

Article

Sustainable Medical Waste Management Using an Intuitionistic Fuzzy-Based Decision Support System

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Abstract: The growing urban population and increased use of healthcare services have brought significant attention to the safe and sustainable management of medical waste. Selecting the proper technology in medical waste management (MWM) represents one of the most critical challenges for decision-makers to ensure public health. In order to evaluate and choose the best MWM methodology, the current research provides a novel multi-criteria decision-making (MCDM) strategy for a variety of social stakeholders, to compute criteria weights, decision-making weights, and alternative ranking algorithms. The suggested structure addresses uncertain assessments of alternatives by extending weighting and ranking methods to acquire the decision-making weight and rank the MWM alternatives based on uncertain conditions. It also uses ‘intuitionistic fuzzy’ linguistic variables to indicate criteria weights. To assess all the factors pertaining to the sustainability of MWM actions, this study suggests the creation of a decision support system (DSS). Our DSS is built upon a novel strategy that utilizes a collection of MCDM models that are grounded on contemporary intuitionistic fuzzy logic methodologies. Alternative scenarios have been assessed for the instance of Greece, after specialists in the healthcare management field imposed 17 criteria and sub-criteria. The IF-MCDM methodologies used were the Intuitionistic Fuzzy DEMATEL, TOPSIS, and CORPAS. The alternative scenarios ranged from the prioritizing of safety laws and regulations to public acceptance and awareness, with the handling of hazardous risks and transportation playing a crucial part in the process. All ensemble methods produced the same ranking of the alternatives, demonstrating that safety and risk avoidance is the most significant scenario for sustainable urban development and public health.

Keywords: medical (healthcare) waste; sustainable management; decision support system; intuitionistic fuzzy logic; urban development; public health



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1. Introduction

As the global population, the number of healthcare facilities, and the demand for medical services have all grown over the last decade, there has been a corresponding increase in the generation of healthcare wastes (HCWs) on a global scale. Simultaneously, trends such as the production of medical devices with multiple uses and a shift towards safer, single-use alternatives have contributed to the rise in HCW production. Consequently, managing HCW has become a challenging task for municipalities and regions, particularly in European countries that have enforced stringent regulations governing the safe handling, transport, and management of municipal and HCW waste [1]. Given that the improper disposal of HCWs poses a serious risk of infection or injury to healthcare workers and the general public, it is now a top priority in global public health and environmental concerns.

These factors have fueled a growing interest in HCW management within academic and professional circles [2].

The intricate and complex process of HCW management involves waste collection, the careful selection of transfer routes to minimize hazards, choosing appropriate disposal plant sites, selecting suitable HCW treatment technologies to minimize pollution, and, ultimately, recovering some of the lost energy in the entire chain. Numerous socio-cultural factors associated with these processes concurrently lead local societies to erect barriers and impose bureaucratic procedures ('red tape') to mitigate the adverse impacts resulting from improper HCW management. The selection of the best and most efficient treatment technique for HCWs has garnered significant scientific interest due to its far-reaching ecological and economic consequences. In general, the use of the multi-criteria decision-making (MCDM) tool can be of considerable assistance in evaluating HCW treatment options, addressing this complex and significant challenge.

2. Related Work

MCDM assists various decision-makers and businesses in reaching reasonable conclusions, both in quantitative and qualitative terms. It offers suggestions for improving options in the direction of a particular objective or utility, making use of a variety of analytical techniques [3] and instruments to assess how all pertinent data affect the decision-making process. MCDM is a goal-oriented procedure that offers the assistance required to accomplish this aim. While the traditional approach aims to find a single optimal solution, real-life problems often involve multiple options and evaluation criteria, making this goal unattainable [4]. In practice, many problems require the consideration of numerous criteria before a final decision can be reached. Unfortunately, as the number of assessment criteria increases, the decision-making process becomes more challenging. To address this issue, decision-makers often employ ensembles of various techniques in order to achieve near optimal performance in the system. The ensemble approaches have proven advantageous in improving the effectiveness and reliability of the produced DSS. Another challenge may also refer to deciding which scenario is beneficial and/or which approach to follow amongst alternative choices [5]. Simultaneously, when criteria evaluation is expressed through linguistic terms, fuzzy and intuitionistic fuzzy MCDM (IFMCDM) have demonstrated their effectiveness. Among various IFMCDM methodologies [6], intuitionistic fuzzy TOPSIS (IFTOPSIS) stands out as the most popular. According to [7], IFTOPSIS has been shown to yield results close to optimal when ordering criteria in multi-objective constrained waste management optimization problems [8].

Studies on Medical/Hazardous Waste Management via Intuitionistic Fuzzy MCDM Methodologies

Healthcare waste (HCW) can be classified as either hazardous or non-hazardous based on specific characteristics it exhibits. Medical waste is inherently categorized as hazardous due to its potential inclusion of unwanted flammable, oxidizing, poisonous, radioactive, toxic, or explosive materials. The improper handling of such waste poses significant threats to both humans and the environment. Extensive research has been conducted on multiple-criteria decision-making (MCDM) methodologies for handling hazardous waste, including medical waste. However, there has been limited research utilizing intuitionistic fuzzy methodologies in this field until the occurrence of the COVID-19 pandemic. Due to the exponential growth in medical waste generated post-pandemic, there has been a rapid increase in research employing intuitionistic fuzzy methodologies to establish a practical hierarchy of criteria for effective waste management. The most recent and up-to-date insights on technologies for the treatment of solid medical waste have been presented by [9]. The classification of medical waste, as outlined by [7], is depicted in Figure 1 and is representative of the current state in the Greek region in terms of hospital-produced waste. The authors list incineration, autoclaving, chemical disinfection, microwaving, irradiation, biological treatment, and encapsulation as the most popular methodologies for treating

medical waste from a chemical-engineering perspective. The nature and categorization of medical waste, along with local laws and regulations, determine the most effective treatment procedure. To ensure the efficient and secure disposal of medical waste, some facilities may additionally employ a variety of treatment techniques.

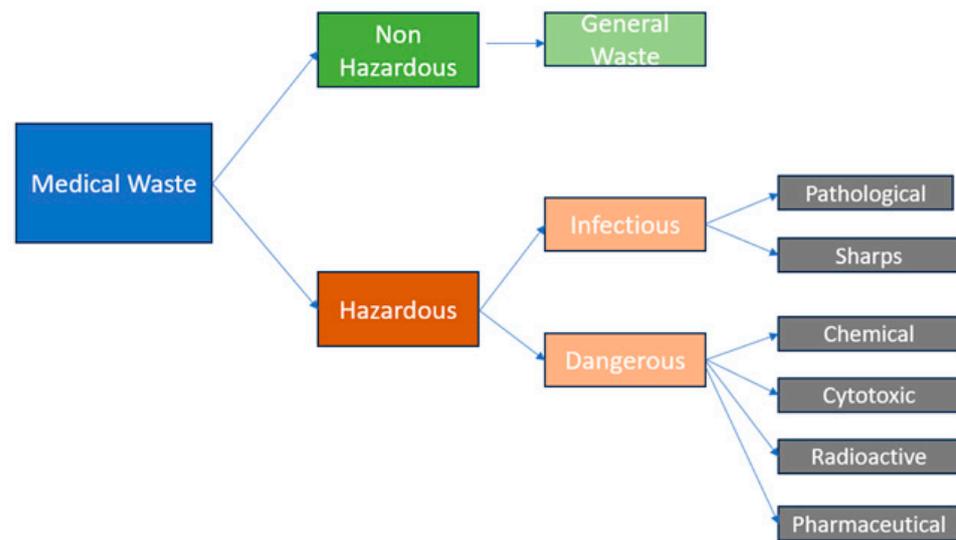


Figure 1. Classification of medical waste (inspired by [7]).

In our original work, we explore the issue of medical waste treatment using an innovative holistic approach that encompasses social, transportation, management, and policy aspects. These include collection, storage, segregation, transportation, accident avoidance during transportation, safety practices of health workers, waste treatment, sanitation processes, disposal, capacity building of appointed companies, public awareness, monitoring processes, and overall safety. Our research on healthcare waste treatment and management is unique due to its unique approach to holistically treating the significant importance of related criteria using a repertoire of methodologies. This research is unique as it combines fuzzy methodologies with a holistic methodology, making it a unique study. Additionally, our research is the first to relate HCW holistic treatment methodologies with the region of Thessaly, Greece, making it a unique attempt in this area. Furthermore, our work successfully connects results from similar methodologies like IF-CORPAS and IF-TOPSIS with alternative objectives and scope methodologies like IF-DEMATEL, making it a unique comparative approach in the literature.

Furthermore, our focus is on advanced fuzzy logic methodologies to address the multi-criteria decision making involved in the aforementioned aspects. In this novel approach, we propose using an ensemble of such methodologies as the primary decision-making engine in a unique decision support system (DSS). Table 1 summarizes the research on IF approaches used for this multi-objective issue.

Table 1. HCW management/treatment research based on IF methodologies.

Public. Year	References	Main Topic
2022	[10]	Novel approach based on intuitionistic fuzzy sets (IFSs) and the VIKOR method to establish recycling channel capacity evaluation index system that improves efficiency. The process incorporates the best–worst method and entropy to comprehensively determine decision-makers’ weighting. New aggregation operator is used to define capacity rankings of hospitals.
2023	[11]	Intuitionistic fuzzy multi-criteria decision-making (IFMCDM) methods to determine the most effective hospital for medical waste management. The methodology includes intuitionistic fuzzy weighted averaging (IFWA), IF analytical hierarchy process (IFAHP), IF technique for order preference by similarity to ideal solution (IFTOPSIS), and one-dimensional sensitivity analysis. The most important criteria are qualified personnel, health institution infrastructure, and waste control.

Table 1. Cont.

Public. Year	References	Main Topic
2021	[12]	It investigates landfill sites' evaluation using fuzzy multi-criteria decision making. A novel circular intuitionistic fuzzy MCDM approach is developed, extending the use of circular intuitionistic fuzzy sets (C-IFS) and proposing defuzzification functions. The proposed method aims to guide future C-IFS MCDM methodologies.
2023	[13]	It presents the IF-EM-SWARA-TOPSIS technique, which assesses HCW based on social, environmental, economic, and technical criteria in an intuitionistic fuzzy environment. The technique uses an entropy measure to evaluate objective weights of criteria, while the distance measure constructs a technique for order performance by similarity to ideal solution (TOPSIS). The stepwise weight assessment ratio analysis (SWARA) technique obtains subjective weights for criteria. The sustainability and stability of the proposed framework are demonstrated through comparative studies and sensitivity assessments.
2016	[14]	A two-level hierarchical multicriteria decision model for HCW disposal method selection. It assesses methods against intuitionistic fuzzy preference relations and real values, using cross-ratio-based values. The model uses a weighted geometric operator, a cross-ratio-based bipolar 0.1–0.9 scale, and a two-level hierarchical structure to handle multicriteria decision problems with intuitionistic preference relations. The framework is applied to HCW management DM to demonstrate feasibility and effectiveness.
2020	[15]	Evaluation based on distance from average solution framework using parametric divergence measures and IF sets. The framework evaluates four HCW disposal alternatives, including incineration, steam sterilization, microwave, and landfill disposal. The framework's validity is demonstrated through comparisons with existing approaches.
2017	[16]	A systematic, integrated MCDM approach based on the TOPSIS method in an intuitionistic fuzzy (IF) environment. The group decision-making approach minimizes bias and manages uncertainties. A real case application from Turkey illustrates the use of this methodology.
2020	[17]	The framework investigates different disposal methods based on social acceptance, technology, environmental protection, cost, noise, and health risk. The hesitant MCDM method is used to select the best treatment method. The HF-SOWIA and HF-MOOSRA novel methods are proposed. The evaluation results show autoclaving is the best alternative for HCW disposal treatment. Sensitivity analysis is conducted to observe the difference in alternative ranking when subjective and objective weights change.
2022	[18]	Proposition of a novel strategy using IF-MOORA in spherical fuzzy sets (SFSs) to counterbalance FMEA's disadvantages. The method identifies barriers using FMEA, assigns risk factors, and prioritizes them in the SF area. The proposed methodology is compared to IF-MOORA and TOPSIS for reliability and correlation.
2021	[19]	Pythagorean fuzzy-based decision-making methodology is developed to rank HCW alternatives and develop weight-determining procedures. A case study demonstrates the effectiveness of the proposed framework, with autoclaving technology being the most suitable alternative. A sensitivity analysis and comparative study highlight the methodology's strength and validity.
2021	[20]	Proposition of a novel approach to selecting the optimal landfill for medical waste disposal using MCDM methods and SFS. The criteria include environmental, economic, and social factors. The weights of the criteria were computed using SFSWARA, and alternatives were analyzed and ranked using SFWASPAS. The results were compared with the IF-SWARA-WASPAS method, showing more reliability and accuracy.
2023	[21]	IF-MCDM model using the CRITIC method for objective criterion weights and the WASPAS method for ranking alternatives. The methodology is developed in single and interval-valued spherical fuzzy environments, allowing users to model membership, non-membership, and hesitancy parameters independently.
2022	[22]	Proposition of a new MCDM approach to compute criteria weights, DMs' weights, and alternative ranking methods for assessing and selecting the best HCW treatment technology. The model uses IF variables and extends weighting and ranking methods for uncertain conditions. Results show the first alternative and DM have a high preference, and the final ranking results are reliable with changing criteria weights.

Table 1. Cont.

Public. Year	References	Main Topic
2023	[23]	A robust integrated methodology using SWARA and COPRAS techniques is developed. The methodology is applied to a large-scale international hospital chain, revealing that storage conditions are the most important criterion for selecting the best disposal and logistics firm. The implications provide managerial insights and decision aids to improve the sustainability of the healthcare industry.
2023	[24]	Optimizing treatment procedures involves complex multi-criteria decision making. This study extends the DNMA approach with interval-valued intuitionistic fuzzy sets (IVIFSs) to address this problem. The proposed approach efficiently tackles HCW treatment selection, with steam sterilization being the optimal choice. The prioritization options obtained are reliable and suitable.
2023	[25]	It presents an integrated MAGDM methodology for selecting the most capable organization to manage HCW using IVFFS data. The study combines PROMETHEE II and SWARA methods, estimating attribute weights and determining preference order of options. Results demonstrate the bio-chemistry lab as the best management option in terms of stability and reliability.
2023	[26]	The framework uses MCDM to identify the best and worst medical waste management techniques. Results show that incineration, microwave, pyrolysis, autoclave chemical, vaporized hydrogen peroxide, dry heat, ozone, and ultraviolet light were the most effective methods for disposing of medical waste during the pandemic. Ozone was identified as the most suitable technique for the circular economy of HCW. Integration of MCDM with other techniques including AHP, LDFN-FDOSM, and ANN to generate more robust results.
2021	[27]	A new MCDM approach is introduced under IF conditions to evaluate the importance of criteria and decision-makers. The approach uses an integrated weighting criteria method (OWA), aggregating subjective and objective criterion weights, and a ranking approach with ideal and anti-ideal distance-based methods. The IF condition ensures high performance in making appropriate decisions.
2021	[28]	This IF TOPSIS-Sort approach achieves classification into low-, moderate-, and high-exposure classes, providing insights for planning and policy formulation. Comparative analysis with other distance-based MCS methods revealed that the IF TOPSIS-Sort is pessimistic and may underestimate assignments, and is potentially counterintuitive in public health applications. The novel IF TOPSIS-Sort is suitable for many domain-sorting applications.
2021	[29]	This study presents a novel framework for assessing socioeconomic phenomena using survey data, focusing on complex phenomena like quality of life and services. The intuitionistic fuzzy TOPSIS (IF-TOPSIS) method is proposed, considering the uncertainty in object assessments and the use of continuous data from public statistics. This approach addresses the challenges of traditional multicriteria methods in evaluating these complex phenomena.

3. Preliminaries

Since real-world HCW management issues are, by their very nature, multi-objective, we use intuitionistic fuzzy sets (IFS). The use of IFS guarantees the coverage of all participating criteria in the process and the inclusion of categorical data (linguistic expert responses) when needed. In support of that, many associated methodologies have been developed lately such as interval-valued [26], IF-DEMATEL [27], Pythagorean IFS [30], etc. to address the HCW-related problems. A membership function and a non-membership function are used to represent an IFS of this type. This feature makes IFS superior compared to conventional fuzzy systems since it enables them to integrate reluctance and uncertainty at the same time. The fundamental definitions of IFS are provided in this section, while subsequent subsections provide thorough descriptions of the particular IFS approaches used in this study.

3.1. IF Sets and Relevant Terminology

Definition 1 ([30]). *Assuming a nonempty set X , and the existence of mapping as shown in the following function definition:*

$$\begin{aligned}
 f_A : X &\rightarrow [0, 1] \times [0, 1] \\
 x &\mapsto (\mu_A(x), v_A(x))
 \end{aligned}
 \tag{1}$$

where the IFS of X , designated as A , is activated by f_A with $A = \{ \langle x, \mu_A(x), v_A(x) \rangle \mid x \in X \}$. Furthermore, let $\mu_A(x)$ be the membership function, displaying the quantity of membership of x to the IFS A , and $v_A(x)$ be the non-membership quantity which both indicate the level of membership of x to the IFS A , presuming the restriction that $0 \leq \mu_A(x) + v_A(x) \leq 1$.

Definition 2 ([30]). Let $\pi(x)$ be the uncertainty degree with $\pi(x) = 1 - \mu_A(x) - v_A(x)$ that introduces the hesitation principle so that IFSs are to be [resented as tuples of three elements $(\mu_A(x), v_A(x), \pi(x))$.

Definition 3 ([30,31]). For an IF number $\alpha = (\mu_A(x), v_A(x))$, we now define the Score and the Accuracy functions given by the following equations. Let us note that this initial definition of Score and Accuracy has been updated (update is indicated by $*$) and shown in Equation (2b):

$$\begin{aligned}
 S(a) &= \mu - v \quad \text{where } S(\alpha) \in [-1, 1] \\
 H(a) &= \mu + v \quad \text{where } H(\alpha) \in [-0, 1]
 \end{aligned}
 \tag{2a}$$

$$\begin{aligned}
 S^*(a) &= \frac{S(\alpha)+1}{2} \quad \text{where } S^*(\alpha) \in [0, 1] \\
 H^*(a) &= \frac{\mu+v}{2} \quad \text{where } H^*(\alpha) \in [-0, 1]
 \end{aligned}
 \tag{2b}$$

Definition 4. Let $Q = \{ \alpha_i = (\mu_i, v_i) \mid i = 1 \dots n \}$ be a set of IF numbers. Moreover, let $w = (w_1, w_2, \dots, w_n)^T$ be the ordered set of their weights assuming an imposed multi-objective and multi-criteria decision-making methodology. For the set Q , we call IFWAA $_w(Q)$ the IF weighted average operator which is illustrated below:

$$\text{IFWAA}_w(Q) = \bigoplus_{i=1}^n w_i \alpha_i = \left(1 - \prod_{i=1}^n (1 - \mu_i)^{w_i}, \prod_{i=1}^n v_i^{w_i} \right)
 \tag{3}$$

3.2. Intuitionistic Fuzzy MCDM Methodology

Many components in an MCDM process cannot be precisely evaluated due to the heterogeneity of information and the inherent fuzziness in defining criteria weights by stakeholders. As an alternative, a significant number of decision-makers and stakeholders express their evaluations and assessments using linguistic phrases. Table 2 below presents the most commonly used rating scale, when evaluating events in fuzzy theory. This rating scale is also commonly used in evaluating and/or rating criteria in real-life questionnaire and focus group responses. Similarly, in Table 3, we display the most frequent ratings for the expertise level of each evaluator in the criteria evaluation process.

Table 2. IF rating terminology, equivalent notation, and equivalent IF numbers [30].

Linguistic Terms	Rate Notation	Equivalent IFN
Extremely Good Efficiency (EGE)	s_9	(1.00, 0.00, 0.00)
Very Very Good Efficiency (VVGE)	s_8	(0.95, 0.05, 0.05)
Very Good Efficiency (VGE)	s_7	(0.85, 0.10, 0.05)
Good Efficiency (GE)	s_6	(0.75, 0.20, 0.05)
Medium Efficiency (ME)	s_5	(0.65, 0.30, 0.05)
Fair Efficiency (FE)	s_4	(0.55, 0.40, 0.05)
Medium Bad Efficiency (MBE)	s_3	(0.40, 0.50, 0.10)
Bad Efficiency (BE)	s_2	(0.30, 0.60, 0.10)
Very Bad Efficiency (VBE)	s_1	(0.20, 0.70, 0.10)
Extremely Bad Efficiency (EBE)	s_0	(0.10, 0.80, 0.10)

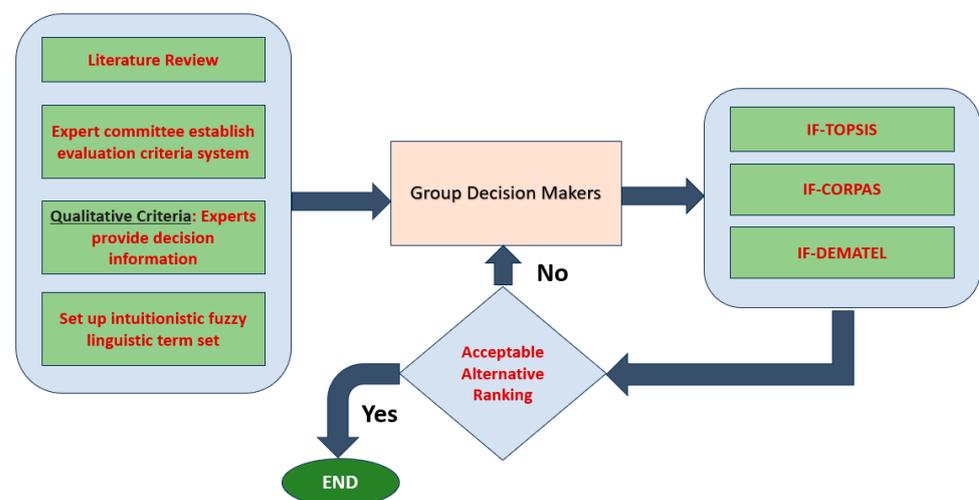
Table 3. Fuzzy linguistic terms for the levels of significance of experts and equivalent IFNs.

Linguistic Terms	Equivalent IFN
Extremely Significant (ES)	(1.00, 0.00, 0.00)
Very Significant (VS)	(0.90, 0.05, 0.05)
Significant (S)	(0.70, 0.20, 0.10)
Moderate (M)	(0.60, 0.30, 0.10)
Insignificant (I)	(0.40, 0.50, 0.10)
Very Insignificant (VI)	(0.30, 0.60, 0.10)
Extremely Insignificant (EI)	(0.10, 0.80, 0.10)

This work addresses the challenge of selecting the optimal alternative solution for healthcare waste (HCW) treatment by introducing a decision-making technique along with an illustrative use-case solution. HCW and other healthcare professionals, as well as municipal staff members focusing on public safety and regional planning, are considered experts in the field. We are particularly interested in the treatment of HCW, as it has the potential to significantly impact municipality operators, local and regional couriers, small- and medium-sized enterprises (SMEs), and the broader society.

Any produced DSS must facilitate the IFWAA operator of Equation (3) to implement an ensemble of IF methodologies. In this research work, we utilize this operator in conjunction with the IF-TOPSIS and IF-CORPAS methods [32]. The linguistic terms are converted to IF- numbers. This is predicated on the existence of plausible employment scenarios for HCW. The overall methodology begins with an extensive literature review to identify all the criteria involved in examining and evaluating the best possible solution for HCW treatment. This list of criteria, along with the metrics and performance indicators needed for evaluating the DSS under construction, is finalized through verification by field experts. Simultaneously, we establish an intuitionistic fuzzy linguistic term set for all criteria to obtain expert responses, thus organizing the process of expert evaluation.

Given a set of criteria for evaluation and a set of alternative solutions, the relative importance decision matrix for the criteria ratings is formed. It is important to note that, for each alternative solution and each overall scenario of development, different matrices must be created and computed. Moreover, the model is immune to scalability issues since the number of criteria used for the ranking process does not affect the outcome, thus model resilience is preserved. The selected methodology builds an ensemble DSS holistically using three models for criteria evaluation and ranking. Each model, when run, indicates which alternative solution scenario, out of all the candidates, has the best potential. We first give a detailed explanation of each IF methodology, and then we illustrate the logical architecture of this methodology in Figure 2.

**Figure 2.** The logical architecture of the DSS based on an ensemble of IF models.

3.3. The IFTOPSIS Model [33]

Input:

Given a set of experts in the HCW management and treatment technology research, denoted as k , let $\vec{W} = \{\vec{w}_1, \vec{w}_2, \dots, \vec{w}_k\}$ with $\sum_{d=1}^k w_d = 1$ be the weights vector of k indicating the importance of their opinion. Moreover, let $C = \{1, 2, \dots, n\}$ be the set of criteria under the process of evaluation and ranking. For this set, let us also denote this with $W_C = \{w_{1c}, w_{2c}, \dots, w_{nc}\}$ and $\sum_{i=1}^n w_{ic} = 1$.

Step 1: Initially the discrete experts linguistically rate the criteria C using the rating scale of Table 1. Immediately afterwards, we calculate the IF decision matrix $A[k \times n] = \{\alpha_{i,j} | i = 1 \dots k, j = 1 \dots n\}$ with $\alpha_{i,j} = (\mu_{\alpha_{ij}}, v_{\alpha_{ij}}, \pi_{\alpha_{ij}})$ to be the corresponding IFN number and $\pi_{i,j} = (1 - \mu_{\alpha_{ij}} - v_{\alpha_{ij}})$.

Step 2: Based on the results of Step 1, we compute the aggregated IF decision matrix \hat{A} . This is achieved by calculating the corresponding IFWAA operators. In the computation process of \hat{A} , we basically compute each matrix element using the two equations below:

$$\begin{aligned} \hat{A}_{[k \times n]} &= IFWAA_w(p_{1,1}, p_{1,2}, \dots, p_{2,1} \dots p_{i,j} \dots p_{k,n}) \\ &= \left(1 - \prod_{i=1}^k (1 - \mu_{p_i})^{\varphi_i}, \prod_{i=1}^k (1 - v_{p_i})^{\varphi_i}, \prod_{i=1}^k (1 - \mu_{p_i})^{w_i} - \prod_{i=1}^k (1 - \mu_{p_i})^{\varphi_i} \right) \end{aligned} \quad (4)$$

where

$$\varphi_i = \frac{\left(\mu_i + \pi_i \left(\frac{\mu_i}{\mu_i + v_i} \right) \right)}{\sum_{i=1}^k \left(\mu_i + \pi_i \left(\frac{\mu_i}{\mu_i + v_i} \right) \right)} \quad (5)$$

Step 3: In this step, we compute the ideal solutions denoted as τ_1 and τ_2 , respectively. Using τ_1 (beneficial) and τ_2 (non-beneficial). We compute the IF positive ideal solution (IFPIS) and the IF negative ideal solution (IFNIS), respectively (which are denoted as θ_1 and θ_2), according to the following equations:

$$\tilde{r}_{ij} = w_j \cdot p_{i,j} \quad | \quad i = 1 \dots k, \quad j = 1 \dots n \quad (6)$$

$$\theta_1 = \left\{ \left(\left(\max_i \tilde{r}_{ij} \right) | j \in \tau_1 \right), \left(\left(\min_i \tilde{r}_{ij} \right) | j \in \tau_2 \right) | i = 1 \dots k \right\} = \{r_1^+, r_2^+, \dots, r_n^+\} \quad (7a)$$

$$\theta_2 = \left\{ \left(\left(\min_i \tilde{r}_{ij} \right) | j \in \tau_1 \right), \left(\left(\max_i \tilde{r}_{ij} \right) | j \in \tau_2 \right) | i = 1 \dots k \right\} = \{r_1^-, r_2^-, \dots, r_n^-\} \quad (7b)$$

Step 4: Using the values θ_1 and θ_2 above, we now calculate the distances from the positive and negative ideal solution IFPIS and IFNIS, respectively. These are calculated in the following equations, respectively, using the notion of the IF normalized Euclidean distance:

$$\delta_i^+ = \sqrt{\sum_{j=1}^n (\tilde{r}_{ij} - r_j^+)^2} \quad (i = 1, 2, \dots, k) \quad \delta_i^- = \sqrt{\sum_{j=1}^n (\tilde{r}_{ij} - r_j^-)^2} \quad (i = 1, 2, \dots, k) \quad (8)$$

Step 5: Using the two equations above, we calculate the closeness coefficient values (CCVs). Note that, for each criterion C_i , the corresponding CCV, which, from now on, is denoted as \hat{C}_i , is found by the following equation:

$$\hat{C}_i = \frac{\delta_i^-}{\delta_i^- + \delta_i^+} \quad \text{where } 0 \leq \hat{C}_i \leq 1 \text{ and } i = 1, 2, \dots, n \quad (9)$$

Step 6: Finally, we compute the criteria weights using the CCV where we presume that the total of the weights is equal to 1. In the opposite case, we repeat the normalization process to achieve the aforementioned summation.

3.4. The IF-COPRAS Model [34]

Input:

The aggregated IF decision matrix \hat{A} calculated in Equation (4) and in step 2 of the IF-TOPSIS model process is as follows

Step 1: We first calculate the weighted normalized values for each matrix cell of \hat{A} . In order to do that, we initially calculate the value \bar{x}_{im} . This is computed either for the normalized case by Equation (10) or for the weighted normalized case by Equation (11) as shown below:

$$\bar{x}_{im} = \frac{x_{im}}{\sum_{i=1}^n x_{im}}, \quad (10)$$

$$\bar{x}_{im} = \frac{w_m * (x_{im})}{\sum_{i=1}^n x_{im}} \quad (11)$$

Step 2: Calculate the total weighted normalized value for each expertly recommended alternative in relation to the beneficial (BC) and non-beneficial (NBC) criteria, respectively. The following formulae illustrate this:

$\delta_p^+ = \sum_{m \in BC} \bar{x}_{im}$ for the beneficial criteria and $\delta_p^- = \sum_{m \in NBC} \bar{x}_{im}$ for the non-beneficial criteria.

Step 3: From the aforementioned δ_p^+ and δ_p^- values, we calculate the relative importance for each expertly recommended alternative solution w_p . In addition, using the value of w_p , we then compute the utility degree α_p as follows:

$$w_p = \delta_p^+ + \frac{\sum_{p=1}^n \delta_p^-}{\delta_p^- \sum_{p=1}^n \frac{1}{\delta_p^-}} \quad (12)$$

$$\alpha_p = \left[\frac{w_p}{w_{max}} \right] \times 100 \quad (13)$$

Step 4: Either the value of w_p or the value of α_p can equally help determine the ranking of the expertly recommended alternative solutions.

3.5. Algorithm Intuitionistic Fuzzy DEMATEL [35]

Step 1: Construct a direct-relation matrix where the entries are based on the obtained linguistic scale data.

Ratings given by k -th experts on the interrelationship between criteria are collected and used to construct a direct-relation matrix where entries are rating scales.

Step 2: Construct a direct-relation matrix where entries are IFNs.

The IFNs defined in Table 3 are substituted according to their linguistic terms into the direct-relation matrix.

$$A^k = [a_{ij}^k] = \begin{bmatrix} a_{11}^k & a_{12}^k & \dots & a_{1n}^k \\ a_{21}^k & a_{22}^k & \dots & a_{2n}^k \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}^k & a_{m2}^k & \dots & a_{mn}^k \end{bmatrix} \quad (14)$$

where $a_{ij}^k = [\mu_{ij}^k, \nu_{ij}^k, \pi_{ij}^k]$, $i = 1, 2, \dots, m, j = 1, 2, \dots, n$ is the rating for each one of the experts that participate on the criteria interrelationship evaluation process.

Step 3: Expert weight determination.

According to their level of expertise, the evaluators are assigned specific weights (levels of expertise). This is in accordance with their job experience and knowledge in the field of HCW and medical waste management. The determination of the weight for each expert is given in Equation (15) and it is based on the study of [33]. More specifically, if $a_{ij}^k = [\mu_{ij}^k, \nu_{ij}^k, \pi_{ij}^k]$, $i = 1, 2, \dots, m, j = 1, 2, \dots, n$, the rating of the k th expert weight φ_k is:

$$\varphi_k = \frac{\left(\mu_k + \pi_k \left(\frac{\mu_k}{\mu_k + v_k}\right)\right)}{\sum_{k=1}^l \left(\mu_k + \pi_k \left(\frac{\mu_k}{\mu_k + v_k}\right)\right)} \quad \text{where} \quad \sum_{k=1}^l \varphi_k = 1 \quad (15)$$

Step 4: Find the aggregated intuitionistic fuzzy decision matrix.

To construct the aggregated intuitionistic fuzzy decision matrix, the intuitionistic fuzzy weighted average (IFWA) operator is used to fuse the weights of all decision-makers into one evaluation matrix of decision-makers:

$$\begin{aligned} \hat{A}_{[k \times n]} &= IFWAA_w(\alpha_{1,1}, \alpha_{1,2}, \dots, \alpha_{2,1}, \dots, \alpha_{i,j}, \dots, \alpha_{k,n}) \\ &= \left(1 - \prod_{i=1}^k (1 - \mu_{\alpha_i})^{\varphi_i}, \prod_{i=1}^k (1 - v_{\alpha_i})^{\varphi_i}, \prod_{i=1}^k (1 - \mu_{\alpha_i})^{w_j} - \prod_{i=1}^k (1 - \mu_{\alpha_i})^{\varphi_i}\right) \end{aligned} \quad (16)$$

Step 5: Transform the aggregated matrix into its numeric equivalent according to [34]. Then, the crisp values are computed for the total relationship matrix using the following equation:

$$p(x) = \frac{\mu - v + 1}{2} \quad (17)$$

using the same terminology for the membership and non-membership as in Equation (2a) and in Equation (2b).

Step 6: Construct the normalized direct-relation matrix X using the crisp matrix A and the constant k , $X = k \times A$ where the equation is as follows:

$$k = \min\left(\frac{1}{\max\sum_{j=1}^n a_{ij}}, \frac{1}{\max\sum_{i=1}^n a_{ij}}\right) \quad (18)$$

Step 7: Construct the total-relation matrix T from the following equation:

$$T = X(I - X)^{-1} \quad (19)$$

with I to be the identity matrix.

Step 8: Determine the sum of rows and the sum of columns from the matrix T . The sum of the rows and the sum of the columns (denoted by D and R , respectively) can be calculated by Equations (20) and (21):

$$R = \left[\sum_{i=1}^n t_{ij}\right]_{1 \times n} = [t_j]_{1 \times n} \quad (20)$$

$$D = \left[\sum_{j=1}^n t_{ij}\right]_{n \times 1} = [t_i]_{n \times 1} \quad (21)$$

Step 9: Find the quantities $(D + R)$ and $(D - R)$, respectively. With the calculation of $(D + R)$, we can obtain the Cartesian co-ordinate values with respect to both axes.

Step 10: Draw the causal diagram.

Once the values of $(D + R)$ and $(D - R)$ are determined, then the two co-ordinates of each one of the criteria are determined and they can be mapped on the plane. The values of $(D + R)$ represent the *Prominence Vector*. Using this vector, we can visualize the importance of the criteria. On the other hand, the values of $(D - R)$ represent the *Relation Vector*. Depending on the values of $(D - R)$, we can then classify the criteria either in the *Cause Group* or in the *Effect Group* if the values of the Relation Vector are positive or negative, respectively.

Step 11: The construction of the network relationship map (NRM) using the threshold is as follows: the threshold value is computed, finding the mean of all cells of the total-relation matrix.

4. Applying the IF-Models of IFTOPSIS, IFCORPAS, and IFDEMATEL for the Thessaly Case Study: Detailed Analysis and Results

Optimizing the use of effective healthcare waste (HCW) treatment methods is crucial for promoting a sustainable and environmentally friendly urban environment. Concurrently, effective HCW management has the potential to generate energy through processes like anaerobic digestion and incineration. This promotes the production of sustainable energy while also helping to reduce waste. Therefore, in order to maximize the benefits of HCW management, competent authorities and regional decision-makers are very interested in choosing the most effective treatment alternative.

Our research focuses on identifying the best alternative methodologies for HCW treatment based on various related criteria and aspects in the Thessaly region of Greece. Thessaly, one of the thirteen regions of Greece, is located in the central part of the country and is known for its diverse landscapes, including mountains, plains, and coastal areas. Within Thessaly, several cities and towns, including Larissa (the regional capital), Volos, and Trikala, house hospitals and healthcare facilities to serve the local population. Medical or clinical waste produced from these facilities, including needles, syringes, bandages, expired medicines, and other biomedical materials, is predominantly non-hazardous, although the existence of hazardous medical waste remains significant. Proper HCW management is crucial in order to prevent the spread of diseases and protect both healthcare workers and the general public.

The volume of HCW produced is closely related to population density, the number of healthcare facilities, the types of medical services provided, and healthcare practices in the region. As depicted in the thematic map in Figure 3, Larissa has the greatest concentration of facilities, with three other smaller cities contributing with medium-sized hospital facilities. Healthcare waste management in Thessaly adheres to national regulations and guidelines, outlining proper segregation, collection, treatment, and disposal methods for HCW. Common methods include incineration, autoclaving (sterilization), and, sometimes, landfilling for non-hazardous biomedical waste. Given the importance of environmental sustainability, efforts may also be in place to promote eco-friendly HCW treatment practices, such as waste-to-energy technologies or the recycling of certain medical materials.

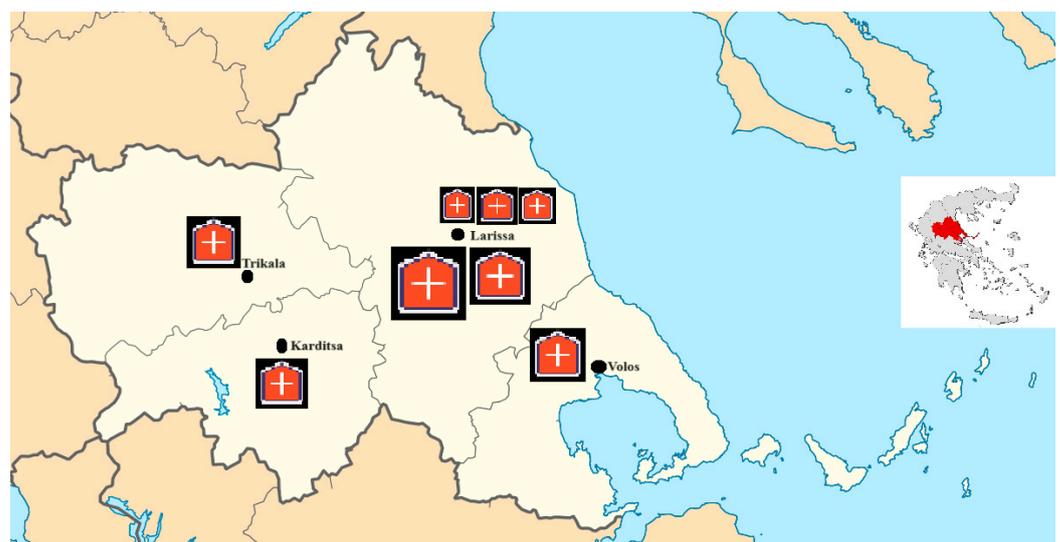


Figure 3. Thematic map of the HCW locations for the Thessaly region, Greece.

The following actions are necessary to address the problem of determining the most practical and effective waste treatment for HCW in a large area with dispersed healthcare facilities, like Thessaly, Greece. The steps involved in this process include: (a) selecting the most relevant impact factors (criteria); (b) involving experts to evaluate and rank the importance of these factors/criteria; (c) selecting the most pertinent treatment alternatives

based again on expert opinions and the regional priorities; and (d) compiling the responses from all decision-makers to establish a hierarchy of the criteria and compare the significance of the criteria for each proposed solution.

Various indicators, including environmental and economic costs, sensitivity to the environment, and social aspects, demonstrate that the introduction of organized infrastructures and facilities, along with integrated HCW treatment methodologies, may offer solutions to numerous challenges in hazardous material transportation, management, and treatment. To address the complex problem of choosing the best methodology or creating a comprehensive policy for HCW treatment, multiple IF methodologies can be integrated. As seen in Table 4, we present 17 criteria grouped into six main categories: environmental, economic, social, organizational, waste-related, and legislation. The selection of the criteria is based on relevant literature, the professional judgment of hospital staff, capable authorities, and experts in the field of hazardous material treatment facilities:

Table 4. Categories of aspects, criteria, and justification of usage.

Criteria ID	Aspect	Criteria Name	Justification
C ₁	Environmental	Hazard/risk potential	Proper waste management strategy is needed to ensure avoidance of any risk factors that affect public health [35,36].
C ₂		Distance of storing facility in relation to society	Regional society avoids having hazardous-material-storing facilities nearby residential areas (Not In My Back Yard (NIMBY) phenomenon) [37,38].
C ₃		Segregation, categorization, and transportation of HCW	The type of treatment, as well as the transportation of hazardous medical waste, is of great consideration [39–41].
C ₄		Occupational health and safety	Investigation of health risks to staff from various hazards and suggestion of control measures to prevent recurrence of accidents [22,42]
C ₅		Water and residue disposal and emission control	Control incineration of HCW residues via thermal treatment and improve volatilization to minimize the effects from the residue disposal in HCW treatment [43–46].
C ₆	Economic	Cost of the waste treatment methodology	Waste management planning to ensure socio-economic and environmental sustainability [47].
C ₇		Energy and other resource utilization	Beneficial and effective biomedical waste treatment technologies generate byproducts that can be further utilized as useful inputs in other industries, reinforcing the circular economy concept [48–50].
C ₈	Social	Qualified personnel availability	The management of HCW involves a substantial amount of effort by healthcare professionals who are involved in daily care and other healthcare tasks [51,52]
C ₉		Sensitivity to the environment, existence of the NIMBY phenomenon	Because of NIMBYism, waste facilities have to be located farther away from inhabited areas, which results in significant cost savings as trash management efficiency rises [53,54].
C ₁₀	Organizational	HCW plan management substance and execution	Emphasize the role that medical waste management plays in creating a sustainable, environmentally friendly HCW setting [55].
C ₁₁		Supply chain management and finance	A sustainable model for medical waste supply chain network is needed [56].
C ₁₂		Health institution resources and infrastructure	Exploit the learnings from COVID-19 to identify any potential opportunities in post-pandemic waste infrastructure [57].
C ₁₃	Waste Related	HCW type and hazard	Extra vigilance is necessary in order to reduce the danger of injury, cross-contamination, and infection; as a result, waste management professionals and healthcare personnel must adhere to the legal safety precautions [58].
C ₁₄		HCW material	Material may affect generation of energy but, at the same time, may be dangerous for public health [59].
C ₁₅		HCW treatment monitoring and control	Managing medical waste has become crucial, given its potential environmental and public health risks [60].

Table 4. Cont.

Criteria ID	Aspect	Criteria Name	Justification
C ₁₆	Authorities and Legislation	Municipality services, competence, and treatment facility functions	Establishing a sustainable network for the handling of HCW under the supervision of appropriate authorities and municipal oversight [61]
C ₁₇		Personnel competences in the treating facilities	Personnel inability to properly handle the hazardous material leads to disastrous accidents and many risks for public health [62,63]

In order to maximize the environmental, economic, and social sustainability of the regional societies, public safety and health, and regional development, we employ the IFTOPSIS, IFCORPAS, and IFDEMATEL IF methodologies in this research to choose the best alternative HCW treatment methodology. Four HCW treatment options are available as stated:

- **Incineration** is a method to treat medical waste, including hazardous materials and sharps. The process involves segregation and collection, receiving and inspection, loading the incinerator, and burning the waste at high temperatures. At the same time, air pollution control devices are used to capture and neutralize harmful emissions. After incineration, the remaining ash is inspected and disposed of in designated landfills or undergoes further treatment if necessary. We denote this alternative solution as ALT1.
- **HCW Storage** is a methodology that includes a series of steps: Initially, HCW is segregated into categories like sharps, infectious waste, pharmaceutical waste, and chemical waste, and placed in designated containers. Containers must be sturdy and leak-proof to prevent leaks. Proper labeling and documentation are essential for proper tracking and disposal. Medical waste is stored on-site in secure areas, with storage times regulated by local, state, and national regulations. Refrigeration is necessary for certain wastes, such as biological samples and certain pharmaceuticals. Healthcare staff are trained in proper protocols, and medical waste is prepared for transportation to treatment facilities. Facilities have emergency response and contingency plans in place to mitigate risks. Regulatory compliance is essential, with regular inspections and adherence to guidelines ensuring healthcare facilities maintain a safe environment for patients and staff. We denote this alternative solution as ALT2.
- **HCW Recycling** is a complex process that converts HCW material into reusable products, reducing the environmental impact and strain on natural resources. It involves the identification and segregation of waste, decontamination to remove harmful substances, and shredded or crushed materials for transportation and processing. Specialized facilities handle processed HCW using advanced technologies. Methods include mechanical recycling, chemical recycling, and energy recovery. Quality control checks ensure materials meet required standards, especially for medical devices or sensitive applications. Regulatory compliance is essential throughout the recycling process to ensure safety and environmental standards are met. However, there are limited methodologies for treating medical waste, particularly for biohazardous materials. We denote this alternative solution as ALT3.
- **HCW Segregation and Landfilling** is a methodology that involves identifying waste types, using color-coded containers, and training healthcare staff on proper segregation. Segregated waste is stored securely in containers, labeled with information about the type, date of generation, and facility name. On-site storage is also used to prevent environmental contamination. Packaging is carried out using double-bagged or leak-proof containers, while manifests document the type and quantity of waste being transported. Landfills are lined with protective liners and monitoring systems to prevent the leaching of hazardous materials. The waste is compacted to reduce volume and minimize environmental impact. Covering is carried out daily to minimize odor

and disease transmission. Regulatory compliance ensures the safe management of medical waste and public health. We call this alternative scenario ALT4.

Under the following scenarios, experts assess the alternatives: (a) public safety; (b) environmental safety, efficiency, and pollution prevention; and (c) risk assessment for the use of HCW treatment. It is also important to note that safety cannot be quantified, meaning it cannot be assigned a weight value. Consequently, even with interactive modeling approaches, it is impossible to compare the two scenarios. The categorical phrases that the experts used to compare the 17 criteria in Table 4 with the rating scale are listed in Table 5:

Table 5. Criteria evaluation terms and their corresponding IFN.

Linguistic Term	Equivalent IFN Triplet
Very Important (VI)	(0.88, 0.08, 0.04)
Important (I)	(0.75, 0.20, 0.05)
Medium (M)	(0.50, 0.45, 0.05)
Unimportant (UI)	(0.35, 0.60, 0.05)
Very Unimportant (VUI)	(0.08, 0.88, 0.04)

4.1. IFTOPSIS Analysis

Expert evaluators $E_1, E_2, E_3,$ and E_4 responded, evaluating the pertinent criteria. Their findings in terms of criteria importance rates are presented in Table 3. It is important to emphasize that E_1, E_2 are competent authorities' officials, whilst the other two are hospital-focused personnel in different hospitals of the region. Additionally, we assume that each expert response is equally important, with an importance weight of 0.250.

Table 6 displays the linguistic responses from the expert evaluators $E_1, E_2, E_3,$ and E_4 according to the criteria importance rates. We must also emphasize that E_1, E_2 are competent authorities' officials and the other two are hospital-focused personnel. Furthermore, we assume a 0.250 importance weight for each expert response, meaning that they are all equally important.

Table 6. Coded linguistic expert responses.

Crit. Code	Crit. Category	E_1	E_2	E_3	E_4
C_1	Environmental	M	M	M	I
C_2		I	M	M	M
C_3		I	M	M	M
C_4		VI	I	VI	VI
C_5		M	M	VI	VI
C_6	Economic	VI	I	M	I
C_7		I	I	I	I
C_8	Social	I	M	M	M
C_9		I	I	VI	UI
C_{10}	Organizational	VI	VI	UI	UI
C_{11}		VI	VI	I	M
C_{12}		VI	I	M	M
C_{13}	Waste Related	VI	I	M	M
C_{14}		VI	VI	I	I
C_{15}		M	I	M	I
C_{16}	Authorities and Legislation	VI	VI	I	I
C_{17}		M	I	M	I

The stated expert criteria evaluations and objectives and the aims of the under-consideration alternatives serve as the primary guides in the selection and formulation of assessment criteria. A hierarchical criteria tree could be created, but, since the weights

of the experts’ opinions have equal weight and importance for all respondents, the hierarchical tree may not provide any new information. Furthermore, unlike a multi-criteria analysis, which often uses the results or effects of the activities themselves as assessment criteria, MCDM procedures use the goals and objectives of the experts when these serve as evaluators of criteria. If all pertinent experts/stakeholders are included, these consequences will automatically show in the aims of the experts. Thus, the experts are responsible for providing non-redundant and legibility data.

Equations (4) and (5) of the IF-TOPSIS method drive the calculations. Table 5 shows the outcomes of this process including the membership, non-membership, and the uncertainty elements. It is imperative to acknowledge that these results align with the initial scenario, which pertains to environmental safety, efficiency, and pollution prevention. Two other sets of tables similar to Tables 6 and 7, respectively, have been produced and they are related to the public safety and the risk evaluation for the use of HCW treatment scenarios. However, due to space limitation reasons, they are not included but can be submitted in the supplementary material. In Table 8, for each criterion. We indicate whether it is a beneficial or not beneficial (B/NB), the calculated values columns μ , v , and π from the aggregated intuitionistic fuzzy decision matrix, and the values δ_i^+ and δ_i^- , as well as \hat{C}_i .

Table 7. Coded linguistic responses/valuations of experts for each alternative solution.

	ALT-1				ALT-2				ALT-3				ALT-4			
	E_1	E_2	E_3	E_4												
C_1	VGE	GE	FE	GE	ME	FE	ME	GE	EGE	VVGE	VVGE	VVGE	GE	ME	VVGE	VVGE
C_2	EGE	VGE	FE	GE	ME	ME	VGE	VGE	VGE	VGE	VVGE	VVGE	EGE	EGE	EGE	EGE
C_3	VVGE	VGE	GE	GE	ME	ME	GE	GE	GE	VGE	VGE	EGE	VVGE	VVGE	GE	GE
C_4	EGE	EGE	EGE	VGE	EGE	EGE	EGE	EGE	ME	FE	ME	ME	VGE	VVGE	VVGE	VGE
C_5	EGE	GE	ME	VGE	GE	EGE	EGE	EGE	EGE							
C_6	GE	ME	VVGE	VVGE	ME	FE	VGE	GE	VGE	VGE	VVGE	VVGE	EGE	EGE	VGE	GE
C_7	EGE	EGE	EGE	EGE	ME	FE	GE	GE	GE	VGE	VVGE	GE	EGE	EGE	VVGE	VVGE
C_8	VVGE	VVGE	GE	GE	ME	ME	EGE	EGE	GE	ME	ME	VGE	EGE	VVGE	VVGE	VGE
C_9	VGE	VVGE	VVGE	VGE	ME	ME	GE	VGE	VGE	VVGE	GE	GE	ME	GE	VGE	VGE
C_{10}	EGE	EGE	EGE	EGE	ME	ME	VGE	VGE	VGE	ME	ME	GE	VGE	GE	EGE	EGE
C_{11}	EGE	EGE	VGE	GE	GE	VGE	VGE	GE	VGE	GE	GE	VGE	ME	FE	ME	GE
C_{12}	EGE	EGE	VVGE	VVGE	GE	GE	VGE	VVGE	EGE	EGE	ME	ME	ME	ME	VGE	VGE
C_{13}	EGE	VVGE	VVGE	VGE	GE	GE	VGE	VVGE	VGE	GE	FE	GE	ME	ME	GE	GE
C_{14}	EGE	EGE	ME	ME	ME	FE	ME	GE	EGE	VGE	FE	GE	EGE	EGE	EGE	EGE
C_{15}	EGE	VVGE	VVGE	VGE	GE	GE	VGE	VGE	VVGE	VGE	GE	GE	EGE	EGE	EGE	EGE
C_{16}	ME	GE	VGE	VGE	ME	FE	ME	GE	EGE	EGE	EGE	VGE	ME	FE	VGE	GE
C_{17}	VGE	GE	EGE	EGE	VGE	GE	GE	GE	EGE	EGE	EGE	EGE	ME	FE	GE	GE

Table 8. Intuitionistic fuzzy decision matrix δ_i^+ , δ_i^- and \hat{C}_i (IFTOPSIS)—Scenario (a).

Criteria ID	B/NB	μ	v	π	δ_i^+	δ_i^-	\hat{C}_i
C_1	NB	0.811	0.132	0.057	0.140	0.934	0.916
C_2	B	0.742	0.194	0.064	0.113	0.947	0.927
C_3	B	0.764	0.176	0.06	0.042	1.004	0.955
C_4	B	0.857	0.102	0.041	0.196	0.912	0.886
C_5	NB	0.699	0.236	0.065	0.217	0.907	0.872
C_6	B	0.684	0.252	0.064	0.165	0.924	0.902
C_7	B	0.723	0.216	0.061	0.109	0.949	0.942
C_8	B	0.768	0.175	0.057	0.086	0.961	0.950
C_9	B	0.788	0.153	0.059	0.354	0.917	0.766
C_{10}	B	0.587	0.358	0.055	0.150	0.931	0.914
C_{11}	B	0.735	0.207	0.058	0.200	0.912	0.882
C_{12}	B	0.697	0.242	0.061	0.140	0.934	0.921
C_{13}	NB	0.811	0.132	0.057	0.113	0.947	0.936
C_{14}	NB	0.857	0.102	0.041	0.200	0.912	0.877
C_{15}	B	0.699	0.236	0.065	0.042	1.004	0.957
C_{16}	B	0.684	0.252	0.064	0.109	0.949	0.939
C_{17}	B	0.723	0.216	0.061	0.150	0.931	0.906

Using the findings from Table 8, we can compute the IFPIS and IFNIS solutions. Applying the corresponding equations, we find that $\theta_1 = \{0.857, 0.132, 0.011\}$ and

$\theta_2 = \{0.587, 0.242, 0.171\}$, respectively. We then calculate the relative assessment matrix. For each matrix cell, there exists a threshold function σ in order to recognize and break alternatives of equal distance from the ideal solution. As it has been proposed in [64], this threshold is allowed to obtain values between 0.01 and 0.05. The ranking of the four alternatives is shown in Table 9:

Table 9. Relative assessment matrix ranking.

	ALT_1	ALT_2	ALT_3	ALT_4	$\sum q_{ij}$	Ranking
ALT_1	0.000	0.317	0.247	0.189	0.753	1
ALT_2	−0.317	0.000	−0.295	−0.224	−0.836	4
ALT_3	−0.247	0.295	0.000	−0.175	−0.127	3
ALT_4	−0.189	0.224	0.175	0.000	0.210	2

The above ranking indicates that the incineration alternative (ALT_1) solution is the most preferable, with the ALT_4 (segregation and landfill) to follow. The third preferable is ALT_3 , which refers to HCW recycling, with the ALT_2 (HCW storage) being the least preferable.

4.2. IFCORPAS Analysis

The intuitionistic fuzzy decision matrix, which comprises all expert responses for all alternatives and is displayed in Table 5, is the input used by the approach. We then compute the weighted decision matrix in a way that each cell is the aggregated outcome of all 17 criteria and all four alternative solutions. This is achieved by the use of Equations (10) and (11) in order to obtain the normalized value \bar{x}_{im} . The IFCORPAS algorithm's first step includes both procedures. Table 10 displays the acquired results.

Table 10. Normalized and weighted normalized decision matrix for IFCORPAS—Scenario (a).

Criteria ID	B/NB	Normalized				Weighted Normalized			
		ALT_1	ALT_2	ALT_3	ALT_4	ALT_1	ALT_2	ALT_3	ALT_4
C_1	NB	0.274	0.329	0.297	0.253	0.379	0.346	0.359	0.357
C_2	B	0.315	0.362	0.404	0.295	0.345	0.407	0.305	0.331
C_3	B	3.891	4.592	5.004	3.718	0.329	0.297	0.253	0.303
C_4	B	0.658	0.617	0.566	0.583	0.362	0.404	0.295	0.339
C_5	NB	0.387	0.391	0.402	0.338	4.592	5.004	3.718	4.387
C_6	B	0.331	0.329	0.357	0.300	0.617	0.566	0.583	0.547
C_7	B	0.267	0.273	0.255	0.251	0.391	0.402	0.338	0.341
C_8	B	0.372	0.479	0.518	0.354	0.329	0.357	0.300	0.298
C_9	B	0.324	0.317	0.366	0.248	0.273	0.255	0.251	0.256
C_{10}	B	0.311	0.308	0.350	0.284	0.479	0.518	0.354	0.455
C_{11}	B	0.334	0.329	0.289	0.295	0.317	0.366	0.248	0.243
C_{12}	B	0.388	0.374	0.398	0.362	0.308	0.350	0.284	0.282
C_{13}	NB	0.436	0.361	0.378	0.420	0.329	0.289	0.295	0.290
C_{14}	NB	0.367	0.381	0.379	0.346	0.374	0.398	0.362	0.349
C_{15}	B	0.424	0.318	0.345	0.407	0.638	0.658	0.617	0.566
C_{16}	B	0.322	0.274	0.329	0.297	0.461	0.387	0.391	0.402
C_{17}	B	0.431	0.315	0.362	0.404	0.394	0.331	0.329	0.357

We calculate the overall weighted normalized value for Step 2 of the IFCORPAS model in relation to the non-beneficial criteria (NBC) and the beneficial criteria (BC). The last four columns of Table 10 can be immediately utilized to obtain the results for δ_p^+ and δ_p^- , respectively. Lastly, using Step 3, we determine each alternative's relative importance and utility degree, providing us with a ranking of the alternatives. Table 11 displays the acquired results. There is agreement between the IFTOPSIS rankings as seen in Section 4.1.

Table 11. Distances for the ideal solution and ranking of the alternatives in the IFCORPAS model for scenario (a).

	δ_p^+	δ_p^-	a_p	Ranking
<i>ALT</i> ₁	8.416	1.962	1.000	1
<i>ALT</i> ₂	6.492	1.613	0.681	4
<i>ALT</i> ₃	7.127	1.672	0.743	3
<i>ALT</i> ₄	7.437	1.707	0.814	2

4.3. IF-DEMATEL Analysis

We employed the intuitionistic fuzzy DEMATEL method for capturing the complex relationships among the 17 criteria and the four alternative options for HCW treatment. Incorporating the experts’ responses in terms of the comparative linguistic rating of the 17 criteria, as well as their rating of the criteria within each one of the alternatives *ALT*₁ – *ALT*₄, we first calculate the direct-relation matrix where the entries are IFNs. At the next step, we compute the intuitionistic fuzzy decision matrix. The transformation of this matrix into crisp values used the Equation (17) of the IF-DEMATEL methodology. Table 12 shows the crisp values of the intuitionistic fuzzy transform. In this table, we included Step 8 of the methodology, determining the sum of the rows and the sum of the columns to compute R and D from Equation (20) and Equation (21), respectively. Finally, in Table 13, we construct the total-relation matrix T.

Table 12. Relative importance of alternatives and ranking of IF DEMATEL for Scenario (a).

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₁₅	C ₁₆	C ₁₇	D
C ₁	0.5904	0.5737	0.5582	0.6272	0.5709	0.6707	0.5911	0.5737	0.6177	0.6606	0.5709	0.6190	0.5911	0.6278	0.6177	0.6349	0.6606	10.3562
C ₂	0.5916	0.5550	0.5569	0.6247	0.5500	0.6594	0.6196	0.5550	0.6245	0.6698	0.5500	0.6203	0.6196	0.6296	0.6245	0.6428	0.6698	10.3631
C ₃	0.6046	0.5735	0.5636	0.6054	0.5734	0.6622	0.5828	0.5735	0.6061	0.6643	0.5734	0.6308	0.5828	0.6306	0.6061	0.6239	0.6643	10.3213
C ₄	0.5803	0.5363	0.5217	0.5611	0.5168	0.5913	0.5093	0.5363	0.6046	0.5735	0.5636	0.6054	0.5734	0.6622	0.5828	0.5482	0.5935	9.6603
C ₅	0.6280	0.6098	0.6077	0.6727	0.6180	0.7192	0.6374	0.6098	0.5311	0.4934	0.5064	0.5644	0.5521	0.5890	0.5310	0.6659	0.7034	10.2393
C ₆	0.5963	0.5730	0.5479	0.6056	0.5289	0.6783	0.5780	0.5730	0.6030	0.5552	0.5616	0.6174	0.5487	0.6494	0.5978	0.6150	0.6261	10.0552
C ₇	0.5036	0.5570	0.5115	0.5516	0.4925	0.5912	0.5418	0.5570	0.6262	0.5978	0.5804	0.6700	0.5802	0.6675	0.6574	0.5525	0.5558	9.794
C ₈	0.5718	0.5517	0.5920	0.6037	0.5552	0.6374	0.5542	0.5517	0.5913	0.5843	0.5732	0.6393	0.5879	0.6633	0.5969	0.5943	0.6195	10.0677
C ₉	0.5622	0.5620	0.5468	0.6260	0.5044	0.6065	0.5676	0.5620	0.5730	0.5479	0.6056	0.5289	0.6783	0.5780	0.5730	0.5504	0.5980	9.7706
C ₁₀	0.6046	0.5735	0.5636	0.6054	0.5734	0.6622	0.5828	0.5735	0.5570	0.5115	0.5516	0.4925	0.5912	0.5418	0.5570	0.6239	0.6643	9.8298
C ₁₁	0.5311	0.4934	0.5064	0.5644	0.5521	0.5890	0.5310	0.4934	0.6245	0.6698	0.5500	0.6203	0.6196	0.6296	0.6245	0.6428	0.6698	9.9117
C ₁₂	0.6030	0.5552	0.5616	0.6174	0.5487	0.6494	0.5978	0.5552	0.6061	0.6643	0.5734	0.6308	0.5828	0.6306	0.6061	0.6239	0.6643	10.2706
C ₁₃	0.6262	0.5978	0.5804	0.6700	0.5802	0.6675	0.6574	0.5978	0.6046	0.5735	0.5636	0.6054	0.5734	0.6622	0.5828	0.5482	0.5935	10.2845
C ₁₄	0.5913	0.5843	0.5732	0.6393	0.5879	0.6633	0.5969	0.5843	0.5311	0.4934	0.5064	0.5644	0.5521	0.5890	0.5310	0.6659	0.7034	9.9572
C ₁₅	0.6088	0.5881	0.5854	0.6419	0.5801	0.6862	0.6044	0.5881	0.6030	0.5552	0.5616	0.6174	0.5487	0.6494	0.5978	0.6150	0.6261	10.2572
C ₁₆	0.5904	0.5737	0.5582	0.6272	0.5709	0.6707	0.5911	0.5737	0.6262	0.5978	0.5804	0.6700	0.5802	0.6675	0.6574	0.5525	0.5558	10.2437
C ₁₇	0.5567	0.5180	0.5213	0.5923	0.5304	0.6238	0.5708	0.5180	0.5913	0.5843	0.5732	0.6393	0.5879	0.6633	0.5969	0.5943	0.6195	9.8813
R	9.9409	9.5760	9.4564	10.4359	9.4338	11.0283	9.9140	9.5760	10.1213	9.9966	9.5453	10.3356	9.9500	10.7308	10.1407	10.2944	10.7877	0.5926

Table 13. Total-relation matrix T for IF DEMATEL for Scenario (a).

	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	C ₇	C ₈	C ₉	C ₁₀	C ₁₁	C ₁₂	C ₁₃	C ₁₄	C ₁₅	C ₁₆	C ₁₇
C ₁	0.0000	0.0000	0.0000	0.6272	0.0000	0.6707	0.0000	0.0000	0.6177	0.6606	0.0000	0.6190	0.0000	0.6278	0.6177	0.6349	0.6606
C ₂	0.0000	0.0000	0.0000	0.6247	0.0000	0.6594	0.6196	0.0000	0.6245	0.6698	0.0000	0.6203	0.6196	0.6296	0.6245	0.6428	0.6698
C ₃	0.6046	0.0000	0.0000	0.6054	0.0000	0.6622	0.0000	0.0000	0.6061	0.6643	0.0000	0.6308	0.0000	0.6306	0.6061	0.6239	0.6643
C ₄	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6046	0.0000	0.0000	0.6054	0.0000	0.6622	0.0000	0.0000	0.5935
C ₅	0.6280	0.6098	0.6077	0.6727	0.6180	0.7192	0.6374	0.6098	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6659	0.7034
C ₆	0.5963	0.0000	0.0000	0.6056	0.0000	0.6783	0.0000	0.0000	0.6030	0.0000	0.0000	0.6174	0.0000	0.6494	0.5978	0.6150	0.6261
C ₇	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6262	0.5978	0.0000	0.6700	0.0000	0.6675	0.6574	0.0000	0.0000
C ₈	0.0000	0.0000	0.0000	0.6037	0.0000	0.6374	0.0000	0.0000	0.0000	0.0000	0.0000	0.6393	0.0000	0.6633	0.5969	0.5943	0.6195
C ₉	0.0000	0.0000	0.0000	0.6260	0.0000	0.6065	0.0000	0.0000	0.0000	0.0000	0.6056	0.0000	0.6783	0.0000	0.0000	0.0000	0.5980
C ₁₀	0.6046	0.0000	0.0000	0.6054	0.0000	0.6622	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6239	0.6643
C ₁₁	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6245	0.6698	0.0000	0.6203	0.6196	0.6296	0.6245	0.6428	0.6698
C ₁₂	0.6030	0.0000	0.0000	0.6174	0.0000	0.6494	0.5978	0.0000	0.6061	0.6643	0.0000	0.6308	0.0000	0.6306	0.6061	0.6239	0.6643
C ₁₃	0.6262	0.5978	0.0000	0.6700	0.0000	0.6675	0.6574	0.5978	0.6046	0.0000	0.0000	0.6054	0.0000	0.6622	0.0000	0.0000	0.5935
C ₁₄	0.0000	0.0000	0.0000	0.6393	0.0000	0.6633	0.5969	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6659	0.7034
C ₁₅	0.6088	0.0000	0.0000	0.6419	0.0000	0.6862	0.6044	0.0000	0.6030	0.0000	0.0000	0.6174	0.0000	0.6494	0.5978	0.6150	0.6261
C ₁₆	0.0000	0.0000	0.0000	0.6272	0.0000	0.6707	0.0000	0.0000	0.6262	0.5978	0.0000	0.6700	0.0000	0.6675	0.6574	0.0000	0.0000
C ₁₇	0.0000	0.0000	0.0000	0.0000	0.0000	0.6238	0.0000	0.0000	0.0000	0.0000	0.0000	0.6393	0.0000	0.6633	0.5969	0.5943	0.6195

We obtained the cause-and-effect diagram (Figure 4) by mapping a dataset of $(D + R, D - R)$ where the horizontal axis $(D + R)$ represents the importance of the 17 criteria and $(D - R)$ classifies the identified challenges into each of the cause groups as shown in Table 14.

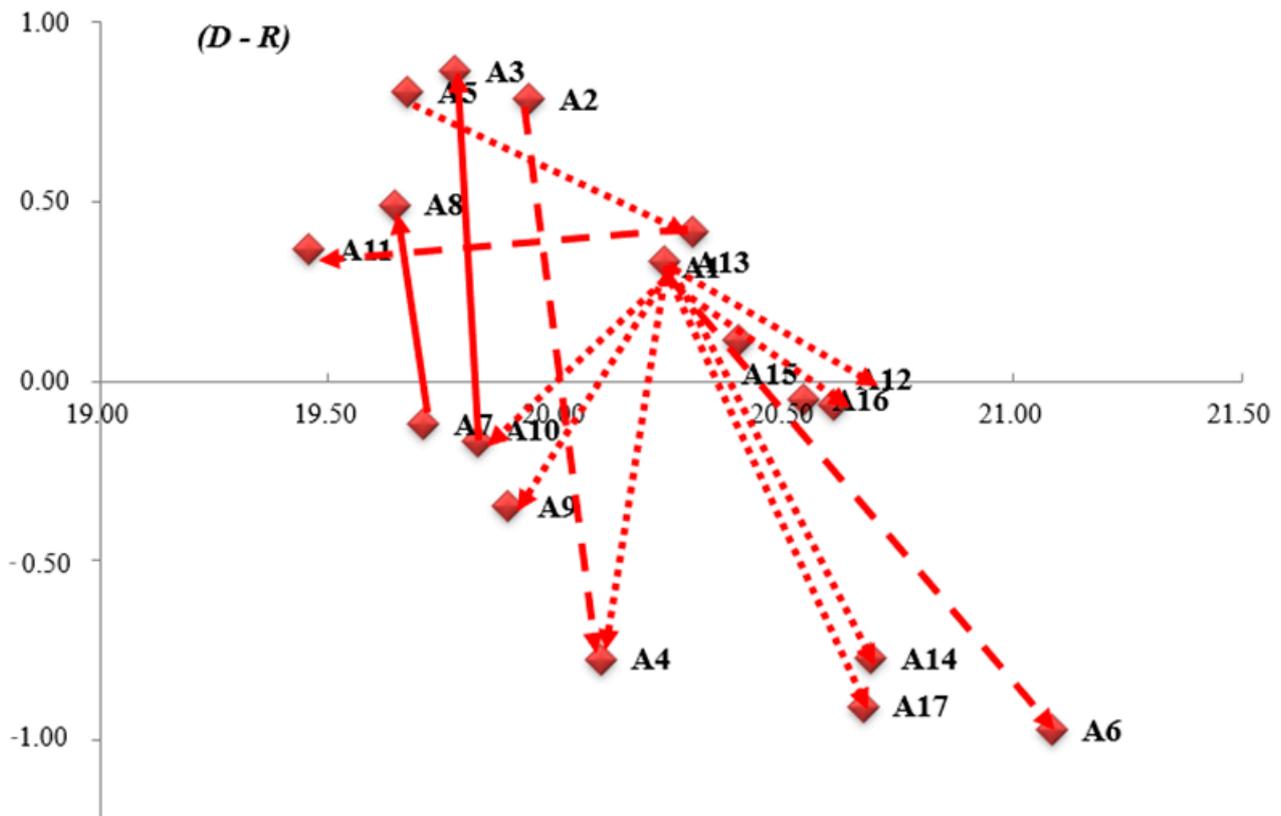


Figure 4. Causal relationships of the criteria for Scenario (a).

Table 14. Criteria (network) relationship map using the (D–R) and the mean threshold of the causal relationships of the 17 criteria in Scenario (a).

Crit. Code	Crit. Category	R	D	D+R	D–R
C ₁	Environmental	9.9409	10.3562	20.2971	0.4153
C ₂		9.576	10.3631	19.9391	0.7871
C ₃		9.4564	10.3213	19.7777	0.8649
C ₄		10.4359	9.6603	20.0962	−0.7756
C ₅		9.4338	10.2393	19.6731	0.8055
C ₆	Economic	11.0283	10.0552	21.0835	−0.9731
C ₇		9.914	9.794	19.708	−0.12
C ₈	Social	9.576	10.0677	19.6437	0.4917
C ₉		10.1213	9.7706	19.8919	−0.3507
C ₁₀	Organizational	9.9966	9.8298	19.8264	−0.1668
C ₁₁		9.5453	9.9117	19.457	0.3664
C ₁₂		10.3356	10.2706	20.6062	−0.065
C ₁₃	Waste Related	9.95	10.2845	20.2345	0.3345
C ₁₄		10.7308	9.9572	20.688	−0.7736
C ₁₅		10.1407	10.2572	20.3979	0.1165
C ₁₆	Authorities and Legislation	10.2944	10.2437	20.5381	−0.0507
C ₁₇		10.7877	9.8813	20.669	−0.9064

The ranking of the four alternatives is calculated indirectly from their relative importance in terms of the scenarios. The IF-DEMATEL method is supportive of the ranking process since the ranking of alternatives can be calculated the same way as IF-TOPSIS from the intuitionistic fuzzy decision matrix of the 17 criteria. The ranking of the criteria is shown in Table 15.

Table 15. Relative criteria ranking from IF-DEMATEL for Scenario (a).

Crit. ID	Aspect	Criteria Name	B/NB	Closeness Coefficient	Ranking
C ₁	Environmental	Hazard/risk potential	NB	0.916	9
C ₂		Distance of storing facility in relation to society	B	0.927	7
C ₃		Segregation, categorization, and transportation of HCW	B	0.955	2
C ₄		Occupational health and safety	B	0.886	13
C ₅		Water and residue disposal and emission control	NB	0.872	16
C ₆	Economic	Cost of the waste treatment methodology	B	0.902	12
C ₇		Energy and other resource utilization	B	0.942	4
C ₈	Social	Qualified personnel availability	B	0.950	3
C ₉		Sensitivity to the environment, existence of the NIMBY phenomenon	B	0.766	17
C ₁₀	Organizational	HCW plan management substance and execution	B	0.914	10
C ₁₁		Supply chain management and finance	B	0.882	14
C ₁₂		Health institution resources and infrastructure	B	0.921	8
C ₁₃	Waste-Related	HCW type and hazard	NB	0.936	6
C ₁₄		HCW material	NB	0.877	15
C ₁₅		HCW treatment monitoring and control	B	0.957	1
C ₁₆	Authorities and Legislation	Municipality services, competence and treatment facility functions	B	0.939	5
C ₁₇		Personnel competences in the treating facilities	B	0.906	11

For that reason, the results of IF-DEMATEL are identical to IF-TOPSIS as shown in Table 16:

Table 16. Relative importance of alternatives and ranking of IFCORPAS for Scenario (a).

	ALT_1	ALT_2	ALT_3	ALT_4	$\sum q_{ij}$	Ranking
ALT_1	0.000	0.317	0.247	0.189	0.753	1
ALT_2	−0.317	0.000	−0.295	−0.224	−0.836	4
ALT_3	−0.247	0.295	0.000	−0.175	−0.127	3
ALT_4	−0.189	0.224	0.175	0.000	0.210	2

5. Discussion of Results

Discussing the qualitative data results, as opposed to the quantitative analysis of Section 4, we now focus on the chosen models used in the evaluation/ranking process, prioritizing the ranking of the alternatives. For frameworks utilized in the formulation of policies for sustainable urban development, this is always important [65]. As a result, it is critical to evaluate the framework in its entirety as a tool to assist the policy-maker in supporting their decision. The results show that the three alternatives were ranked identically by all models. When the above methodologies are used on the same dataset, this demonstrates their consistency. However, if all the participating models yield the same outcome, then this fact invites the question of whether the comparative analysis is necessary for the study. To make such an argument, one must, however, further demonstrate that every issue is incorporated in this framework, which is not obviously the case. On the contrary, there are many other aspects, criteria, and parameters which have not been included in the study because they have not indicated critical significance relative to the 17 already-taken criteria. But the factor of the direct relevance of these criteria with the region of study is the one that justifies the existence of alternative methodologies working on the same aspect to produce justifiable results. We collected all data pertaining to the ranking outcomes of IF-TOPSIS, IF-CORPAS, and IF-DEMATEL, respectively, from the relative tables. More specifically, the exact relevance weights that each approach allocated to each of the different alternatives are of greater interest to us. Only IF-CORPAS gives

normalized significance weights among the methodologies used. The other approaches have been normalized by us so that their performance is consistent across the board. The outcomes are displayed in Table 17:

Table 17. Relative performance matrix for all methodologies for Scenario (a).

Alternatives	Initial			Normalized		
	IF-Topsis	IF-Corpas	IF-Dematel	IF-Topsis	IF-Corpas	IF-Dematel
<i>ALT</i> ₁	7.257	1.000	0.349	0.300149	0.281136	0.262209
<i>ALT</i> ₂	5.732	0.814	0.327	0.237075	0.228845	0.24568
<i>ALT</i> ₃	4.958	0.781	0.321	0.205062	0.219567	0.241172
<i>ALT</i> ₄	6.231	0.962	0.334	0.257714	0.270453	0.250939

Incineration is ranked as the most preferable solution due to its ability to safely dispose of a wide range of medical waste types. When operated correctly, modern incinerators can efficiently burn medical waste at high temperatures, minimizing the risk of contamination and emissions. The method is considered effective for medical waste disposal because it reduces the volume of waste significantly and can destroy pathogens and harmful chemicals.

On the other hand, the storing of HCW is ranked as the least preferable alternative. This is justified by the fact that storing HCW for prolonged periods can lead to the risk of contamination, environmental pollution, and potential health hazards for workers and nearby communities. At the same time, the method does not address the disposal issue, and the waste may pose increased risks over time.

Segregation and landfill is the second most preferable alternative for the case of the Thessaly region. Experts indicated that segregating medical waste before landfilling can help reduce the volume of hazardous waste going into landfills, making it easier to manage. Properly engineered landfills can contain medical waste and prevent environmental contamination if managed effectively. On the other hand, there is still a great hazard imposed due to possible soil contamination because of the landfills.

Finally, recycling was ranked as the third important alternative HCW treatment for Thessaly. Experts indicated that recycling certain types of medical waste, such as plastics and glass, can reduce the demand for new raw materials and lower the environmental impact. However, recycling HCW is also challenging due to the risk of contamination. Not all medical waste materials are suitable for recycling, especially those contaminated with biohazardous materials. Therefore, while it is environmentally friendly, it is limited in scope due to the specific nature of medical waste. Recycling can be a part of the waste management process but cannot be the sole solution due to its limitations in handling all types of medical waste.

6. Conclusions

Rapid global urbanization and population growth have presented municipalities with a significant challenge in managing healthcare waste (HCW), attracting increased attention in recent years. Selecting the appropriate HCW treatment technology is a complex task, involving conflicting criteria and multiple social stakeholders. HCW management systems often grapple with imprecise parameters expressed through uncertain linguistic expressions. The use of fuzzy membership functions in decision making can sometimes result in the loss of valuable information.

In this study, we introduced a comprehensive decision-making framework to facilitate optimal HCW treatment technology selection, considering various stakeholders' perspectives and employing a range of fuzzy intuitionistic methodologies, including IF-TOPSIS, IF-CORPAS, and IF-DEMATEL. We utilized an ensemble of these models to handle the linguistic assessments of experts in the field, focusing on the use case of the Thessaly region, Greece. Our approach objectively calculates decision-makers' weights, addressing their

uncertainty and divergence levels. We demonstrated our methodology through a practical case study and conducted a comparative analysis to validate its effectiveness. The study showed that our decision-making approach effectively resolves HCW disposal technology selection problems in uncertain and complex environments, thereby strengthening public health. We used the aforementioned three methods to identify the best alternative HCW treatment methods for environmental, economic, and social sustainability. Four options are identified: incineration, storage, recycling, and segregation and landfilling. We also assumed that regulatory compliance ensures the safe management of medical waste and public health. By employing distances from the ideal solution, two techniques—IF-TOPSIS and IF-CORPAS—basically distinguish criteria and alternative solutions, respectively. Distance is the basis of the IF-DEMATEL model. Every model managed to generate an identical rating amongst the alternatives, regardless of the model's core. For the incineration alternative which was the most preferred by all IF-methodologies, IF-TOPSIS presents the highest critical significance of ~ 0.30 , with IF-CORPAS in second place with ~ 0.28 , and IF-DEMATEL in third place, computing ~ 0.26 out of the whole critical importance vector. The second-best ranking alternative is HCW segregation and landfilling. Even though, in other studies, this alternative is not popular, the Greek study showed an augmented preference. However, the most popular choice was the incineration of HCW because it can securely dispose of various kinds of medical waste. Modern incinerators can effectively burn medical waste at high temperatures while limiting the danger of contamination and pollution when used properly. The safety criterion was intended to be non-negotiable across all participants, avoiding competition with other options. We must mention that our study compares the most dominant technologies for HCW treatment in a holistic way (multiple categories of criteria have been used). Even though the results could support the medical waste hierarchy, we strongly believe that life-cycle assessment is a crucial tool in waste management practice, but little research has been performed on the evaluation of medical waste treatment from a life-cycle perspective.

Future research will focus on expanding this integrated approach to address HCW management issues involving diverse interrelationships among evaluation criteria. Moreover, methods for objectively determining criteria weights should be developed, especially in real-world situations where subjective estimation is challenging. Another avenue for future research involves creating a computer-based application system to streamline the implementation of our proposed HCW treatment technology selection algorithm and enhance human-machine interaction for presenting and analyzing selection results. This framework can be made more flexible by adding more models for more comprehensive evaluation procedures. Furthermore, further research is needed to examine the characteristics of ensemble-based systems in scenarios with inconsistent ranking outcomes. Inter-val-valued, Pythagorean, or interval type-2 fuzzy sets can also be added to a more complete framework to improve the current approach and guarantee public health.

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References

- Mondal, R.; Mishra, S.; Pillai, J.S.K.; Sahoo, M.C. COVID-19 Pandemic and biomedical waste management practices in healthcare system. *J. Fam. Med. Prim. Care* **2022**, *11*, 439–446. [[CrossRef](#)] [[PubMed](#)]
- Ranjbari, M.; Esfandabadi, Z.S.; Shevchenko, T.; Chassagnon-Haned, N.; Peng, W.; Tabatabaei, M.; Aghbashlo, M. Mapping healthcare waste management research: Past evolution, current challenges, and future perspectives towards a circular economy transition. *J. Hazard. Mater.* **2022**, *422*, 126724. [[CrossRef](#)] [[PubMed](#)]
- Ervural, B.Ç.; Öner, S.C.; Çoban, V.; Kahraman, C. A novel Multiple Attribute Group Decision Making methodology based on Intuitionistic Fuzzy TOPSIS. In Proceedings of the 2015 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE), Istanbul, Turkey, 2–5 August 2015; pp. 1–6. [[CrossRef](#)]
- Alvarez, P.A.; Ishizaka, A.; Martínez, L. Multiple-criteria decision-making sorting methods: A survey. *Expert Syst. Appl.* **2021**, *183*, 115368. [[CrossRef](#)]
- Kaya, G.K.; Ozturk, F. A Comparison of the Multi-criteria Decision-Making Methods for the Selection of Researchers. In *Industrial Engineering in the Internet-of-Things World*; Calisir, F., Ed.; Lecture Notes in Management and Industrial Engineering; Springer International Publishing: Cham, Switzerland, 2022; pp. 147–159. [[CrossRef](#)]
- Schitea, D.; Deveci, M.; Iordache, M.; Bilgili, K.; Akyurt, İ.Z.; Iordache, I. Hydrogen mobility roll-up site selection using intuitionistic fuzzy sets based WASPAS, COPRAS and EDAS. *Int. J. Hydrogen Energy* **2019**, *44*, 8585–8600. [[CrossRef](#)]
- Chhibber, D.; Srivastava, P.K.; Bisht, D.C.S. Intuitionistic fuzzy TOPSIS for non-linear multi-objective transportation and manufacturing problem. *Expert Syst. Appl.* **2022**, *210*, 118357. [[CrossRef](#)]
- Sharma, K.; Singh, V.P.; Ebrahimnejad, A.; Chakraborty, D. Solving a multi-objective chance constrained hierarchical optimization problem under intuitionistic fuzzy environment with its application. *Expert Syst. Appl.* **2023**, *217*, 119595. [[CrossRef](#)]
- Mazzei, H.G.; Specchia, S. Latest insights on technologies for the treatment of solid medical waste: A review. *J. Environ. Chem. Eng.* **2023**, *11*, 109309. [[CrossRef](#)]
- Liu, S.; Zhang, J.; Niu, B.; Liu, L.; He, X. A novel hybrid multi-criteria group decision-making approach with intuitionistic fuzzy sets to design reverse supply chains for COVID-19 medical waste recycling channels. *Comput. Ind. Eng.* **2022**, *169*, 108228. [[CrossRef](#)]
- Çelik, S.; Peker, İ.; Gök-Kısa, A.C.; Büyüközkan, G. Multi-criteria evaluation of medical waste management process under intuitionistic fuzzy environment: A case study on hospitals in Turkey. *Socio-Econ. Plan. Sci.* **2023**, *86*, 101499. [[CrossRef](#)]
- Çakir, E.; Taş, M.A.; Ulukan, Z. A New Circular Intuitionistic Fuzzy MCDM: A Case of COVID-19 Medical Waste Landfill Site Evaluation. In Proceedings of the 2021 IEEE 21st International Symposium on Computational Intelligence and Informatics (CINTI), Budapest, Hungary, 18–20 November 2021; pp. 143–148. [[CrossRef](#)]
- Patel, A.; Jana, S.; Mahanta, J. Intuitionistic fuzzy EM-SWARA-TOPSIS approach based on new distance measure to assess the medical waste treatment techniques. *Appl. Soft Comput.* **2023**, *144*, 110521. [[CrossRef](#)]
- Qian, W.; Wang, Z.-J.; Li, K.W. Medical Waste Disposal Method Selection Based on a Hierarchical Decision Model with Intuitionistic Fuzzy Relations. *Int. J. Environ. Res. Public Health* **2016**, *13*, 896. [[CrossRef](#)] [[PubMed](#)]
- Mishra, A.R.; Mardani, A.; Rani, P.; Zavadskas, E.K. A novel EDAS approach on intuitionistic fuzzy set for assessment of health-care waste disposal technology using new parametric divergence measures. *J. Clean. Prod.* **2020**, *272*, 122807. [[CrossRef](#)]
- Büyüközkan, G.; Gocer, F. An Intuitionistic Fuzzy MCDM Approach for Effective Hazardous Waste Management. In *Intelligence Systems in Environmental Management: Theory and Applications*; Kahraman, C., Sari, İ.U., Eds.; Intelligent Systems Reference Library; Springer International Publishing: Cham, Switzerland, 2017; pp. 21–40. [[CrossRef](#)]
- Narayanamoorthy, S.; Annapoorani, V.; Kang, D.; Baleanu, D.; Jeon, J.; Kureethara, J.V.; Ramya, L. A novel assessment of bio-medical waste disposal methods using integrating weighting approach and hesitant fuzzy MOOSRA. *J. Clean. Prod.* **2020**, *275*, 122587. [[CrossRef](#)]
- Ghoushchi, S.J.; Ghiaci, A.M.; Bonab, S.R.; Ranjbarzadeh, R. Barriers to circular economy implementation in designing of sustainable medical waste management systems using a new extended decision-making and FMEA models. *Environ. Sci. Pollut. Res.* **2022**, *29*, 79735–79753. [[CrossRef](#)] [[PubMed](#)]
- Liu, P.; Rani, P.; Mishra, A.R. A novel Pythagorean fuzzy combined compromise solution framework for the assessment of medical waste treatment technology. *J. Clean. Prod.* **2021**, *292*, 126047. [[CrossRef](#)]
- Ghoushchi, S.J.; Bonab, S.R.; Ghiaci, A.M.; Haseli, G.; Tomaskova, H.; Hajiaghahi-Keshteli, M. Landfill Site Selection for Medical Waste Using an Integrated SWARA-WASPAS Framework Based on Spherical Fuzzy Set. *Sustainability* **2021**, *13*, 13950. [[CrossRef](#)]
- Menekşe, A.; Akdağ, H.C. Medical waste disposal planning for healthcare units using spherical fuzzy CRITIC-WASPAS. *Appl. Soft Comput.* **2023**, *144*, 110480. [[CrossRef](#)]
- Salimian, S.; Mousavi, S.M. The selection of healthcare waste treatment technologies by a multi-criteria group decision-making method with intuitionistic fuzzy sets. *J. Ind. Syst. Eng.* **2022**, *14*, 205–220.
- Görçün, Ö.F.; Aytakin, A.; Korucuk, S.; Tirkolae, E.B. Evaluating and selecting sustainable logistics service providers for medical waste disposal treatment in the healthcare industry. *J. Clean. Prod.* **2023**, *408*, 137194. [[CrossRef](#)]
- Al-Barakati, A.; Rani, P. Assessment of healthcare waste treatment methods using an interval-valued intuitionistic fuzzy double normalization-based multiple aggregation approach. *Environ. Dev. Sustain.* **2023**, *1*, 1–28. [[CrossRef](#)]
- Seikh, M.R.; Mandal, U. Interval-valued Fermatean fuzzy Dombi aggregation operators and SWARA based PROMETHEE II method to bio-medical waste management. *Expert Syst. Appl.* **2023**, *226*, 120082. [[CrossRef](#)]

26. Chew, X.; Khaw, K.W.; Alnoor, A.; Ferasso, M.; Al Halbusi, H.; Muhsen, Y.R. Circular economy of medical waste: Novel intelligent medical waste management framework based on extension linear Diophantine fuzzy FDOSM and neural network approach. *Environ. Sci. Pollut. Res.* **2023**, *30*, 60473–60499. [[CrossRef](#)] [[PubMed](#)]
27. Salimian, S.; Mousavi, S.M. Healthcare waste disposal location selection by a multi-criteria decision-making method with intuitionistic fuzzy sets. *J. Qual. Eng. Prod. Optim.* **2021**, *6*, 143–156.
28. Ocampo, L.; Tanaid, R.A.; Tiu, A.M.; Selerio, E., Jr.; Yamagishi, K. Classifying the degree of exposure of customers to COVID-19 in the restaurant industry: A novel intuitionistic fuzzy set extension of the TOPSIS-Sort. *Appl. Soft Comput.* **2021**, *113*, 107906. [[CrossRef](#)]
29. Roszkowska, E.; Kusterka-Jefmańska, M.; Jefmański, B. Intuitionistic fuzzy TOPSIS as a method for assessing socioeconomic phenomena on the basis of survey data. *Entropy* **2021**, *23*, 563. [[CrossRef](#)]
30. Atanassov, K.T. More on intuitionistic fuzzy sets. *Fuzzy Sets Syst.* **1989**, *33*, 37–45. [[CrossRef](#)]
31. Xu, Z.-S. Methods for aggregating interval-valued intuitionistic fuzzy information and their application to decision making. *Control Decis.* **2007**, *2*, 215–219.
32. Beheshtinia, M.A.; Kahoo, S.J.; Fathi, M. Prioritizing healthcare waste disposal methods considering environmental health using an enhanced multi-criteria decision-making method. *Environ. Pollut. Bioavailab.* **2023**, *35*, 2218568. [[CrossRef](#)]
33. Boran, F.E.; Genç, S.; Kurt, M.; Akay, D. A multi-criteria intuitionistic fuzzy group decision making for supplier selection with TOPSIS method. *Expert Syst. Appl.* **2009**, *36*, 11363–11368. [[CrossRef](#)]
34. Xu, Z. Intuitionistic Fuzzy Aggregation Operators. *IEEE Trans. Fuzzy Syst.* **2007**, *15*, 1179–1187. [[CrossRef](#)]
35. Akter, N. Medical Waste Management: A Review. January 2000. Available online: <http://dspace.bracu.ac.bd/xmlui/handle/10361/12964> (accessed on 9 October 2023).
36. Marinković, N.; Vitale, K.; Holcer, N.J.; Džakula, A.; Pavić, T. Management of hazardous medical waste in Croatia. *Waste Manag.* **2008**, *28*, 1049–1056. [[CrossRef](#)]
37. Kargar, S.; Paydar, M.M.; Safaei, A.S. A reverse supply chain for medical waste: A case study in Babol healthcare sector. *Waste Manag.* **2020**, *113*, 197–209. [[CrossRef](#)] [[PubMed](#)]
38. Luo, X.; Liao, W. Collaborative Reverse Logistics Network for Infectious Medical Waste Management during the COVID-19 Outbreak. *Int. J. Environ. Res. Public Health* **2022**, *19*, 9735. [[CrossRef](#)] [[PubMed](#)]
39. Chand, S.; Shastry, C.S.; Hiremath, S.; Joel, J.J.; Krishnabhat, C.H.; Mateti, U.V. Updates on biomedical waste management during COVID-19: The Indian scenario. *Clin. Epidemiol. Glob. Health* **2021**, *11*, 100715. [[CrossRef](#)] [[PubMed](#)]
40. Lemma, H.; Asefa, L.; Gemed, T.; Dhengesu, D. Infectious medical waste management during the COVID-19 pandemic in public hospitals of West Guji zone, southern Ethiopia. *Clin. Epidemiol. Glob. Health* **2022**, *15*, 101037. [[CrossRef](#)] [[PubMed](#)]
41. Kokkinos, K.; Papadopoulos, E.; Samaras, N.; Chaikalis, K. An Integrated Modeling Framework for Routing of Hazardous Materials. In Proceedings of the 2012 IEEE 21st International Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises, Toulouse, France, 25–27 June 2012; Available online: <https://ieeexplore.ieee.org/abstract/document/6269733> (accessed on 9 October 2023).
42. Eren, E.; Tuzkaya, U.R. Occupational health and safety-oriented medical waste management: A case study of Istanbul. *Waste Manag. Res.* **2019**, *37*, 876–884. [[CrossRef](#)] [[PubMed](#)]
43. Yang, S.; Long, R.; Wu, M.; Chen, H.; Li, Q. Research progress and frontier of global solid waste management based on bibliometrics. *Environ. Dev.* **2023**, *48*, 100922. [[CrossRef](#)]
44. Kokkinos, K.; Karayannis, V.; Moustakas, K. Optimizing Microalgal Biomass Feedstock Selection for Nanocatalytic Conversion Into Biofuel Clean Energy, Using Fuzzy Multi-Criteria Decision Making Processes. *Front. Energy Res.* **2021**, *8*, 622210. [[CrossRef](#)]
45. Hendalianpour, A.; Razmi, J.; Fakhrabadi, M.; Kokkinos, K.; Papageorgiou, E.I. A linguistic multi-objective mixed integer programming model for multi-echelon supply chain network at bio-refinery. *EuroMed J. Manag.* **2018**, *2*, 329–355. [[CrossRef](#)]
46. Shen, W.; Zhu, N.; Xi, Y.; Huang, J.; Li, F.; Wu, P.; Dang, Z. Effects of medical waste incineration fly ash on the promotion of heavy metal chlorination volatilization from incineration residues. *J. Hazard. Mater.* **2022**, *4251*, 128037. [[CrossRef](#)]
47. Govindan, K.; Nosrati-Abarghoee, S.; Nasiri, M.M.; Jolai, F. Green reverse logistics network design for medical waste management: A circular economy transition through case approach. *J. Environ. Manag.* **2022**, *322*, 115888. [[CrossRef](#)]
48. Wang, P.; Gu, X.; Xue, M.; Li, Y.; Dong, S.; Chen, G.; Zhang, J. Resource utilization of medical waste under COVID-19: Waste mask used as crude oil fluidity improver. *J. Clean. Prod.* **2022**, *358*, 131903. [[CrossRef](#)] [[PubMed](#)]
49. Kokkinos, K.; Karayannis, V.; Samaras, N.; Moustakas, K. Multi-scenario analysis on hydrogen production development using PESTEL and FCM models. *J. Clean. Prod.* **2023**, *419*, 138251. [[CrossRef](#)]
50. Kokkinos, K.; Karayannis, V.; Nathanail, E.; Moustakas, K. A comparative analysis of Statistical and Computational Intelligence methodologies for the prediction of traffic-induced fine particulate matter and NO₂. *J. Clean. Prod.* **2021**, *328*, 129500. [[CrossRef](#)]
51. Thirunavukkarasu, A.; Al-Hazmi, A.H.; Dar, U.F.; Alruwaili, A.M.; Alsharari, S.D.; Alazmi, F.A.; Alruwaili, S.F.; Alarjan, A.M. Knowledge, attitude and practice towards bio-medical waste management among healthcare workers: A northern Saudi study. *PeerJ* **2022**, *10*, e13773. [[CrossRef](#)] [[PubMed](#)]
52. Al-Omran, K.; Abahussain, A.; Khan, E. Integrated Environmental Assessment of Medical Waste Management in the Kingdom of Bahrain. *Sustainability* **2023**, *15*, 2397. [[CrossRef](#)]
53. Karimi, N.; Ng, K.T.W.; Richter, A. Development of a regional solid waste management framework and its application to a prairie province in central Canada. *Sustain. Cities Soc.* **2022**, *82*, 103904. [[CrossRef](#)]

54. Ho, P. The Costs and Environmental Justice Concerns of NIMBY in Solid Waste Disposal. *J. Assoc. Environ. Resour. Econ.* **2023**, *10*, 607–654. [CrossRef]
55. Lee, S.M.; Lee, D. Effective Medical Waste Management for Sustainable Green Healthcare. *Int. J. Environ. Res. Public Health* **2022**, *19*, 14820. [CrossRef]
56. Goodarzian, F.; Ghasemi, P.; Gunasekaran, A.; Labib, A. A fuzzy sustainable model for COVID-19 medical waste supply chain network. *Fuzzy Optim. Decis. Mak.* **2023**, *1*, 1–35. [CrossRef]
57. Jayasinghe, P.A.; Jalilzadeh, H.; Hettiaratchi, P. The Impact of COVID-19 on Waste Infrastructure: Lessons Learned and Opportunities for a Sustainable Future. *Int. J. Environ. Res. Public Health* **2023**, *20*, 4310. [CrossRef] [PubMed]
58. Attrah, M.; Elmanadely, A.; Akter, D.; Rene, E.R. A Review on Medical Waste Management: Treatment, Recycling, and Disposal Options. *Environments* **2022**, *9*, 146. [CrossRef]
59. Huda, M.N.; Hailemariam, T.G.; Hossain, S.Z.; Malo, J.S.; Khan, S.; Hadisuyatmana, S.; Ferdous, A.; Akombi-Inyang, B.; Islam, R.M.; Renzaho, A.M. Medical waste management-related factors affecting health and experiences of health risks among medical waste handlers in low and middle-income countries: A systematic review protocol of qualitative studies. *BMJ Open* **2022**, *12*, e056037. Available online: <https://bmjopen.bmj.com/content/12/3/e056037.abstract> (accessed on 9 October 2023). [CrossRef] [PubMed]
60. Yoon, C.-W.; Kim, M.-J.; Park, Y.-S.; Jeon, T.-W.; Lee, M.-Y. A Review of Medical Waste Management Systems in the Republic of Korea for Hospital and Medical Waste Generated from the COVID-19 Pandemic. *Sustainability* **2022**, *14*, 3678. [CrossRef]
61. Joneghani, N.M.; Zarrinpoor, N.; Eghtesadifard, M. A mathematical model for designing a network of sustainable medical waste management under uncertainty. *Comput. Ind. Eng.* **2022**, *171*, 108372. [CrossRef]
62. Chtioui, A.; Bouhaddou, I.; Benabdella, A.C.; Benghabrit, A. A Multi-Agent System for the Optimization of Medical Waste Management. In *Artificial Intelligence and Industrial Applications*; Masrour, T., Ramchoun, H., Hajji, T., Hosni, M., Eds.; Lecture Notes in Networks and Systems; Springer Nature: Cham, Switzerland, 2023; pp. 134–149. [CrossRef]
63. Fadaei, A. Comparison of medical waste management methods in different countries: A systematic review. *Rev. Environ. Health* **2023**, *38*, 339–348. [CrossRef] [PubMed]
64. Ghorabae, M.K.; Zavadskas, E.K.; Turskis, Z.; Antucheviciene, J. A new combinative distance-based assessment (CODAS) method for multi-criteria decision-making. *Econ. Comput. Econ. Cybern. Stud. Res.* **2016**, *50*, 25–44.
65. Vardopoulos, I. Critical sustainable development factors in the adaptive reuse of urban industrial buildings. *A fuzzy DEMATEL approach. Sustain. Cities Soc.* **2019**, *50*, 101684. [CrossRef]

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