ANP) is a robust analytic network process-making (ANPM) approach designed to tackle the complexity of biomedical waste (BMW) management in healthcare. This method integrates the strengths of both DEMATEL, which identifies the cause-and-effect relationships among criteria, and ANP, which handles the interdependence among them. Below is an elaboration of the technique, incorporating essential equations to support the methodology.

In the Fuzzy DEMATEL method, experts assess the direct influence of one criterion over another using linguistic variables, which are then converted into triangular fuzzy numbers. $\tilde{a}_{ij} = (a_{ij}^L, a_{ij}^M, a_{ij}^U)$, representing the lowest, most likely, and highest impact values. The fuzzy influence matrix $\tilde{A} = [\bar{a}_{ij}]$ for all criteria can be computed, where a_{ij} represents the influence of the criterion i on criterion j. The initial step is to normalise the matrix using equation 1:

$$\bar{Z} = \frac{\bar{A}}{\max\left(\sum_{j=1}^{n} a_{ij}^{M}\right)} \quad i, j = 1,2, \dots, n \tag{1}$$

where n is the total number of criteria. The normalised matrix ensures that all fuzzy values lie between 0 and 1.

The total influence matrix is derived as equation 2:

$$\tilde{T} = \tilde{Z} \cdot (I - \tilde{Z})^{-1} \tag{2}$$

where I is the identity matrix, and $\bar{T} = [\tilde{t}_{ij}]$ provides the aggregated influence of the criterion i on criterion j. The sums of rows D_i and columns R_j are used to determine the degree to which each factor acts as a cause or effect in equation 3:

$$D_i = \textstyle\sum_{j=1}^{n} \tilde{t}_{ij},\ R_j = \sum_{i=1}^{n} \tilde{t}_{ij} \tag{3}$$

This equation pertains to the total influence matrix. $\bar{T}$ generated from the fuzzy DEMATEL method. Here's what the components mean: $\tilde{t}_{ij}$ represents the degree of influence (expressed as a fuzzy value) that criterion i has on criterion j. D_i is the sum of the i^{th} row of the matrix $\bar{T}$, which quantifies how much influence criterion i exerts on all other criteria. This is referred to as the "dispatching" or "causal" power. R_j is the sum of the j^{th} column, representing how much criterion j is influenced by all other criteria, known as the "receiving" or "effect" power.

The net effect of a criterion i is given by $D_i - R_i$, where a positive value indicates a causal criterion, and a negative value suggests an effect criterion. If $D_i - R_i > 0$: the criterion is causal (it influences others more than it is influenced). If $D_i - R_i < 0$: the criterion is an effect (it is more influenced by others). This step is crucial because it reveals interdependencies and directionality of influence among criteria, helping identify driving factors (causal) and resultant factors (effects).

In the next stage, the ANP framework accounts for the interdependencies between the criteria. The supermatrix W is constructed based on the weights and influences derived from the DEMATEL analysis. To ensure convergence, the supermatrix is raised to a limiting power in equation 4.

$$W_\infty = \lim_{k \to \infty} W^k \tag{4}$$

This equation is a key step in the Analytic Network Process (ANP): W is the weighted supermatrix, constructed based on influence weights derived from the DEMATEL phase. The supermatrix W contains all possible interrelations between elements (criteria and sub-criteria) across clusters in the network. Raising W to the power k repeatedly (i.e., W^k) allows the weights to propagate through the network of dependencies. When k tends to infinity, the result converges to a limiting supermatrix W_∞, which represents a stable distribution of weights, showing the global priorities of all elements. This ensures that the feedback loops and interdependencies in the system are fully accounted for, producing a robust prioritisation of decision alternatives.

RESULTS

A total of 150 biological waste management decision-makers, including legislators, hospital administrators

Table 1

CRITERIA CHARACTERISTICS						
Criteria	**Environmental Impact (EI)**	**Compliance with regulations (CR)**	**Health Safety (HS)**	**Time Flexibility (TF)**	**Cost-Effectiveness (CE)**	**Social Equity (SE)**
Weight	(0.250, 0.300, 0.350)	(0.150, 0.200, 0.250)	(0.200, 0.250, 0.300)	(0.100, 0.150, 0.200)	(0.100, 0.120, 0.150)	(0.080, 0.100, 0.120)
Type	Positively oriented	Positively oriented	Positively oriented	Positively oriented	Positively oriented	Positively oriented

and practitioners, participated in the study. They assessed various options for biomedical waste management using the Fuzzy DEMATEL-Based ANP method. This diverse input enhanced the validity of the findings and the evaluation procedure. The evaluation took into account real-world concerns in biomedical waste management thanks to the collective expertise of these decision-makers, which enhanced the validity and applicability of the findings for the waste management community.

Quantitative assessment findings

The study's findings, a thorough evaluation methodology and the outcomes of using the Fuzzy DEMATEL-based ANP approach are all provided here. These findings provide valuable information about the effectiveness of different biomedical waste management techniques according to the predetermined standards.

Step 1: Create a decision matrix

In this study, the Fuzzy DEMATEL-Based Analytic Network Process (ANP) approach was used to evaluate the following criteria: Social Equity, Cost-Effectiveness, Health Safety, Environmental Impact and Compliance with Regulations. Each criterion has a different weight assigned to it based on how important it is. The environmental impact criterion has the highest weight (0.250, 0.300, 0.350) indicating its crucial role in the decision-making process. Every one of the six criteria – EI, CR, HS, TF, CE, and SE – is positive oriented, which is illustrated in table 1. Finally, the analysis of biomedical waste management options is influenced to a lesser extent by Social Equity and Cost-Effectiveness, but it is still significant when considering Compliance with Regulations, Health Safety and Time Flexibility.

Linguistic terms are given corresponding Triangular Fuzzy Numbers (TFNs) in this table, which are shown as the upper bound (*U*), middle value (*M*) and lower bound (*L*). The TFN (1,1,3), where 1 is the middle value and lower bound, and 3 is the upper bound, defines the Very Low term. The TFNs rise as the linguistic terms go from Low to Very High, indicating higher levels of the assessed criteria, which is illustrated in table 2. Utilising an organised fuzzy logic-based process, this technique enables decision-makers to translate subjective qualitative evaluations into quantitative values. The TFNs make it possible to handle variability and uncertainty while guaranteeing that expert opinions are recorded in a thorough, adaptable way for later examination.

Table 2

FUZZY SCALE FOR LINGUISTICS WITH TRIANGULAR FUZZY NUMBERS (TFNS)				
Code	**Linguistic term**	**Lower bound**	**Middle value**	**Upper bound**
1	Very low	1	1	3
2	Low	1	3	5
3	Medium	3	5	7
4	High	5	7	9
5	Very high	7	9	9

Key assumptions, such as the use of triangular fuzzy numbers, the assumption of expert consistency, and static criteria relevance, were adopted based on standard practices in fuzzy research. These assumptions are valid as they provide a balance between mathematical rigour and interpretability. The triangular fuzzy representation ensures computational simplicity while effectively modelling uncertainty.

Furthermore, the assumption of criteria stability during the assessment period is essential for meaningful comparison and is supported by expert consensus from multiple healthcare settings.

Six important criteria are compared between recycling and composting in the decision matrix: environmental impact, cost-effectiveness, health safety, compliance with regulations and social equity. In areas such as Environmental Impact (0.85), Compliance with Regulations (0.90), Health Safety (0.88), and Social Equity (0.80), composting outperforms other methods, suggesting a greater overall advantage for the environment and society. Recycling, on the other hand, is more cost-effective and time-efficient because it exhibits advantages in both areas (0.70 and Time Flexibility 0.60). The result was illustrated in the decision matrix (table 3). By taking into account numerous pertinent factors, this matrix assists decision-makers in balancing the advantages and disadvantages of each option, enabling them to make well-informed decisions regarding biomedical waste management (figure 2).

Step 2: Construct the Normalised Decision Matrix

To create the normalised decision matrix, you can use the following formulas:

1. For Positive Ideal Solution:

$$\bar{r}_{ij} = \frac{a_{ij}}{c_j^*}, \quad c_j^* = \max_i c_{ij} \tag{5}$$

Table 3

DECISION MATRIX FOR RECYCLING AND COMPOSTING						
Option	**Environmental Impact**	**Compliance with Regulations**	**Health Safety**	**Time Flexibility**	**Cost-Effectiveness**	**Social Equity**
Recycling	0.75	0.85	0.8	0.6	0.7	0.65
Composting	0.85	0.9	0.88	0.7	0.65	0.8

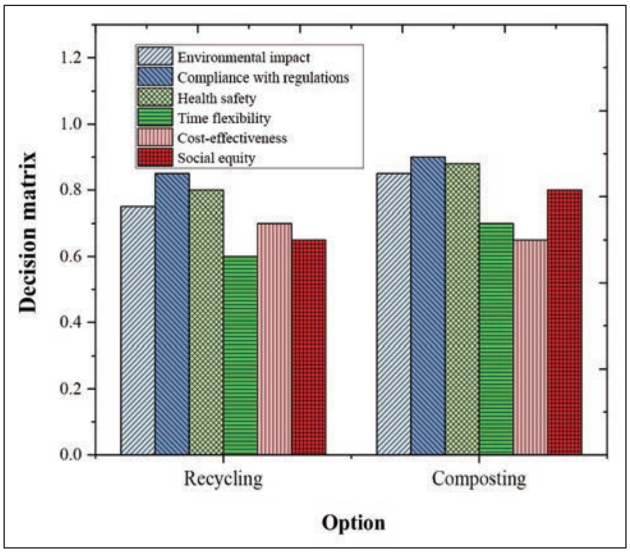

Fig. 2. Recycling and composting selection tool

This calculates the normalised value based on the maximum value for each criterion.

2. For Negative Ideal Solution:

$$\bar{r}_{ij} = \frac{a_j^-}{c_{ij}}, \quad a_j^- = \min_i a_{ij} \tag{6}$$

where, $\bar{r}_{ij}$ is the normalised value for the alternative i and criterion j, a_{ij} – original performance value for the alternative i under criterion j, c_j^* – positive ideal solution, defined as the maximum value of the criterion j, a_j^- – negative ideal solution, defined as the minimum value of the criterion j.

This computes the normalised value based on the minimum value for each criterion.

The triangle fuzzy numbers shown in table 4, bottom, middle, and upper boundaries are represented by a set of three normalised values (L M U) for each criterion. The information regarding recycling and composting is based on six criteria (health, safety, regulations, environmental impact, and compliance). This normalised decision matrix (Time Flexibility, Cost-Effectiveness, and Social Equity) is displayed above. A more uniform comparison over a range of criteria is made possible by this normalisation, which scales the criterion between 0 and 1. Composting performs better overall in terms of social fairness, health, safety, environmental effect, and regulatory compliance, as indicated by the majority of the criteria with higher values.

Recycling's cost and efficiency advantages are shown by its better performance in terms of time flexibility and cost-effectiveness. Parameter comparability is ensured by normalisation, which eliminates scale and unit disparities.

Step 3: Construct the Weighted Normalised Decision Matrix

To create the weighted normalised decision matrix, apply the following formula:

$$\bar{v}_{ij} = \bar{r}_{ij} \times w_j \tag{7}$$

where $\bar{v}_{ij}$ is a weighted, normalised value for the alternative i under criterion j, $\bar{r}_{ij}$ – normalised value for alternative i and criterion j, w_j – weight assigned to criterion j.

The normalised values of recycling and composting are weighted, allowing the weighted normalised decision matrix to account for the relative importance of each parameter, which is illustrated in table 5. Every parameter has a weight that corresponds to its importance in the decision-making process. The parameters with the highest weight (0.25) are environmental impact, and the lowest weight (0.05) is social equity. The weighted contributions of every option across the parameters are represented by the final values.

Table 4

NEGATIVE AND POSITIVE IDEAL SOLUTIONS OF RECYCLING AND COMPOSTING				
Parameter	**Recycling**		**Composting**	
	Positive ideal	**Negative ideal**	**Positive ideal**	**Negative ideal**
Environmental Impact	(0.9, 1.0, 1.0)	(0.0, 0.1, 0.2)	(0.95, 1.0, 1.0)	(0.0, 0.1, 0.2)
Compliance with regulations	(0.85, 0.9, 1.0)	(0.0, 0.1, 0.2)	(0.9, 1.0, 1.0)	(0.0, 0.1, 0.2)
Health Safety	(0.8, 0.85, 0.9)	(0.0, 0.1, 0.2)	(0.9, 0.95, 1.0)	(0.0, 0.1, 0.2)
Time Flexibility	(0.75, 0.8, 0.85)	(0.0, 0.1, 0.2)	(0.7, 0.75, 0.8)	(0.0, 0.1, 0.2)
Cost-Effectiveness	(0.85, 0.9, 1.0)	(0.0, 0.1, 0.2)	(0.75, 0.8, 0.85)	(0.0, 0.1, 0.2)
Social Equity	(0.7, 0.75, 0.8)	(0.0, 0.1, 0.2)	(0.8, 0.85, 0.9)	(0.0, 0.1, 0.2)

Table 5

DISTANCE FROM POSITIVE AND NEGATIVE IDEAL SOLUTIONS		
Method	**Distance from the positive ideal**	**Distance from the negative ideal**
Recycling	0.15	0.2
Composting	0.1	0.1

For example, composting performs better in these areas and makes stronger contributions to Environmental Impact and Health Safety. Recycling, meanwhile, excels in areas where efficiency and cost savings are valued, as evidenced by its noteworthy scores in time flexibility and cost-effectiveness.

Step 4: Identify the Fuzzy Positive Ideal Solution (FPIS, A^*) and Fuzzy Negative Ideal Solution (FNIS, A^-)

The FPIS and FNIS for the alternative can be defined as:

$$A^* - \{\bar{v}_1^*, \bar{v}_2^*, \ldots, \bar{v}_n^*\} - \left\{\max_{i \in B} \bar{v}_{ij}, \min_{i \in C} \bar{v}_{ij}\right\}$$
$$A^- - \{\bar{v}_1^-, \bar{v}_2^-, \ldots, \bar{v}_n^-\} - \left\{\min_{i \in B} \bar{v}_{ij}, \max_{i \in C} \bar{v}_{ij}\right\} \quad (8)$$

where A^* is a Fuzzy Positive Ideal Solution, A^- – Fuzzy Negative Ideal Solution, $\bar{v}_i^*$ – maximum value of the alternative i for all criteria in the set B, $\bar{v}_i^-$ – minimum value of the alternative i for all criteria in the set C, B – set of criteria where higher values are better (positive ideal); C – set of criteria where lower values are better (negative ideal).

The positive and negative ideal solutions are shown in table 6. The ideal solutions, both positive and negative, for recycling and composting are based on six important parameters.

Table 6

CLOSENESS COEFFICIENT	
Criteria	C_i
Composting	0.987
Recycling	0.965

The positive ideal values for recycling consistently represent the lowest acceptable outcomes, indicating ineffectiveness, while the negative ideal values consistently reflect strong performance, especially in Environmental Impact and Compliance with Regulations. Composting performs exceptionally well in these domains, as evidenced by even higher positive ideal values, particularly in Environmental Impact and Health Safety. It is clear from both approaches that shared negative ideal solutions, reaching minimal effectiveness, are undesirable across the board for optimal performance standards. The study presents quantitative assessments that underscore composting's superior performance with scores of 0.85 in environmental sustainability and 0.88 in health impact, derived from the weighted influence matrices and limiting supermatrix of the ANP. These values highlight composting's dual benefits in waste minimisation and public health enhancement.

Step 5: Calculate Distances to the Fuzzy Positive Ideal Solution (FPIS, A^*) and Fuzzy Negative Ideal Solution (FNIS, A^-)

The distances from each alternative to the FPIS and FNIS are calculated as follows:

1. Distance to FPIS (A^*):

$$S_i^* = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_j^*) \text{ for } i = 1, 2, \ldots, m \quad (9)$$

2. Distance to FNIS (A^-):

$$S_i^- = \sum_{j=1}^{n} d(\bar{v}_{ij}, \bar{v}_i^-) \text{ for } i = 1, 2, \ldots, m \quad (10)$$

Distance Calculation for Triangular Fuzzy Numbers

Given two triangular fuzzy numbers (a_1,b_1,c_1) and (a_2,b_2,c_2), the distance d between these fuzzy numbers can be computed using the formula:

$$d_v(\bar{M}_1, \bar{M}_2) = \sqrt{\frac{1}{3}\left[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2\right]} \quad (11)$$

where $d(\bar{v}_{ij}, \bar{v}_j^*)$ and $d(\bar{v}_{ij}, \bar{v}_i^-)$ are crisp numerical values representing the distances from each alternative to the ideal solutions.

The results below show the single values of the separations between the composting and recycling positive and negative ideal solutions (table 7). With recycling's distance from the positive ideal at 0.15, it is comparatively close to reaching optimal performance, but there is still room for improvement. The data indicate a significant deviation from the minimum acceptable standards, as indicated by the 0.2 distance from the negative ideal. Compared to other methods, composting exhibits a lower distance of 0.10 from the positive ideal, indicating its increased effectiveness in attaining the intended results. According to this comparison, composting performs better than recycling in both categories, suggesting that it might be the better choice for managing biomedical waste.

Step 6: Calculate Closeness Coefficient and Rank Alternatives

Table 7

COMPARATIVE ANALYSIS FINDINGS WITH AHP				
Rank order	1	2	3	4
DEMATEL	Recycling	Recycling	Recycling	Recycling
Fuzzy DEMATEL-Based ANP	Compositing	Compositing	Compositing	Recycling

Closeness Coefficient Calculation

To evaluate each alternative, use the following formula to compute the closeness coefficient (*CC*):

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (12)$$

where D_i^- is the distance of the alternative from the Worst Possible Ideal Solution (FNIS), D_i^+ – distance of the alternative *i* from the Best Possible Ideal Solution (FPIS).

The closeness coefficients for recycling and composting are shown in table 8 and show how closely each approach resembles the optimal waste management solution. Composting is a highly advantageous option due to its strong performance and effectiveness in achieving optimal outcomes, as evidenced by its closeness coefficient of 0.987. Recycling, on the other hand, has a closeness coefficient of 0.965, indicating that although it is also effective, it performs marginally less optimally than composting.

Comparative analysis

The results of the comparative study between DEMATEL and fuzzy-based Analytic Network Process (ANP), two distinct decision-making techniques, are presented in table 9. Recycling maintains a top ranking in the DEMATEL method after four evaluations, demonstrating its effectiveness and appropriateness for waste management. On the other hand, composting is ranked first in the first three rankings of the Fuzzy DEMATEL-Based ANP analysis, indicating that it is a good option when taking fuzzy logic into account. As a result of a somewhat less positive evaluation under fuzzy criteria, recycling comes in at number four in this method.

SOCIAL MANAGERIAL IMPLICATIONS

In healthcare settings where waste generation poses serious risks to the environment and public health, this study highlights the significance of sustainable waste management practices. The study emphasises how important it is for healthcare facilities to adopt recycling and composting procedures using a fuzzy DEMATEL-based Analytic Network Process (ANP) framework. By lowering the negative effects of inappropriate waste disposal and advancing long-term social benefits, these practices encourage environmental stewardship, regulatory compliance and public health improvement. Several environmental and infrastructure factors, including geographic location, policy regulations, climate variability and technological infrastructure, may have an impact on how effective the suggested framework is. The model is flexible and context-sensitive since it can be localised by modifying weights and linguistic scales in accordance with expert input specific to a given area. The study also emphasises how introducing recycling and composting procedures in healthcare facilities has positive social and environmental effects. These methods can comply with more stringent environmental regulations, increase social equity and reduce waste management expenses. The study suggests creating integrated waste management frameworks to promote a circular economy while reducing environmental damage and reliance on landfills. The entire medical community eventually gains from a more sustainable healthcare system as a result.

DISCUSSION

This study evaluated biomedical waste management practices with an emphasis on recycling and composting using the Fuzzy DEMATEL-Based ANP method. Through the conversion of qualitative expert opinions into quantifiable fuzzy values, the methodology methodically addressed the complexity of interdependent criteria of interest. 150 decision-makers with specialised knowledge contributed to the discussion of six main criteria: social equity, cost-effectiveness, time flexibility, health safety, environmental impact and regulatory compliance. To control subjectivity and uncertainty, the model used TFNs and incorporated these criteria into a structured decision matrix. The research precisely normalised and weighted the alternatives by calculating the positive and negative ideal solutions, producing a strong framework for comparative analysis. In four of the six major categories, such as Environmental Impact and Health Safety, the results showed that composting performed better than recycling, demonstrating its greater suitability from a societal and environmental perspective. On the other hand, recycling demonstrated better results in terms of cost-effectiveness and time flexibility, which reflected operational and financial efficiency. This study proposes a robust, data-driven framework using Fuzzy DEMATEL-ANP, which integrates expert opinions and systematically addresses uncertainty to support realistic and adaptive decision-making. The approach directly contributes to circular economy implementation in healthcare by offering prioritised strategies such as composting for sustainable biomedical waste management. It was confirmed by the analysis that the Fuzzy DEMATEL-Based ANP approach successfully reconciled competing criteria, giving decision makers a clear and trustworthy way to assess waste management options. This thorough framework made sure the chosen approach took into account the practical limitations that stakeholders face in real-world situations, in addition to complying with legal and environmental requirements.

LIMITATIONS OF THE STUDY

Despite its valuable insights, this study has several limitations. The reliance on expert opinions, while necessary for qualitative assessment, may introduce subjective bias, especially in the context of fuzzy logic interpretations. The model's applicability is constrained by the selection of criteria and alternatives, which may not comprehensively capture the diversity of biomedical waste management practices across different regions or facility types. Additionally, the study assumes static interdependencies among criteria, which may evolve due to policy changes, technological advancements, or emerging environmental concerns. The framework's performance is also limited by the availability and accuracy of expert data, which could affect the generalizability of the findings. Future research should consider dynamic modelling approaches, broader stakeholder inputs, and real-time data integration to enhance robustness and applicability across varied healthcare settings.

CONCLUSION

The application of a Fuzzy DEMATEL-based Analytic Network Process (ANP) has provided valuable insights into the management of biomedical waste, particularly regarding composting and recycling strategies. There are significant practical ramifications for healthcare organisations looking to optimise their biomedical waste management systems using the integrated fuzzy DEMATEL-ANP framework. In order to improve compliance, lower environmental risks, and advance circular economy principles, healthcare administrators can prioritise strategies such as recycling and composting according to a number of interconnected criteria. This model can be applied to healthcare facilities of different sizes and incorporated into policy frameworks to direct staff training, infrastructure investments, and treatment technology selection, guaranteeing sustainable waste management and regulatory compliance. Fuzzy logic is used in this study to handle expert evaluation uncertainties, allowing for a thorough evaluation of the main factors affecting biomedical waste management choices. The integration of Fuzzy DEMATEL and ANP provides methodological innovation by enabling precise evaluation of complex interdependencies in biomedical waste factors.

The model highlights composting as a top priority, offering clear practical implications for healthcare administrators.

Out of all the factors that were examined, the most important ones were environmental impact, compliance with regulations, health and safety, cost-effectiveness, time flexibility and social equity. By enabling experts to offer nuanced inputs, the fuzzy scale improved the reliability of the results' dependability. Weight assignments made the significance of the criteria clear, and a normalised decision matrix compared different approaches. The most successful approach was composting, which received a score of 0 points for compliance and 0 points for environmental benefit. In particular, the fuzzy DEMATEL-based ANP method ranked composting higher than recycling, outperforming conventional methods by providing deeper insights. The significance of using a variety of analytical tools to make well-informed and sustainable waste management decisions is highlighted by these findings.

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