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A Fuzzy TOPSIS-Based Approach for Comprehensive Evaluation of Bio-Medical Waste Management: Advancing Sustainability and Decision-Making

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Abstract: Bio-medical waste management is critical for ensuring public health and environmental sustainability. However, due to the inherent ambiguities and complexities involved with waste characteristics and disposal techniques, measuring the efficiency of bio-medical waste management systems presents major hurdles. This study provides a Fuzzy TOPSIS-based (Technique for Order Preference by Similarity to Ideal Solution) strategy for thorough bio-medical waste management assessment. The suggested method combines the benefits of fuzzy logic and TOPSIS, allowing for the incorporation of subjective judgments and ambiguity in the evaluation procedure. Initially, a thorough set of criteria is constructed based on a review of current literature and recommendations from experts, comprising Environmental Impact, Compliance with Regulations, Health and Safety, Technological Feasibility, and Cost-effectiveness. To accurately represent the inherent ambiguity and imprecision in decision-making, each criterion is evaluated using linguistic variables. Furthermore, the Fuzzy TOPSIS approach is used to rate various bio-medical waste management systems depending on how well they perform in comparison to the identified criteria. The language judgments are represented as fuzzy numbers, and the idea of closeness coefficients is used for calculating the relative distance between each alternative and the ideal answer. An investigation in a healthcare facility is performed to demonstrate the feasibility and effectiveness of the suggested strategy. To assess numerous waste management approaches, the study uses real-world data on waste management practices, expert opinions, and linguistic analyses. The study's findings emphasize the benefits of using a Fuzzy TOPSIS-based technique to evaluate bio-medical waste management. According to the findings of this research study, recycling is the best choice because it has the potential to reduce waste, recover resources, and preserve the environment. It assists decision-makers to account for uncertainties and subjectivity, increases transparency and consistency in decision-making, and aids in choosing of the best waste management system. The proposed approach advances sustainable waste management practices in the bio-medical area and provides a helpful tool for policymakers and practitioners looking to enhance waste management systems.

Keywords: infectious waste; ICT; medical waste; sustainable development; waste generation

1. Introduction

Waste is a consequence of human activity that is made up of resources that are no longer usable. We are all aware that such waste can be hazardous and must be disposed of properly. Waste management is critical for reducing environmental damage, protecting public health, and encouraging resource conservation. Water, soil, and air are polluted by industrial waste, sewage, as well as agricultural waste. It can also be hazardous to humans and the environment. In a comparable manner, hospitals and other medical establishments generate a large amount of garbage, which can transmit illnesses, such as HIV, Hepatitis B and C, and Tetanus, to anyone who handle or come into touch with it. Bio-medical waste is trash produced during the diagnosis as well as treatment of humans or animals [1–5]. This encompasses all individuals and organisations that produce, store, gather, transport, as well as treat any type of bio-medical waste. There are many different forms of bio-medical wastes, a few of which are easy to manage and are neither hazardous or contagious, while others are extremely dangerous because they can transfer highly transmissible illnesses to current and future generations. This type of garbage can also endanger the environment by polluting the water, soil, and air. Several investigations have found that health care personnel have little or no awareness of how to dispose of bio-medical waste that can be dangerous and have a negative impact on the environment. Because of the same reason, there is a greater awareness need of bio-medical waste segregation and treatment.

Bio-medical waste management is a serious issue all over the world since it has an immediate effect on public well-being and the preservation of the environment. Bio-medical waste management differs by country and location, and is impacted by factors like as healthcare infrastructure, legislative frameworks, technological breakthroughs, and cultural practises. While there have been considerable gains in waste management practises around the world, there are still issues and gaps. Bio-medical waste management is governed by severe legislation and guidelines across numerous developed nations. These standards include particular waste segregation, gathering, transporting, treatment, and disposal methods. For waste treatment, modern methods such as autoclaving, microwaving, and advanced heat treatment are routinely used. Furthermore, recycling as well as resource recovery activities are gaining traction, supporting the long-term utilisation of bio-medical waste. Conversely, developing countries frequently have more issues in managing bio-logical waste. Inadequate waste handling and disposal practises are exacerbated by a lack of resources, insufficient facilities, and a lack of knowledge [6–8]. Common problems include dumping in public, uncontrolled burning, as well as combining bio-medical waste with municipal solid garbage. These practises endanger public health, occupational safety, and the surroundings. To tackle these issues, international organisations such as the World Health Organisation (WHO) offer guidelines and assistance in improving bio-logical waste management practises around the world. Initiatives to create capacity, training programmes, and knowledge-sharing forums are critical for raising awareness and promoting best practises. The COVID-19 pandemic has underlined the significance of effective bio-logical waste management. The growing amount of medical waste, especially personal protective equipment (PPE), has put existing waste management systems under strain. It has emphasised the importance of waste segregation, proper disposal procedures, and improved healthcare facility readiness.

Dangerous waste accounted for approximately 22.8% of the market in 2021, and this trend is expected to continue in the near future. This is due to the increased use of sharps as well as chemicals during surgeries, treatments, and medical storage. Anaesthesia gases and ethylene oxide, different acids and bases, toxic fumes and vapours, as well as metal wastes (which includes X-ray and CT scans) are among medically hazardous wastes. Furthermore, hazardous wastes have the potential to harm human health. Consuming drugs that have expired, for example, causes prescription side effects that are detrimental to patients. Such conditions enhance the necessity for proper and efficient medical waste management, pushing into the medical waste treatment market to expand over the predicted period [9].

Figure 1 shows the global medical waste management market prediction by service during 2022 and 2030.

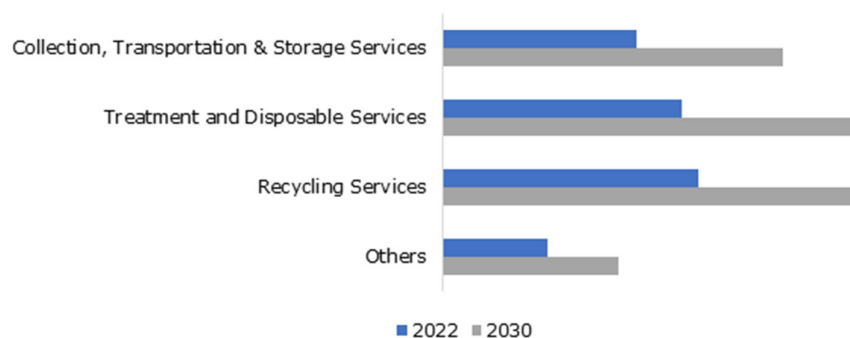


Figure 1. Global Medical Waste Management Market By Service, 2022 and 2030 (USD Million) (Source: Global Market Insights).

Bio-medical waste management is critical for maintaining public health, protecting the environment, and promoting sustainability in healthcare facilities. Bio-medical waste management, encompassing infectious, toxic, and pharmaceutical waste, necessitates effective management solutions that adhere to regulatory criteria while mitigating potential dangers. However, because of the complexity and unpredictability involved with waste characteristics, treatment innovations, and disposal techniques, measuring the efficiency and efficacy of bio-logical waste management systems presents major hurdles. This work offers a Fuzzy TOPSIS-based strategy for thorough bio-medical waste management assessment, with the goal of improving sustainability as well as decision-making in this vital subject. This strategy integrates subjective judgements, linguistic assessments, as well as uncertainty by incorporating fuzzy logic and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) procedure, offering an effective structure for assessing and choosing the most appropriate waste management systems.

The overall manuscript is as Section 2 shows; the elementary concept of PFSs. Section 3 discusses the algorithm of the SWARA-ARAS method under the PFSs context. Section 4 utilizes the developed methodology in a case study of selecting desirable HCWT options that demonstrate the applicability and strength of the introduced methodology. Also, it discusses the comparative discussions and sensitivity analysis that display the steadiness and robustness of the introduced approach. Section 5 deliberates the implications and discussions related to HCW management and treatment method assessment. Section 6 deliberates the conclusions and future scope.

2. Related Works

Bio-medical waste management is a critical issue with considerable consequences for the general population and the sustainability of the environment. Practitioners as well as researchers have long recognised the complicated nature and problems of assessing the efficiency and efficacy of bio-medical waste management systems. To solve these difficulties, several approaches have been proposed, embracing various areas such as waste segregation, gathering, transportation, treatment, as well as disposal [10–14]. This section provides a thorough analysis of related works in the topic of bio-medical waste management assessment, with an emphasis on methodologies and techniques used to analyse the performance of waste management systems. The assessment covers both classic procedures and more modern innovations, outlining their advantages, disadvantages, and areas for improvement. This section presents a basis for the creation and explanation of the suggested Fuzzy TOPSIS-based strategy, which aims towards contributing to the improvement of sustainable waste management practises in the bio-medical sector by analysing the existing body of research.

Datta et al. [15] undertook a full evaluation of the latest 2016 BMW regulations in their paper, stressing the practical obstacles associated with their implementation as well

as the limits of existing techniques. They also investigated the most recent environmentally acceptable strategies for disposing of bio-medical waste (BMW). The new standards' principal goal is to improve segregation, transportation, and disposal processes in order to reduce environmental pollution and revolutionise the BMW treatment procedure in India. The authors emphasise the importance of working together, involving government help in terms of financial assistance as well as development of infrastructure, committed healthcare professionals and resources, continuous monitoring of BMW practises, stringent legislation, as well as robust regulatory organisations for accomplishing successful BMW. BMW's guiding principles are source separation and waste reduction. Furthermore, considerable R&D efforts are necessary to produce ecologically acceptable medical devices as well as BMW disposal systems, which will ultimately contribute to the preservation of the environment.

Deress et al. [16] performed a cross-sectional research investigation to assess healthcare personnel's knowledge, attitude, and practise related bio-logical waste management in Debre Markos town medical facilities. Standardised self-administered questionnaires and observational checklists were used to collect data. The acquired data were then input into the Epi-data 3.1 software and transferred to SPSS version 20 for further analysis. To find any significant connections, bivariate and multivariate logistic regression analyses were performed. In the multivariate logistic regression analysis, variables having p -values less than 0.05 were deemed markers of statistically significant connections.

A study by Ilyas et al. [17] included a thorough analysis of the disinfection techniques applied to COVID waste disposal. The entire procedure, from the distinct collection of COVID-waste to the many physical and chemical stages that followed, was investigated by the authors. They also include policy briefs pertaining to international activities for COVID-waste management, emphasising the use of various disinfection methods. These strategies are illustrated by a number of successful examples, proving their effectiveness in lowering threats to both human health and the environment. The conclusions of this essay will have a considerable impact on the creation of plans for stopping and managing similar pandemics in the future.

The primary problems with hospital waste management in underdeveloped nations were effectively outlined by Ali et al. [18]. The analysis of the extant literature revealed that many of these nations have only recently passed legislation and rules governing hospital waste management. The way these regulations are applied differs considerably amongst hospitals. Substantial differences in trash generation rates were also noted inside and between these nations, mostly as a result of discrepancies in the definition and measurement of such wastes across studies. Hospital waste management practises that are insufficient for waste segregation, collection, transportation, storage, as well as disposal increase occupational and environmental dangers. Because there are not any training programmes for hospital workers, there is still a dearth of understanding and awareness regarding proper waste management. In addition, sanitation workers as well as scavengers function without protective gear or a vaccination, which increases the risks. Safety risks are further increased by the unauthorised recycling of mixed garbage. Overall, managing medical waste in underdeveloped nations is fraught with difficulties. The negative consequences of hospital wastes can be significantly reduced by using sustainable waste management practises.

The review undertaken by Chauhan and Singh [19] highlights the need for a more thorough use of operations management methods and methodologies, and proposes numerous potential research objectives in healthcare waste management. The article identifies unresolved problems with hospital waste management, such as inventory control, warehousing, bin distribution, routing, as well as transportation, which must be addressed for efficient waste management in healthcare contexts.

In another study, Thind et al. [20] looked at the state of BMW-incineration units in India from 21 March 2020, to 31 August 2020, notably during the COVID-19 epidemic. According to their data, each COVID patient in India produced an average of 3.41 kg of bio-medical waste (BMW) each day, with an average percentage of yellow-coloured BMW

(Y-BMW) in it of 50.44%. Moreover, it was found that by 13 July 2020, India's capacity for burning BMW had been entirely utilised by the total amount of Y-BMW produced by both healthy and COVID-infected patients. The pandemic's considerable effects on the nation's capacity for and management of BMW-incineration facilities were highlighted by these findings.

In their study, Benzidia et al. [21] evaluated data from 168 French hospitals using a partial least squares regression-based structural equation modelling approach and generated a conceptual framework. The study's goal was to find out how interactions in the green supply chain and environment process integration are impacted by big data analytics as well as artificial intelligence (BDA-AI) solutions. The results showed that BDA-AI technologies had a considerable positive impact on green supply chain collaboration as well as environmental workflow integration. The research also emphasised the importance of green supply chain collaboration, as well as environmental process integration on environmental sustainability. An important finding that was not thoroughly covered in the body of the current literature is that the outcomes showed the moderating influence of green digital learning in the linkages between BDA-AI technologies as well as green supply chain interaction. For the supply chain and logistics managers, this report offers insightful tips on utilising BDA-AI technologies to assist green supply processes and improve environmental efficiency.

A thorough evaluation of the scientific literature on international healthcare waste management was carried out by Caniato et al. [22] and covered the years 2000 to the present. The objective was to pinpoint the essential laws, customs, difficulties, and best practises in this field. The results were examined in light of each nation's Gross National Income and Human Development Index. According to the report, efficient regulation and precise definitions of waste types are essential elements that call for reform on a nationwide scale. Particularly in connection to waste treatment and disposal, a nation's economic situation is important. The study found a number of areas that needed to be improved, including the introduction of regional clusters, better governance structures, as well as practises for segregating sharps waste. For those concerned in healthcare waste management, including legislators, these recommendations offer insightful information.

In a thorough examination of the fragmented knowledge in the literature on hospital waste management, Thakur and Ramesh [23] concentrated on the time frame from January 2005 to July 2014. The study set out to accomplish the following goals: (i) identify patterns in the literature on healthcare waste management with regard to journals that were published; (ii) identify the primary research areas in healthcare waste management; (iii) look at the methodologies used in healthcare waste management research; (iv) determine the areas that academics tend to focus on the most often; and (v) describe the potential areas for future studies in healthcare waste management.

In the Adar Yazar et al. [24] study, it was distinct from other studies of its kind in the literature. The study concentrated on choosing particular approaches of handling and removing for dangerous solid wastes, comprising municipal and healthcare waste. In contrast to earlier studies, the selection procedure was carried out independently for each category of garbage. The authors also performed thorough studies, including sensitivity as well as comparison, to assess the outcomes. It is predicted that the study's findings will significantly advance the body of knowledge on the management of hazardous solid waste. Table 1 shows the meta-analysis of different related works.

This meta-analysis combines the results of several studies, emphasizing their techniques, major observations, and contributions to our understanding of the management of bio-medical waste. It provides a thorough overview of the body of research in the field and lays the foundation for the suggested Fuzzy TOPSIS-based approach. A variety of strategies and approaches are revealed by the literatures that are currently available on the evaluation of bio-logical waste management. The subjective elements and inherent uncertainties that accompany decision-making are frequently ignored in favour of traditional methodologies' reliance on quantitative indicators or indices. In order to overcome these

constraints, more recent developments investigated the integration of fuzzy logic, multi-criteria decision analysis, and TOPSIS approaches. Although these strategies have showed promise in addressing the complicated nature of managing bio-medical waste, more study and improvement are still required. The suggested Fuzzy TOPSIS-based strategy tries to close the existing gaps by offering a thorough and reliable evaluation framework that takes into account uncertainty, linguistic factors, as well as subjective judgements. The present investigation advances bio-medical waste management procedures by building on prior research's advantages and provides useful information for policymakers, healthcare executives, and waste management professionals to make knowledgeable choices about waste management systems.

Table 1. Meta-analysis of different related works.

Study	Methodology and Focus	Key Findings
Datta et al. [15]	Evaluation of 2016 BMW regulations	Addressed the limitations of current approaches and their practical application issues; stressed the necessity of teamwork between government assistance, development of infrastructure, and strict legislation for a successful BMW.
Deress et al. [16]	Cross-sectional assessment of waste management	Investigated the practises, attitudes, and understanding of healthcare workers; use of logistic regression analysis as well as standardised questionnaires; discovered important links with regard to waste management.
Ilyas et al. [17]	Analysis of COVID waste disposal techniques	Examined various COVID waste decontamination techniques; Effective tactics were highlighted; potential effects on the preparation for a pandemic reaction.
Ali et al. [18]	Challenges in hospital waste management	The importance of adequate waste separation and training has been addressed along with concerns with waste management in developing countries and discrepancies in laws and terminology.
Chauhan & Singh [19]	Operations management in healthcare waste	Found issues with hospital waste management that need to be fixed; areas that are prioritised, such as transportation, warehousing, as well as inventory management.
Thind et al. [20]	BMW-incineration during COVID-19	Evaluated the amount of medical waste generated during the epidemic; stress on the incineration system caused by an increase in waste quantity.
Benzidia et al. [21]	Green supply chain integration and BDA-AI impact	Examined the consequences of BDA-AI on the integration of green supply chains and environmental protection; highlighted favourable influence; and tempered the effect with green digital learning.
Caniato et al. [22]	Literature review on international waste management	Examined international standards for managing medical waste; Recommended need for better definitions and regulations; Influence of economic variables.
Thakur & Ramesh [23]	Literature analysis in healthcare waste management	Healthcare waste management trends, methodology, research areas, as well as potential future study areas have been highlighted.
Adar Yazar et al. [24]	Distinct approach to hazardous solid waste management	Investigated the handling and removal of hazardous solid waste; individual approaches for various waste categories; discussed potential improvements in the field of waste management.

3. Materials and Methods

The selection of evaluation criteria and alternatives for an in-depth evaluation of bio-medical waste management, as well as the use of the Fuzzy TOPSIS method to rank and evaluate the selected alternatives, make up the two main parts of the methodological framework used in this research paper. The approach is thoroughly described in this

section, including the steps involved in choosing criteria, alternative recognition, and the use of the Fuzzy TOPSIS method that begin with a thorough set of assessment standards that are created, which include all of the crucial facets of managing bio-medical waste. These standards were developed after a thorough analysis of the available literature and expert interviews. Environmental Impact, Regulation Compliance, Health and Safety, Technological Feasibility, Cost-Effectiveness, and Stakeholder Engagement are some of the recognised criteria. Each criterion is thoughtfully constructed to reflect the pertinent elements and characteristics related to bio-medical waste management systems. A comprehensive evaluation that takes into consideration the multifaceted character of waste management is ensured by the use of several criteria.

The assessment of a variety of potential bio-logical waste management strategies includes Incineration, Autoclaving, Microwaving, Chemical Treatment, Landfilling and Recycling. These choices reflect various methods, tools, or techniques used in healthcare institutions in the actual world. The alternatives were chosen for the bio-logical waste management domain based on their applicability, diversity, and significance. In order to provide a thorough examination of various waste management strategies, it is important to make sure that a representative collection of alternatives is included in the review process. After the criteria and alternatives are determined, the Fuzzy TOPSIS approach is used to rank and evaluate the alternatives in relation to the determined criteria. The inherent uncertainties and imprecisions involved with decision-making in the setting of bio-medical waste management are handled using fuzzy logic. In order to indicate the subjective evaluations of each criterion, linguistic variables are used. In order to more accurately capture the preferences and perceptions of the decision-makers, linguistic parameters are expressed using fuzzy numbers.

The relative distance between each alternative and the ideal answer is then calculated using the Fuzzy TOPSIS approach by quantifying the proximity coefficients. The best-performing alternative in terms of every criterion of evaluation is the optimum answer. The method gives a ranking that shows the general acceptability and efficacy of each choice by computing the proximity coefficients. This ranking acts as a guide for choice, making it easier to choose the best bio-medical waste management system. The Fuzzy TOPSIS method was used in this work to rank the solutions in a systematic and reliable manner while simultaneously accounting for the subjectivity and uncertainty included in bio-medical waste management assessment. The thorough methodology described in this part guarantees transparency and reproducibility and enables the results to be validated and verified.

This research study uses a Fuzzy TOPSIS-based methodology to provide a thorough analysis of bio-medical waste management. The purpose is to evaluate the efficiency of the waste management system and recommend modifications in light of the findings. In order to develop a strong and sustainable waste management strategy, this article explains several criteria and evaluation possibilities that were taken into account.

3.1. Identification of Different Criteria

When assessing bio-medical waste management systems, the determination of several criteria is of utmost relevance. We can assure a thorough assessment that represents the multifaceted nature of waste management by incorporating a broad range of factors. Each criterion identifies a certain component of waste management and addresses important elements. Decision-makers can take into account a wide range of variables and make well-informed decisions when a full understanding of the advantages and disadvantages of various waste management strategies is available to them. The definition of criteria also offers a uniform framework for evaluation, encouraging openness, uniformity, and comparability in the evaluation procedure. The rigorous selection and identification of criteria ultimately serve as the cornerstone for a thorough and insightful assessment of bio-medical waste management systems, improving both environmental sustainability as well as public health.

3.1.1. Environmental Impact (EI)

The Environmental Impact criterion assesses how bio-logical waste management techniques affect the environment. It considers a number of things, including resource conservation, emissions reduction, and pollution control [25]. The study seeks to ascertain the degree to which the waste management system promotes to environmental conservation by evaluating the environmental impact. This criterion emphasises making sure that the waste management techniques used are environmentally friendly, reduce pollution, and efficiently utilise resources. It offers insightful information about the ecological impact of the bio-medical waste management system, allowing for the identification of potential adjustments to lessen adverse environmental effects.

3.1.2. Compliance with Regulations (CR)

This criterion measures how closely bio-medical waste management practises adhere to regional and federal laws and regulations. Waste management systems must adhere to established regulatory frameworks in order to protect the environment, worker safety, and general public health [26]. With regard to waste segregation, transportation, handling, treatment, as well as disposal, this criterion assesses whether waste management procedures adhere to the necessary requirements. The study's evaluation of compliance tries to find any gaps or instances of non-compliance in the current waste management system. The management of bio-logical waste in a safe and responsible manner in accordance with legal standards can therefore be ensured by using this information to suggest appropriate remedial steps and enhance overall regulatory conformity.

3.1.3. Health and Safety (HS)

This criterion is concerned with assessing the safeguards put in place to ensure the wellbeing of staff members, patients, and the general public throughout the handling of bio-logical waste [27]. The use of proper personal protective equipment (PPE), staff training on handling hazardous waste, the existence of safety protocols, and the prevention of occupational hazards are some of the topics this criterion looks at. It evaluates the efficacy of risk management techniques to reduce the possible health risks connected with handling bio-logical waste, including exposure to pathogens, chemical dangers, and injuries from sharps. The study aims to identify any gaps or shortcomings in the waste management practises and offer modifications to ensure the safety and protection of the individuals working with the trash by taking health and safety standards into account.

3.1.4. Technological Feasibility (TF)

Technological Feasibility criterion looks at the system for managing bio-logical waste from a technological standpoint. It evaluates the accessibility and suitability of the necessary equipment, facilities and cutting-edge technologies for efficient waste management [28]. This criterion takes into account things like how well waste collecting systems, facilities for waste treatment, as well as disposal techniques work. Additionally, it assesses how well technology works with the unique properties of bio-medical waste, as well as its capacity to manage various waste streams. The research's evaluation of technological viability tries to pinpoint any shortcomings or gaps in the current system and suggest technological fixes or advancements that could improve the efficacy, efficiency, and sustainability of the waste management procedure. The objective is to guarantee that the waste management technology is efficient, dependable, and competent to handle the particular difficulties posed by bio-medical waste.

3.1.5. Cost-Effectiveness (CE)

The cost-effectiveness criterion focuses on examining the financial elements of managing bio-logical waste. The total cost of waste management procedures, including garbage collection, transportation, treatment, and disposal, is assessed [29]. This criterion takes into account things like resource allocation, operational effectiveness, and long-term finan-

cial viability. The objective is to determine the most economical solutions that maximise resource utilisation while achieving the intended waste management goals. The study's goal is to find potential cost-saving strategies through the assessment of cost-effectiveness, such as putting into practise effective waste segregation techniques, looking into recycling options, or improving waste treatment procedures. In order to achieve the optimal balance between cost effectiveness, as well as waste management efficiency, this criterion helps decision-makers by taking both the efficacy and economic viability of waste management approaches into account.

3.1.6. Stakeholder Engagement (SE)

This criterion is concerned with the satisfaction and participation of numerous stakeholders during the management of bio-logical waste [30]. The significance of including and taking into account the viewpoints of waste generators, waste handlers, regulatory bodies, and the general public is acknowledged by this criterion. In order to make sure that stakeholders' requirements, concerns, as well as feedback are taken into account during the decision-making process, it evaluates the degree of communication, participation, and collaboration between those parties. Participant involvement in waste management practises fosters accountability, openness, and confidence. By assessing stakeholder engagement, the research hopes to find ways to enhance stakeholder involvement, improve communication channels, and resolve any gaps or difficulties in satisfying the various requirements and demands of stakeholders. The objective is to promote a more inclusive, as well as collaborative approach, to waste management that takes into account the values and interests of all interested parties.

3.2. Identification of Different Alternatives

The assessment of bio-medical waste management strategies requires the identification of various options because it enables a thorough examination of the various methods, tools, and procedures used in actual healthcare establishments. Decision-makers can study the viability and efficacy of various waste management systems by taking into account a wide variety of possibilities, ensuring that a broad range of options is taken into consideration [31–37]. Given the constantly changing nature of waste management procedures and the need to adjust to new laws, technological developments, and emerging best practises, this thorough examination is especially crucial. Identifying several options enables a full analysis of the advantages and disadvantages of each strategy, empowering decision-makers to choose decisions based on their unique requirements, available resources, and environmental situations. Additionally, providing a variety of options encourages creativity and the investigation of new approaches, which leads to ongoing development of bio-logical waste management procedures. Consequently, the identification of many possibilities is crucial to the evaluation process and provides decision-makers with the ability to choose the most appropriate and sustainable waste management solutions.

3.2.1. Incineration

The alternative "Incineration" is a frequently employed technique for managing bio-medical waste. It entails the carefully regulated burning of trash at temperatures typically between 800 and 1200 °C. Through heat destruction, incineration minimises the amount of garbage while also getting rid of potentially dangerous germs. Sharps, infectious materials, and pharmaceutical waste are just a few examples of the different forms of bio-medical waste that can be handled with this technique. Incineration has a number of benefits. First off, because it can manage a lot of garbage, it is appropriate for healthcare facilities that produce a lot of bio-medical waste. Second, incineration can effectively destroy a significant amount of pathogens, lowering the possibility that diseases will spread to those working nearby and the environment. Furthermore, the procedure uses waste-to-energy incinerators to generate energy in the form of heat or electricity, providing a possible source of renewable energy. However, incineration also comes with difficulties and worries.

If not properly managed, the process emits pollutants like dioxins and furans as well as greenhouse gases, which can have a negative impact on the environment and human health. So, in order to reduce these emissions, the adoption of cutting-edge air pollution control devices, including scrubbers and filters, is crucial. Incinerators also need a substantial capital outlay, specialised infrastructure, and regular maintenance in order to run efficiently and safely.

3.2.2. Autoclaving

The alternate process of “autoclaving” is a popular one for the disposal of bio-logical waste. It involves sterilising and sanitising the waste by exposing it to high-pressure saturated steam inside of an autoclave. Medical devices, lab trash, and other solid waste produced in healthcare facilities are all excellent candidates for autoclaving. As a waste management alternative, autoclaving has various benefits. Primarily, it effectively kills pathogens such as bacteria, viruses, as well as spores to reduce the danger of infection spreading. By doing this, the trash is made safe for management and disposal after that. Second, autoclaving enables waste volume reduction, enabling more effective waste storage and transportation. In addition, autoclaves offer lower environmental emissions than other processes such incineration and require fewer infrastructure components to operate.

Additionally, there are several factors to take into account during autoclaving. In order to produce the requisite amount of steam, the process needs a steady supply of both water and energy. Further, autoclaving can be used to treat some waste streams that are chemically contaminated or dangerous, but not all waste streams. The success of autoclaving depends on waste separation and appropriate packing.

3.2.3. Microwaving

Managing bio-medical waste alternatively through “Microwaving” is a growing practice. It involves sterilising and disinfecting the trash using microwave technology. Sharps, laboratory trash, liquid waste, and small amounts of bio-medical waste are all very well suited for microwave treatment. As a waste management alternative, microwaves provide various benefits. First of all, it offers a quick and effective treatment process since microwaves produce heat inside the trash, which quickly and efficiently disinfects it. The technique can effectively eliminate a variety of pathogens, comprising bacteria and viruses, protecting waste handlers and lowering the danger of infection spread. The volume of garbage is also reduced by microwaving, which facilitates storage, transportation, and ultimate disposal. However, there are issues with using the microwave as a waste management technique. For optimal operation, microwaves need a reliable power source and the right setup. To achieve uniform heating as well as disinfection, the procedure also calls for precise waste processing and packaging. Furthermore, some bio-medical waste, such as some chemicals, medications, or radioactive materials, may not be safe for microwaving and may need to be disposed of in another way.

3.2.4. Chemical Treatment

Chemical Treatment is a technique for handling bio-medical waste. It entails the application of chemicals to destroy, disinfect, or inactivate germs found in the waste. For liquid waste, for example, laboratory solutions or objects polluted with chemicals or medications, chemical treatment is especially appropriate. As an alternative for waste management, chemical processing has many benefits. The trash is made safe for handling or disposal by first efficiently neutralising or inactivating microorganisms. Bacteria, viruses, and fungus are just a few of the many microorganisms that chemical agents, including disinfectants and sterilising solutions, can target. Furthermore, chemical treatment can be more economical than other processes like incineration or autoclaving since it uses less energy and less specialised infrastructure. Additionally, there are factors to take into account when using chemicals. To guarantee effective disinfection while minimising environmental impact, the choice of suitable chemicals and their quantities must be carefully considered.

Additionally, some waste types, such as solids or sharps, may not be suited for chemical treatment and need alternate techniques for safe management. In order to safeguard employees and avoid chemical exposure, appropriate training and handling techniques are crucial.

3.2.5. Landfilling

Managing bio-medical waste via the traditional approach of “Landfilling” is an alternative. It entails the dumping of waste at authorised landfill locations that are intended to safely handle and contain waste. Many different kinds of bio-medical waste, such as non-infectious waste, non-hazardous waste, as well as particular kinds of sharps, can be disposed of in landfills. As a substitute for other waste management methods, landfilling has various benefits. First of all, it is a proven and commonly used waste disposal technique, making it quite practical and accessible. The purpose of landfills is to retain waste, inhibit its movement, and reduce the chance of environmental pollution. Additionally, landfilling can offer long-term storage for garbage that does not immediately endanger the environment or public health. In comparison to other waste treatment techniques, it may also be more affordable. Landfilling does come with some issues and worries, though. If not handled appropriately, bio-medical waste may leak dangerous compounds into the environment, endangering both individuals and their ecosystems. In order to ensure the secure disposal of medical waste in landfills, strong laws and appropriate waste segregation methods must be put into place. Additionally, to avoid contaminating soil, water, and air, landfills must be properly designed, monitored, and maintained.

3.2.6. Recycling

To manage bio-medical waste, “Recycling” is a significant and environmentally responsible alternative. Recycling strives to recover and reuse waste stream materials, lowering the need for raw resources and generating less garbage. There are unique prospects for recycling some components of bio-medical trash, such as plastics, metals, and glass, despite the fact that recycling is typically linked with non-bio-medical waste. As a substitute for traditional trash management, recycling has various benefits. By removing valuable elements from waste and reusing them in the production cycle, it first encourages resource conservation. By doing this, the need for additional raw materials is decreased, energy is conserved, and the environmental effects of the mining and production processes are lessened. Recycling can also help reduce the amount of waste produced and the overall environmental impact of waste management. Still, recycling bio-medical waste comes with several issues and difficulties. Some bio-medical waste products could contain toxic or pathogenic elements, necessitating careful cleaning procedures prior to recycling. To maintain worker safety and the strength of the recycled materials, proper segregation, managing, and treatment processes are essential. Also working with specialised recycling facilities and abiding by strict regulatory guidelines may be necessary to set up effective recycling systems for bio-medical waste.

The Fuzzy TOPSIS-based approach for assessing bio-medical waste management is built on these criteria and alternatives. The goal of the study paper is to highlight the advantages and disadvantages of the current waste management techniques, pinpoint the best substitutes, and make suggestions for enhancing the entire waste management system.

3.3. Fuzzy TOPSIS Based MCDM Approach

To handle uncertainties and imprecisions in the evaluation process, the Fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method combines the principles of fuzzy logic with TOPSIS. It provides a methodical method for evaluating and choosing alternatives according to how well they perform in comparison to a set of criteria. The process starts by converting verbal judgments into fuzzy numbers that accurately represent the decision-makers’ subjective assessments and linguistic uncertainty. The relative distances among each alternative as well as the ideal solution, corresponding

to the alternative that performs the best in terms of the assessed criteria, are then calculated using the closeness coefficients concept. The complete suitability as well as ranking of every option is determined using the fuzzy numbers and proximity coefficients [38–46]. The Fuzzy TOPSIS technique offers a quantitative foundation for decision-making, enabling decision-makers to weigh both the advantages and disadvantages of each possibility and making it easier to choose the best one. The Fuzzy TOPSIS technique, which has grown significantly in popularity in decision support applications, provides a strong and flexible framework for analysing complex systems, including bio-medical waste management, and is able to handle subjective judgements and uncertainty. The following Figure 2 illustrates the flow diagram of fuzzy TOPSIS approach.

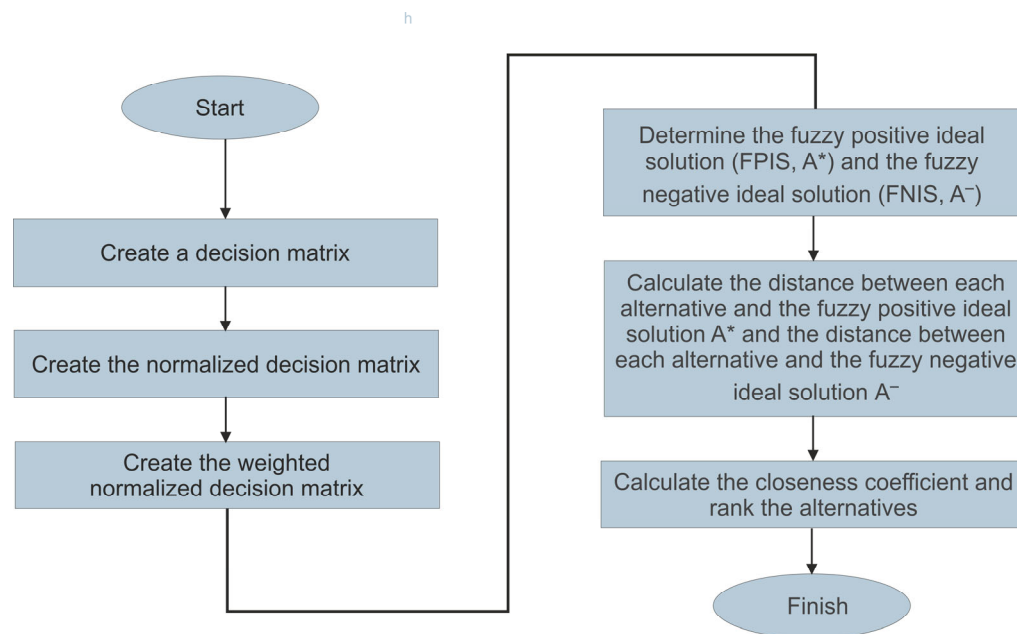


Figure 2. Flow Diagram of Fuzzy TOPSIS Approach.

4. Results

The study enlisted the help of 55 decision-makers with substantial experience in bio-logical waste management. These decision-makers were chosen based on their experience and engagement in waste management practises, which included lawmakers, hospital administrators, and waste management practitioners. Their insightful thoughts and skills laid the groundwork for the Fuzzy TOPSIS method's evaluation of bio-medical waste management choices. A varied range of opinions and personal experiences were incorporated into the assessment procedure as a result of their participation, boosting the reliability and importance of the results of the investigation. The decision-makers' pooled expertise and previous experience guaranteed that the evaluation covered the practical features and real-world issues of bio-medical waste management. The participation of these decision-makers helps to the results' validity and application, making them useful for the broader bio-medical waste management community.

4.1. Quantitative Assessment Findings

The study's findings are described below, along with a step-by-step evaluation methodology and the outcomes acquired utilising the Fuzzy TOPSIS approach. Based on the defined criteria, these findings provide useful insights into the performance of various bio-medical waste management approaches.

Step 1: Create a decision matrix

In this study, six criteria and six options are ranked using the FUZZY TOPSIS approach. Table 2 below indicates the type of criterion as well as the weight assigned to each one. The "+" symbol indicates that all six criteria (EI, CR, HS, TF, CE, SE) are positively oriented.

Table 2. Characteristics of Criteria.

	Name	Type	Weight
1	EI	+	(0.167, 0.167, 0.167)
2	CR	+	(0.167, 0.167, 0.167)
3	HS	+	(0.167, 0.167, 0.167)
4	TF	+	(0.167, 0.167, 0.167)
5	CE	+	(0.167, 0.167, 0.167)
6	SE	+	(0.167, 0.167, 0.167)

As shown in Table 3, a systematic approach based on the linguistic evaluations of the specialists is used to convert verbal judgements into fuzzily defined numbers. Using well-established linguistic quantifiers, every linguistic phrase (such as Very low, Low, Medium, High, Very high) is assigned a matching fuzzy number, converting qualitative judgements into numerical representations. By using language scales and expert consensus to guide the transformation, it is ensured that the resulting fuzzy numbers accurately represent the underlying subjective evaluations. The following Table 3 shows the fuzzy scale used in the model.

Table 3. Fuzzy Scale.

Code	Linguistic Terms	L	M	U
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

The alternatives in terms of various criteria are evaluated and the results of the decision matrix are shown as follows. Note that if multiple experts participate in the evaluation, then the matrix below in Table 4 represents the arithmetic mean of all experts.

Table 4. Decision Matrix.

	EI	CR	HS	TF	CE	SE
Incineration	(3.267, 5.267, 6.867)	(2.733, 4.733, 6.600)	(2.867, 4.733, 6.333)	(2.333, 4.333, 6.200)	(2.467, 4.467, 6.467)	(2.733, 4.733, 6.733)
Autoclaving	(4.067, 6.067, 7.800)	(2.867, 4.867, 6.600)	(4.200, 6.200, 7.533)	(3.267, 5.267, 6.867)	(4.333, 6.333, 7.667)	(4.067, 5.933, 7.533)
Microwaving	(3.133, 5.000, 6.733)	(2.867, 4.867, 6.867)	(3.933, 5.800, 7.400)	(3.400, 5.267, 6.867)	(3.800, 5.800, 7.133)	(2.333, 4.333, 6.333)
Chemical Treatment	(2.733, 4.733, 6.600)	(3.000, 5.000, 6.867)	(2.867, 4.600, 6.467)	(3.400, 5.400, 7.267)	(2.467, 4.333, 6.333)	(2.467, 4.333, 6.333)
Landfilling	(2.067, 3.933, 5.933)	(2.467, 4.333, 6.333)	(2.600, 4.467, 6.200)	(2.733, 4.600, 6.467)	(2.733, 4.600, 6.333)	(2.733, 4.467, 6.333)
Recycling	(3.667, 5.667, 7.267)	(3.667, 5.533, 7.133)	(4.333, 6.333, 8.067)	(3.800, 5.800, 7.667)	(4.333, 6.333, 7.933)	(4.200, 6.200, 8.067)

Step 2: Create the normalized decision matrix

Based on the positive and negative ideal solutions, a normalized decision matrix can be calculated by the following relation:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right); c_j^* = \max_i c_{ij}; \text{ Positive ideal solution}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}} \right); a_j^- = \min_i a_{ij}; \text{ Negative ideal solution}$$

The normalized decision matrix is shown in Table 5 below.

Table 5. A normalized decision matrix.

	EI	CR	HS	TF	CE	SE
Incineration	(0.419, 0.675, 0.880)	(0.383, 0.664, 0.925)	(0.355, 0.587, 0.785)	(0.304, 0.565, 0.809)	(0.311, 0.563, 0.815)	(0.339, 0.587, 0.835)
Autoclaving	(0.521, 0.778, 1.000)	(0.402, 0.682, 0.925)	(0.521, 0.769, 0.934)	(0.426, 0.687, 0.896)	(0.546, 0.798, 0.966)	(0.504, 0.735, 0.934)
Microwaving	(0.402, 0.641, 0.863)	(0.402, 0.682, 0.963)	(0.488, 0.719, 0.917)	(0.443, 0.687, 0.896)	(0.479, 0.731, 0.899)	(0.289, 0.537, 0.785)
Chemical Treatment	(0.350, 0.607, 0.846)	(0.421, 0.701, 0.963)	(0.355, 0.570, 0.802)	(0.443, 0.704, 0.948)	(0.311, 0.546, 0.798)	(0.306, 0.537, 0.785)
Landfilling	(0.265, 0.504, 0.761)	(0.346, 0.607, 0.888)	(0.322, 0.554, 0.769)	(0.356, 0.600, 0.843)	(0.345, 0.580, 0.798)	(0.339, 0.554, 0.785)
Recycling	(0.470, 0.727, 0.932)	(0.514, 0.776, 1.000)	(0.537, 0.785, 1.000)	(0.496, 0.756, 1.000)	(0.546, 0.798, 1.000)	(0.521, 0.769, 1.000)

Step 3: Create the weighted normalized decision matrix

Considering the different weights of each criterion, the weighted normalized decision matrix can be calculated by multiplying the weight of each criterion in the normalized fuzzy decision matrix, according to the following formula.

$$\tilde{v}_{ij} = \tilde{r}_{ij} \cdot \tilde{w}_{ij}$$

where \tilde{w}_{ij} represents weight of criterion c_j .

The following Table 6 shows the weighted normalized decision matrix.

Table 6. The weighted normalized decision matrix.

	EI	CR	HS	TF	CE	SE
Incineration	(0.070, 0.113, 0.147)	(0.064, 0.111, 0.155)	(0.059, 0.098, 0.131)	(0.051, 0.094, 0.135)	(0.052, 0.094, 0.136)	(0.057, 0.098, 0.139)
Autoclaving	(0.087, 0.130, 0.167)	(0.067, 0.114, 0.155)	(0.087, 0.128, 0.156)	(0.071, 0.115, 0.150)	(0.091, 0.133, 0.161)	(0.084, 0.123, 0.156)
Microwaving	(0.067, 0.107, 0.144)	(0.067, 0.114, 0.161)	(0.081, 0.120, 0.153)	(0.074, 0.115, 0.150)	(0.080, 0.122, 0.150)	(0.048, 0.090, 0.131)
Chemical Treatment	(0.059, 0.101, 0.141)	(0.070, 0.117, 0.161)	(0.059, 0.095, 0.134)	(0.074, 0.118, 0.158)	(0.052, 0.091, 0.133)	(0.051, 0.090, 0.131)
Landfilling	(0.044, 0.084, 0.127)	(0.058, 0.101, 0.148)	(0.054, 0.092, 0.128)	(0.060, 0.100, 0.141)	(0.058, 0.097, 0.133)	(0.057, 0.092, 0.131)
Recycling	(0.079, 0.121, 0.156)	(0.086, 0.130, 0.167)	(0.090, 0.131, 0.167)	(0.083, 0.126, 0.167)	(0.091, 0.133, 0.167)	(0.087, 0.128, 0.167)

Step 4: Determine the fuzzy positive ideal solution (FPIS, A^*) and the fuzzy negative ideal solution (FNIS, A^-)

The FPIS and FNIS of the alternatives can be defined as follows:

$$A^* = \{\tilde{v}_1^*, \tilde{v}_2^*, \dots, \tilde{v}_n^*\} = \left\{ \left(\max_j v_{ij} | i \in B \right), \left(\min_j v_{ij} | i \in C \right) \right\}$$

$$A^- = \{\tilde{v}_1^-, \tilde{v}_2^-, \dots, \tilde{v}_n^-\} = \left\{ \left(\min_j v_{ij} | i \in B \right), \left(\max_j v_{ij} | i \in C \right) \right\}$$

where \tilde{v}_i^* is the max value of i for all the alternatives and \tilde{v}_1^- is the min value of i for all the alternatives. B and C represent the positive and negative ideal solutions, respectively.

The positive and negative ideal solutions are shown in Table 7 below.

Table 7. The positive and negative ideal solutions.

	Positive Ideal	Negative Ideal
EI	(0.087, 0.130, 0.167)	(0.044, 0.084, 0.127)
CR	(0.086, 0.130, 0.167)	(0.058, 0.101, 0.148)
HS	(0.090, 0.131, 0.167)	(0.054, 0.092, 0.128)
TF	(0.083, 0.126, 0.167)	(0.051, 0.094, 0.135)
CE	(0.091, 0.133, 0.167)	(0.052, 0.091, 0.133)
SE	(0.087, 0.128, 0.167)	(0.048, 0.090, 0.131)

Step 5: Calculate the distance between each alternative and the fuzzy positive ideal solution A^+ and the distance between each alternative and the fuzzy negative ideal solution A^-

The distance between each alternative and FPIS and the distance between each alternative and FNIS are, respectively, calculated as follows:

$$S_i^+ = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^+) \quad i = 1, 2, \dots, m$$

$$S_i^- = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad i = 1, 2, \dots, m$$

d is the distance between two fuzzy numbers; when given two triangular fuzzy numbers (a_1, b_1, c_1) and (a_2, b_2, c_2) , e , the distance between the two can be calculated as follows:

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

Note that $d(\tilde{v}_{ij}, \tilde{v}_j^+)$ and $d(\tilde{v}_{ij}, \tilde{v}_j^-)$ are crisp numbers.

Table 8 below shows distance from positive and negative ideal solutions.

Table 8. Distance from positive and negative ideal solutions.

	Distance from Positive Ideal	Distance from Negative Ideal
Incineration	0.168	0.048
Autoclaving	0.047	0.172
Microwaving	0.112	0.105
Chemical Treatment	0.157	0.059
Landfilling	0.2	0.017
Recycling	0.01	0.205

Step 6: Calculate the closeness coefficient and rank the alternatives

The closeness coefficient of each alternative can be calculated as follows:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

The best alternative is closest to the FPIS and farthest to the FNIS. The closeness coefficient of each alternative and the ranking order of it are shown in Table 9 below.

Table 9. Closeness coefficient.

	C_i	Rank
Incineration	0.222	5
Autoclaving	0.786	2
Microwaving	0.484	3
Chemical Treatment	0.272	4
Landfilling	0.076	6
Recycling	0.955	1

The graph below presented in Figure 3 depicts the proximity coefficient of each possibility.

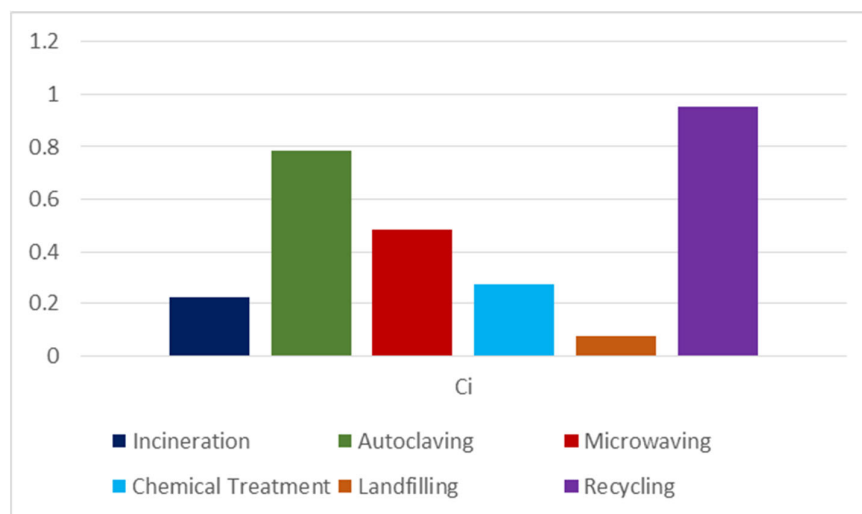


Figure 3. Closeness coefficient graph.

The Fuzzy TOPSIS Multiple Criteria Decision Making (MCDM) method was used to evaluate bio-medical waste management solutions, and the results were informative. The Fuzzy TOPSIS approach yielded the following ranking: Recycling is ranked first, followed by autoclaving (ranked second), microwaving (ranked third), chemical treatment (ranked fourth), incineration (ranked fifth), and landfilling (ranked sixth).

Recycling, the highest-ranked alternative, outperforms the others across all categories. It exhibits effectiveness in terms of reducing environmental impact, adhering to rules, assuring health and safety, and being cost-effective. The Fuzzy TOPSIS technique has acknowledged recycling's beneficial features as a sustainable waste management practise, emphasising its potential for waste reduction, resource recovery, as well as overall responsibility to the environment. Autoclaving, the second-ranked method, also does well in a number of areas. It demonstrates effectiveness in terms of regulatory compliance, health and safety factors, and technological viability. While it has slightly lower environmental impact and cost-effectiveness scores than recycling, autoclaving is still a feasible alternative for bio-medical waste management due to its capacity to efficiently sterilise and treat infectious materials.

Microwaving, ranked third, has an advantage in terms of regulatory compliance and health and safety factors. However, it may have worse scores in terms of environmental impact and cost-effectiveness. Microwaving is a quick and effective way to manage garbage, but it may necessitate additional precautions to avoid potential environmental risks. Chemical Treatment, ranked fourth, performs moderately across all categories tested. It has the potential for successful waste treatment and regulatory compliance, but it may necessitate careful monitoring and management to address environmental hazards and financial considerations connected with chemical use.

The fifth option, incineration, has been recognised as a standard practise in biological waste management. It provides effective waste treatment, regulatory compliance, and health and safety issues. Nonetheless, it may have larger environmental and cost repercussions than other solutions, resulting in a lower rank. Ultimately, landfilling, ranked sixth, has the greatest environmental impact and is widely regarded as the least desirable choice for bio-medical waste treatment. It may confront regulatory obstacles, concerns about health and safety, and long-term sustainability issues. The Fuzzy TOPSIS technique identifies landfilling's limits as a waste management practise, resulting in a lower ranking among the studied options.

As a whole, the Fuzzy TOPSIS MCDM technique provides a thorough assessment of bio-medical waste management choices, allowing decision-makers to grasp their respective strengths and shortcomings. The method's ranking is a useful tool for identifying the

best waste management solution depending on the specific context, priorities, and factors addressed in the evaluation.

4.2. Comparative Analysis

By comparing the suggested Fuzzy TOPSIS-based technique with the well-known Analytic Hierarchy Process (AHP) methodology, the comparative study conducted in this research work offers a significant validation of the proposed strategy. This comparison performs a variety of vital tasks, each of which adds to the ultimate rigour and dependability of the study's conclusions. This comparison evaluation's main goal is to rate the consistency and dependability of the outcomes produced by the Fuzzy TOPSIS method. The goal of the research is to determine the degree of agreement and concurrence among these two different procedures by contrasting the results produced by the Fuzzy TOPSIS and AHP methods. Such alignment would demonstrate the Fuzzy TOPSIS approach's dependability and robustness in addressing the complexity of bio-medical waste management assessment.

The goal of the study work is to validate the Fuzzy TOPSIS approach's fuzzy number alterations, linguistic evaluations, and underlying assumptions through this comparison. The recommended Fuzzy TOPSIS-based strategy's credibility as a solid and reliable instrument for thorough waste management evaluation is increased by demonstrating a significant correspondence among the findings of the two techniques. This comparison analysis not only supports the study's findings but also sheds light on the distinct benefits and shortcomings of each approach. Through taking into account elements like data accessibility, complexity of computation, and simplicity of implementation, professionals are better equipped to choose an acceptable technique for assessing bio-medical waste management systems. The following Table 10 shows the comparative analysis findings with the AHP approach.

Table 10. Comparative Analysis Findings with AHP.

Rank Order	1	2	3	4	5	6
AHP	Recycling	Microwaving	Autoclaving	Incineration	Chemical Treatment	Landfilling
Fuzzy TOPSIS	Recycling	Autoclaving	Microwaving	Chemical Treatment	Incineration	Landfilling

The ranking of alternative methods for managing bio-medical waste is improved by comparing the research outcomes among the AHP and the Fuzzy TOPSIS approach. Recycling comes out on top in the AHP approach's ranking, followed closely by microwaving as well as autoclaving. This conclusion is consistent with the Fuzzy TOPSIS findings, where Recycling continues to hold the top spot. Notably, the positions of Autoclaving and Microwaving shift between the two techniques, demonstrating their relative competitiveness. It's interesting to note that Chemical Treatment and Incineration both show identical ranks, supporting their respective places. It is significant to notice that whereas Fuzzy TOPSIS gives Chemical Treatment the advantage, AHP gives Incineration the upper hand. This tiny difference draws attention to the subtle changes that can result from using various techniques to deal with subjective judgements and uncertainty.

Landfilling's ranking as the least desirable choice in both AHP and Fuzzy TOPSIS reinforces its unfavourable standing relative to the other alternatives that were considered. The reliability of the conclusions about landfilling's usefulness as a bio-medical waste management option is highlighted by this constancy in ranking. The comparative analysis shows that the rankings generated by AHP and Fuzzy TOPSIS are significantly aligned, demonstrating a consistent assessment of different performance between the two approaches. This consistency strengthens the suggested Fuzzy TOPSIS-based approach's consistency and reliability, demonstrating that it can successfully capture the nuances of bio-medical waste management assessment. The consistency in the rankings of the majority of alternatives improves the validity of the study, supporting the conclusions reached and allowing for well-informed decision-making in the situation of choosing a waste management system.

5. Discussion

This work is significant because of its addition to the field of bio-medical waste management assessment. Bio-medical waste management is crucial for ensuring public health and the preservation of the environment. Even so, due to the inherent uncertainties and complications involved, measuring the efficacy of waste management systems involves major hurdles. This paper tackles these issues by presenting a Fuzzy TOPSIS-based approach to evaluation that integrates subjective judgements, linguistic variables, and uncertainty.

The results of the investigation provide useful insights into the performance of various bio-logical waste management approaches. The ranking achieved by using the Fuzzy TOPSIS approach emphasises the advantages and disadvantages of each choice based on the stated criteria. The findings indicate that recycling is the most advantageous option, highlighting the possibilities for waste reduction, resource recovery, and overall environmental stewardship. Autoclaving and Microwaving trail in terms of efficiency in terms of regulatory compliance, health and safety considerations, and technological viability. Chemical Treatment, Incineration, and Landfilling are ranked lower due to their higher environmental and financial costs. The strength of suggested Fuzzy TOPSIS-based methodology is highlighted by the congruent rankings among the AHP and Fuzzy TOPSIS approaches, proving its efficiency in identifying the relative performance of bio-medical waste management alternatives. This congruence strengthens the validity of our study's findings as well as gives decision-makers a dependable and consistent framework for making intelligent decisions in this crucial area.

While the study adds to our understanding of bio-medical waste management evaluation, it has several drawbacks. To begin with, the selection of criteria and alternatives may be influenced by subjective judgements and expert opinions, introducing bias into the evaluation process. It is critical to recognise that different stakeholders may prioritise criteria differently, and that the particular alternatives evaluated may differ depending on regional, organisational, or resource constraints. Second, the study is based on publicly available data and expert judgements, which may have inherent limitations and uncertainties. More study and data collection activities are required to improve the evaluation's accuracy and resilience.

Furthermore, the study's emphasis on the Fuzzy TOPSIS method may limit the investigation of other decision-making methodologies and approaches. Alternative techniques, such as Data Envelopment Analysis (DEA), or Multi-Attribute Utility Theory (MAUT), might offer new views on bio-medical waste management system assessment. In the future, studies might compare and integrate these strategies to improve decision-making. By presenting a Fuzzy TOPSIS-based approach for comprehensive evaluation, this study adds to the progress of bio-medical waste management practises. The findings emphasise the necessity of taking subjective judgements, linguistic characteristics, and uncertainties into account during the appraisal process. The findings highlight the possibility of recycling and other waste management methods. However, it is critical to accept the study's shortcomings and to investigate other techniques in order to increase the robustness and usefulness of bio-medical waste management assessment. This research lays the groundwork for politicians, healthcare professionals, and waste management professionals to make educated decisions and improve waste management systems for public health and the sustainability of the environment.

6. Conclusions

A Fuzzy TOPSIS-based approach for the full evaluation of bio-logical waste management systems was offered in this research work. The suggested methodology addresses the issues associated with measuring the efficiency and effectiveness of waste management choices by including subjective judgements, language variables, and uncertainty. The results of this research offered significant insights into the effectiveness of various bio-logical waste management solutions. The findings suggest that recycling is the most advantageous option, demonstrating its potential for waste reduction, resource recovery, and environ-

mental sustainability. Autoclaving and Microwaving additionally demonstrate promise in terms of regulatory compliance, health and safety considerations, as well as technological viability. In comparison, Incineration and Landfilling are ranked lower due to their greater environmental impact and cost implications. This study is significant because it contributes to the progress of sustainable waste management practises in the bio-medical industry. The suggested Fuzzy TOPSIS-based approach provides decision-makers with a transparent and systematic framework for evaluating and selecting the best waste management systems by considering a variety of factors. This technique improves the transparency, consistency, and efficacy of the evaluation process by taking into account the inherent uncertainties and subjectivity in decision-making. This research study uses the Fuzzy TOPSIS and AHP techniques as a reliable validation procedure. This comprehensive validation strengthens the validity of the study's conclusions and offers a thorough framework for making decisions in the complicated field of bio-medical waste management. Future study can improve on this work by addressing some of its shortcomings. In addition, including bigger and more diverse sampling of decision-makers from various areas and healthcare organisations might improve the findings' generalizability. This study advances the field of bio-medical waste management by delivering a solid evaluation technique and providing significant insights into waste treatment choices. The findings emphasise the need of taking into account many criteria and subjective judgements in decision-making, which will ultimately aid in the selection of sustainable waste management solutions. The suggested approach is a useful tool for policymakers, healthcare professionals, as well as waste management practitioners who want to enhance waste management practises and promote sustainable development in the bio-medical industry.

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