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RESEARCH ARTICLE

A Quantitative Assessment of Effective Sustainable Waste Management using an AHP-TOPSIS Methodology in a Neutrosophic Environment (in India)

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ABSTRACT

Waste management is a key to sustainable development and environmental safety, particularly in the environment of the fast evolving smart cities. This study proposes a new decision-making model that will assist in the process of choosing effective sustainable methods in waste management for smart cities. It compares the four methods of waste management in relation to seven factors. Two Multi-Criteria Decision Making (MCDM) are used i) Analytical Hierarchy Process (AHP) and ii) Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) in a Neutrosophic Soft Set (NSS) environment. NSS have a more adaptive structure on dealing with the uncertainty and incapacity to be precise in the decision-making on waste management. In this methodology, AHP determines the weights of decision criteria, while TOPSIS ranks the effective waste management strategies for final selection. Ten professionals in the universities, industry, and government sector were used. This assessment was done by way of structured questionnaires of subjective opinions. As a result, the alternatives were ranked based on their closeness coefficient values as follows: A2 (0.632) > A1 (0.509) > A4 (0.352) > A3 (0.261). The given ranking shows that A2 is more effective than A1, A4, and A3.

Keywords: AHP, Decision-making, Effective waste management, Neutrosophic soft sets, TOPSIS

Introduction

Urbanization is one of the most outstanding tendencies of the 21st century, and cities are becoming the vibrant centres of economic activity and innovations and population influx. Nevertheless, swift urbanization has brought urgent environmental and logistical problems, such as traffic jams, poor waste collections, rising utility prices and rising needs of important services, like education, housing, water, healthcare and transportation. In order to overcome these complex problems, city officials should consider the prudent utilization of natural and economic resources and attempt to reduce environmental pollution. Since the 1990s, this necessity has led to the emergence of the "smart city" concept in urban planning. Use of advanced technologies in smart cities is vital in the provision of more sustainable waste management (SWM), cost-effective, and efficient services. The implementation and sustenance of sound SWM practices are determined by a number of technical, political and economic issues. MCDM approach will provide holistic solution to the above problems, especially in determining the best waste management practices by evaluating and ranking various strategic options using technical, scientific, and economic feasibility, and the needs of inhabitants. The use of the NSSs in MCDM assists in the management of vagueness or incomplete information in making decisions. Neutrosophic sets are an extension of fuzzy sets, including

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functions of degree of truth membership, false membership and indeterminacy membership. NSSs build upon traditional soft sets, but they bring in the evaluation of the neutrosophic principles, which makes a decision-making issue to be analyzed more thoroughly.

The proposed research addresses a major gap in the existing literature since it uses a new hybrid MCDM approach which is a combination of the AHP and TOPSIS in a NSS context in establishing effective SWM strategies in the smart cities. The initial stage of describing the issue in a systematic way was to choose four successful strategies of waste management in a sustainable fashion. These plans incorporate some sustainable practices and intelligent technologies in both literature and practical applications. The literature was then used to select seven criteria and evaluate the performance of these strategies. In this hierarchical system, ten decision-making experts were formed from academia, the public, and the private sector for conducting linguistic assessments. AHP has been used to compute the weights of the criteria. Lastly, TOPSIS was used to rank the alternatives. This approach ensures a structured evaluation and ranking process for identifying effective SWM strategies in smart cities.

Literature review

Sustainability as a concept in the environmental context was developed in the 1970s, and it was called "sustainable development" at first.[1] It focuses on securing ecological life and natural resources in economic, social, and environmental levels. More so, Goodland,[2] Seadon[3] and Morelli[4] talked about environmental sustainability, the concept of proper management of resources, waste and pollution to address the current and future needs without destroying ecosystems. Petts[5] and Esmaeilian[6] consider modern methods, which involve uniting waste operations with an emphasis on its environmental efficiency, economic feasibility, and social appropriateness. Recent researches like Hannan,[7] Kang et al.[8] and Jiang et al.[9] emphasized the improvement of waste management technologies, including review of solid waste system, Internet of Things (IoT)-based e-waste management, and data-driven framework of waste-dumping behavior analysis. Senthilkumar et al.[10], Anh et al.[11] and Gopikumar et al.[12] considered the use of IoT in the development of smart cities, such as the landfill leachate system, air pollution system, and the university waste management system. Additionally, other improvements of waste management, such as LoRa and deep learning, an IoT-enabled scrap metal management solution, and a Blockchain-based smart waste management system are mentioned in the works of Sheng et al.[13] Mastos et al.[14] and Sen et al.[15]; they focus on minimizing the pollution and time and energy-saving, which they consider dynamic waste collection routes, smart containers to separate waste, and IoT systems to monitor and improve the waste disposal patterns. They also encompass deep learning to classify waste and combine it with blockchain to have clear data management in areas such as hospital waste and wastewater. Such developments have potential improvements on the sustainability of the environment and the efficiency of operation in management of waste.

MCDM methods play a crucial role across sectors by aiding complex decision-making processes. They also consider alternatives in terms of pre-determined criteria which is vital in terms of sustainability and waste management. Moreover, such methods are AHP and TOPSIS. In 1980, Saaty[16] presented the AHP in the form of ratio scales to compute weights of criteria. It has been widely applied in various decision-making cases and scenarios such as the selection of landfill locations, the selection of cloud service suppliers, the optimization of the parameters to use to produce green manufacturing, and the selection of the location of hospitals based on Şahin et al.[17] Singh et al.[18] Hasan et al.[19] and Saketa et al.[20] The TOPSIS decision-making process is founded on picking the best alternatives that are nearest to the ideal best solution (Hwang).[21] TOPSIS has been highly explored by various researchers in MCDM including Zhang, Xu,[22] Peng, and Dai,[23] Adeel et al.[24] Saqlain et al.[25] Selvachandran, and Peng[26] and Zhu et al.[27] applied this MCDM method to forecast the CWC 2019. In addition, Patil and Singh[28] introduced a model that helps a person to select biometric technology based on their preferences by using AHP and TOPSIS. Ilangkumaran *et al.*[29] Zorpas & Saranti,[30] Topaloglu *et al.*[31] and Torkayesh *et al.*[32] examined MCDM approaches for SWM. Coban *et al.*[33] utilized multi-criteria decision-making methods to enhance municipal solid waste management in Istanbul, Turkey. Finally, four SWM strategies are analysed utilizing Fuzzy AHP and TOPSIS by Demircan and Yetilmezsoy.[34]

The neutrosophic set, developed by Smarandache,[35] has three degrees: membership, non-membership, and indeterminacy functions, making it more effective in handling incomplete and uncertain data than Zadeh (1965)'s Fuzzy Set Theory,[36] which uses a single membership function. This innovation has garnered considerable attention from Abdel-Basset *et al.*[37] Naeem *et al.*[38] Tehrim *et al.*[39] and Abdel-Basset *et al.*[40] as it enhances the credibility of linguistic analysis and provides significant

Table 1. Alternatives for evaluation.

Alternative Number	Alternatives
A1	Incorporating formal recyclable garbage collection into a official intelligent system
A2	A pay-as-you-throw system that employs blockchain technology
A3	Community composting powered by IoT technology
A4	Using IoT to prevent illegal sewage discharge

qualitative insights. In addition, Maji[41] developed the concept of the NSS. In the literature, the Accuracy Function is used for TOPSIS with Neutrosophic Hypersoft Sets according to Saqlain *et al.*[42] According to studies of Saeed *et al.*[43] Saqlain *et al.*[44] Riaz *et al.*[45] and Saqlain *et al.*[46] numerous researchers extensively used neutrosophic sets combined with the TOPSIS method to solve MCDM problems. Moreover, Saqlain *et al.*[47] introduced a new NSS approach combined with generalized fuzzy TOPSIS for smartphone selection applications. Finally, Mohammed and Ashour[48] proposed a weighted Euclidean distance to improve fuzzy clustering performance.

A lot of researches have been done recently on efficient SWM. For instance, Moftah et al.[49] claimed that choosing leaders for the hospitality sector should be based on their level of sustainable performance. In addition, Abdelmawgoud[50] demonstrated that food waste management and food operations efficiency have a strong positive correlation; food waste management and food operations sustainability have a moderate positive correlation; and food waste management has no moderating effect on the relationship between operations sustainability and operations efficiency. Moreover, Abdelmawgoud[51] stated that there is no correlation between the level of sustainable lighting practices and the level of sustainable waste practices. As a result, according to Abdelmawgoud,[52] to attain the maximum level of operational performance efficiency, hotels must constantly implement sustainable practices.

Materials and methods

Creating the problem's hierarchical structure

In an MCDM process, the initial step is to recognize the problem that needs to be solved. Next, a hierarchical structure is established, incorporating both alternatives and criteria. In this analysis, the aim was to find out effective waste management techniques. Based on the literature review, four alternatives and seven criteria have been selected. Table 1 illustrates these alternatives that will be considered.

Table 1 shows the alternatives that have been discussed in the research to promote SWM procedures. A1 aims at encompassing formal recycling mechanisms within the smart systems to increase efficiency and traceability. A2 suggests a model of payment as you throw (pay-as-you-throw) based on blockchain to promote appropriate waste disposal. A3 is also interested in using IoT to create effective community composting models. Finally, A4 will handle the issue of unauthorized sewage release through the application of IoT-based solutions. These alternatives are designed to be assessed using the AHP-TOPSIS framework within a neutrosophic environment.

Table 2 presents the criteria that will be used to assess the alternatives.

Table 2. Criteria for evaluation.

Criteria Number	Criteria	Reference
C1	Atmospheric Emissions	29
C2	Pollution of Surface Water	29
C3	Energy Recovery	30
C4	Soil Pollution	29
C5	Maintenance Costs	31
C6	Innovativeness	32
C7	Initial Investment Expenditures	33

Table 2 identifies the criteria involved in the assessment of the suggested SWM alternatives. All the criteria have been given their own identifier to be referenced systematically, and the source has been placed respectively in the column of Reference. C1, C2, and C4 capture the ecological aspects of evaluation as environmental factors. C3 deals with energy recovery as it is highly applicable in improving sustainability. The use of C5 and C7 to indicate the economic factors includes its significance in the viability of the alternatives. Lastly, C6 will determine the innovativeness of each alternative, which would indicate the importance of technological advancement to waste management problems.

Analytic hierarchy process (AHP)

The AHP is MCDM method used for calculating the criteria weights. It was developed by Saaty (1980);[16] weights are calculated by following steps:

Step 1: Create a pairwise comparison matrix using a scale of relative importance.
Step 2: Determine the priority weights from the pairwise comparisons to reflect the relative significance of each element.

Step 3: Compute the consistency ratio to verify that the weights are consistent. A ratio below 0.1 is considered acceptable.

The consistency ratio is computed using Eqs. (1) and (2).

$$C.I. = \frac{\lambda_{max} - n}{n-1} \quad (1)$$

$$\text{Consistency Ratio} = \frac{\text{Consistency Index}}{\text{Random Index}} \quad (2)$$

Technique for order preference by similarity to ideal solution (TOPSIS)

TOPSIS is a widely recognized MCDM approach that aids in ranking and selecting a set of alternatives by comparing their distance to an ideal solution, according to Zhu *et al.* (2023).[23] The TOPSIS method assesses the decision matrix $[X_{ij}]_{IxJ}$, which involves evaluating I alternatives $\{X_i \mid i = 1,2,\ldots I\}$ based on specific J criteria $\{C_j \mid j = 1,2,\ldots J\}$.

The steps of the TOPSIS methodology are as follows:

Step 1: Create the weighted normalized decision matrix.

Firstly, the normalized decision matrix is calculated by Eq. (3).

$$Z_{ij} = \frac{Xij}{\sqrt{\sum_{j=1}^{J} X_{ij}^2}} \quad (3)$$

Then, the weighted normalized decision matrix is obtained by Eq. (4).

$$r_{ij} = w_j * Z_{ij};\ i = 1,\ 2,\ \ldots,\ I;\ j = 1,\ 2,\ \ldots,\ J. \quad (4)$$

Where, $w_j$indicates the criteria weights.

Step 2: Define the ideal best and ideal worst solutions.

The ideal best (A^+) and ideal worst (A^-) solutions are defined as shown in Eqs. (5) and (6).

$$A^+ = \left(r_1^+,\ r_2^+, \ldots., r_J^+\right) \quad (5)$$

$$A^- = \left(r_1^-,\ r_2^-, \ldots., r_J^-\right) \quad (6)$$

Where,$r_j^+ = \begin{cases} \max r_{ij}, & if jisabenefitcriteria \\ \min r_{ij}, & if jisacostcriteria \end{cases}$,

$r_j^- = \begin{cases} \min r_{ij}, & if jisabenefitcriteria \\ \max r_{ij}, & if jisacostcriteria. \end{cases}$

Step 3: Calculate the separation measures.

The separation measures are calculated by Eqs. (7) and (8).

$$P_i^+ = \sqrt{\sum_{j=1}^{J} \left(r_{ij} - r_j^+\right)^2} \quad (7)$$

$$P_i^- = \sqrt{\sum_{j=1}^{J} \left(r_{ij} - r_j^-\right)^2} \quad (8)$$

Step 4: Determine relative closeness.

The relative closeness is determined by Eq. (9).

$$C_i = \frac{P_i^-}{P_i^+ + P_i^-} \quad (9)$$

Step 5: Rank the preferences.

Order the preferences based on rank obtained in step 4.

The linguistic terms in the neutrosophic environment for the evaluation are illustrated in Table 3.

Table 3. Representation of neutrosophic numbers (NNs) for linguistic variables.

No.	Linguistic Variable	Code	NNs
1	Very Weak	VW	(0.1,0.35,0.8)
2	Weak	W	(0.3,0.45,0.7)
3	Acceptable	A	(0.5,0.49,0.5)
4	Strong	S	(0.8,0.35,0.4)
5	Very Strong	VS	(1,0.15,0.2)

The linguistic variables, their corresponding codes, and neutrosophic numbers are shown in Table 3. Each neutrosophic number represents truth, indeterminacy, and falsity. For instance, "Very Week" (VW) is assigned the neutrosophic number (0.1, 0.35, 0.8), indicating a low degree of truth, a moderate level of indeterminacy, and a high level of falsity. These values make a systematic assessment of the alternatives.

Opinions from decision-makers

Expert opinions provide significant value in MCDM contexts because they are essential in setting the weights of the criteria as well as in the assessment of strategy alternatives. In this paper, a collection of ten decision-makers was gathered, consisting of four academic members, three representatives of the private industry, and three representatives of the public sector working in the field of environmental engineering. Fig. 1 shows the professional backgrounds of these decision-makers and their affiliations. The evaluation of seven criteria by experts with the help of AHP was followed by the evaluation of four strategy alternatives with the help of TOPSIS. Decision-makers were contacted through

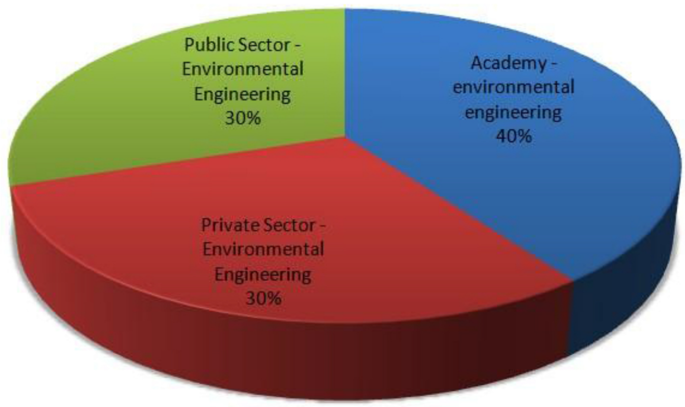

Fig. 1. Professional backgrounds of the experts.

email and the questionnaire, which is designed in Google forms (https://docs.google.com/forms/d/e/1FAIpQLSefEKABqTk5Ho_Zwey6yQzjSZsOoqtxP_Bw6LC2ehr2D76Eg/viewform?usp=header), was sent to them. The results of the expert assessments based on linguistic terms were obtained through the Google Forms.

Fig. 1 in the pie chart gives the areas of specialization and the type of organization each member of the decision-making committee belongs to. Most of the professionals, who comprise 40%, belong to the academic institutions that are dealing with environmental engineering. The next group to follow is the public sector and the private sector, which contribute up to 30% of the experts each. This distribution highlights a balance between academic, regulatory, and industry perspectives.

Results and discussion

Algorithm

In order to determine the effective waste management method through MCDM, the following steps are followed:

Step 1: Define a problem.
Step 2: Develop a hierarchical structure.
Step 3: Use AHP for calculating weights.
Step 4: Linguistic parameters are assigned to attributes and alternatives.
Step 5: Replace linguistic parameters with NNs.
Step 6: NNs can be converted to FNs with the help of the Accuracy function[42] as follows:

$$A\,(F) = \left(\frac{u_x + v_x + w_x}{3}\right)$$

Where, u_x represents True Membership, v_x represents Indeterminacy Membership, and w_x represents False Membership in NNs.

Step 7: Rank the values through the TOPSIS method.
Step 8: Discussion.

Fig. 2 shows the flowchart of the algorithm that was employed in the selection of the effective waste management techniques.

Fig. 2 represents the flowchart of the process of identifying effective sustainable approaches to waste management through the combination of AHP and TOPSIS in NSS structure. It will start by defining the problem and building a hierarchical system to organize the decision criteria in a hierarchical way. The weights of the criteria are calculated with the help of AHP. The criteria and alternatives are assigned to the linguistic parameters. All these parameters are then expressed as NNs which are further transformed into FNs. Finally, the TOPSIS method is used to prioritize the alternatives, and the results are assessed and analyzed to facilitate decision-making.

Implementation of the suggested algorithm

Step 1: The problem statement.
Step 2: Tables 1 and 2 contain the formulation of alternatives and criteria.
Step 3: The second step is to use the AHP algorithm with Pairwise Comparison Matrix to get the criterion weights as in Table 4.

The pairwise comparison matrix of criteria presented in Table 4 indicates the relative significance of one criterion over the other basing the significance on the preferences of a decision-maker. All the diagonal values are equal to 1 because all the criteria are equally important to themselves. The off-diagonal elements show the ratios of the importance in the eyes of Saaty on his 9-point scale. Table 4 is evaluated by

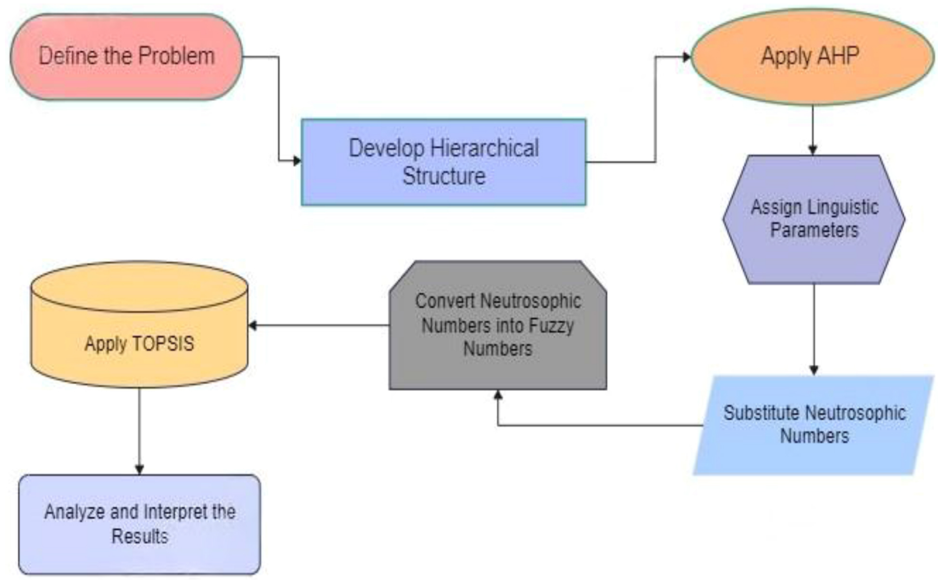

Fig. 2. Algorithm used in the selection of effective waste management techniques.

Table 4. Pairwise comparison matrix.

Criteria	C1	C2	C3	C4	C5	C6	C7
C1	1	2	2	2	2	2	3
C2	0.5	1	0.33	0.5	0.5	0.5	2
C3	0.5	3	1	0.5	0.5	0.5	3
C4	0.5	2	2	1	0.25	0.5	2
C5	0.5	2	2	4	1	0.5	2
C6	0.5	2	2	2	2	1	2
C7	0.33	0.5	0.33	0.5	0.5	0.5	1

finding the relative criteria weights that are provided in Table 5.

Table 5 shows the relative weight (W_j) of seven criteria (C1–C7), considered during the assessment. These values are indicators of the level of importance that each criterion will bear in the decision-making model. C1 has the highest weight (0.239792) and it is the most important criteria with C6 (0.185645) and C5 (0.178704) coming after. C7, conversely, is the lightest (0.062799) in terms of weight, which means that it has a relatively lower priority.

Step 4: Assign linguistic parameters to criteria and alternatives based on the perspectives of decision-makers as in Table 6.

Table 6 is a decision matrix depending on the preferences of the decision-makers, with four alternatives (A1 to A4) being rated regarding seven criteria (C1 to C7). The results in the matrix are the qualitative decisions, expressed in the form of the linguistic terms, to define the performance of each alternative in relation to each of the criteria.

Step 5: Assigning NNs for linguistic parameters of Table 3.

Table 7 indicates the substitution of each linguistic parameter with its corresponding NN.

Table 7 shows the allocation of the NNs to the linguistic variables provided by the decision-makers against each of the alternatives (A1 to A4) in accordance with the criteria (C1 to C7). These numbers are obtained based on the linguistic variables in Table 6, which shows the opinions of the decision-makers.

Step 6: Converting NNs to FNs of step 5 using the accuracy function. Table 8 depicts the result after the accuracy function has been applied and the results were converted into a FN that will be analyzed and interpreted.

The outcomes of the accuracy function of NNs to turn them into FNs are presented in Table 8. The table has a fuzzy value in each cell, which is a numerical representation of the NNs that each alternative and criterion represents.

Step 7: Next, we apply TOPSIS. Table 9 shows the normalized form of the decision matrices.

Table 5. Criteria weights.

Criteria	C1	C2	C3	C4	C5	C6	C7
W_j	0.239792	0.084378	0.126667	0.122015	0.178704	0.185645	0.062799

Table 6. Linguistic parameters.

	C1	C2	C3	C4	C5	C6	C7
A1	VW	V S	V W	S	A	W	S
A2	W	W	S	V W	V W	S	W
A3	A	V W	V S	W	A	V S	A
A4	S	V S	A	V S	S	A	V S

Table 7. Substitute a NN for each linguistic parameter.

	C1	C2	C3	C4	C5	C6	C7
A1	(0.1, 0.35, 0.8)	(1, 0.15, 0.2)	(0.1, 0.35, 0.8)	(0.8, 0.35, 0.4)	(0.5, 0.49, 0.5)	(0.3, 0.45, 0.7)	(0.8, 0.35, 0.4)
A2	(0.3, 0.45, 0.7)	(0.3, 0.45, 0.7)	(0.8, 0.35, 0.4)	(0.1, 0.35, 0.8)	(0.1, 0.35, 0.8)	(0.8, 0.35, 0.4)	(0.3, 0.45, 0.7)
A3	(0.5, 0.49, 0.5)	(0.1, 0.35, 0.8)	(1, 0.15, 0.2)	(0.3, 0.45, 0.7)	(0.5, 0.49, 0.5)	(1, 0.15, 0.2)	(0.5, 0.49, 0.5)
A4	(0.8, 0.35, 0.4)	(1, 0.15, 0.2)	(0.5, 0.49, 0.5)	(1, 0.15, 0.2)	(0.8, 0.35, 0.4)	(0.5, 0.49, 0.5)	(1, 0.15, 0.2)

Table 8. Once the accuracy function has been applied the resulting outcome is changed to an FN.

	C1	C2	C3	C4	C5	C6	C7
A1	0.417	0.45	0.417	0.517	0.497	0.483	0.517
A2	0.483	0.483	0.517	0.417	0.417	0.517	0.483
A3	0.497	0.417	0.45	0.483	0.497	0.45	0.497
A4	0.517	0.45	0.497	0.45	0.517	0.497	0.45

Table 9. Normalized form of decision matrices.

	C1	C2	C3	C4	C5	C6	C7
A1	0.434404	0.499329	0.441849	0.552076	0.513931	0.495525	0.530407
A2	0.503159	0.535947	0.547808	0.445292	0.431206	0.530407	0.495525
A3	0.517743	0.462712	0.476815	0.515769	0.513931	0.461669	0.509888
A4	0.538578	0.499329	0.526616	0.48053	0.534613	0.509888	0.461669

Table 10. Normalized weighted matrix.

W_j	0.23979	0.084378	0.126667	0.122015	0.178704	0.185645	0.062799
	C1	C2	C3	C4	C5	C6	C7
A1	0.104167	0.042132	0.055968	0.067362	0.091842	0.091991	0.033309
A2	0.120654	0.045222	0.069389	0.054332	0.077058	0.098467	0.031118
A3	0.124151	0.039043	0.060397	0.062932	0.091842	0.085706	0.03202
A4	0.129147	0.042132	0.066705	0.058632	0.095538	0.094658	0.028992

Step 7.1: Calculation of the normalized matrix that has weighted values are depicted in Table 10.

Table 10 shows the normalized weighted matrix, which is determined by multiplying all the elements of the normalized decision matrix (Table 9) by the corresponding criterion weight. Table 5 shows the weights that were used to reflect the relative weight of each criterion. This weighted matrix is important to assess the performance of each of the alternatives considering the overall impact of all criteria.

Step 7.2: Identification of ideal best and worst values. The ideal best and worst values are presented in Table 11.

The ideal best (r_j^+) and ideal worst (r_j^-) values of each criterion are given in Table 11. The ideal best values represent the maximum possible performance for each criterion, while the ideal worst values represent the minimum. These values are calculated from the normalized matrix with weighted values (Table 10) and are used in subsequent steps to compute the separation measures.

Table 11. Ideal best and ideal worst values.

	C1	C2	C3	C4	C5	C6	C7
A1	0.104167	0.042132	0.055968	0.067362	0.091842	0.091991	0.033309
A2	0.120654	0.045222	0.069389	0.054332	0.077058	0.098467	0.031118
A3	0.124151	0.039043	0.060397	0.062932	0.091842	0.085706	0.03202
A4	0.129147	0.042132	0.066705	0.058632	0.095538	0.094658	0.028992
r_j^+	0.104167	0.039043	0.069389	0.054332	0.077058	0.098467	0.028992
r_j^-	0.129147	0.045222	0.055968	0.067362	0.095538	0.085706	0.033309

Table 12. Determining the rank based on relative closeness.

	P_i^+	P_i^-	$P_i^+ + P_i^-$	C	Rank
A1	0.02527	0.026205	0.051475	0.509086	2
A2	0.017735	0.030515	0.048249	0.632437	1
A3	0.030736	0.010849	0.041586	0.260889	4
A4	0.031863	0.017315	0.049178	0.352089	3

Step 7.3: Determining relative closeness. Table 12 illustrates the determination of the rank based on relative closeness.

Table 12 provides the ranking of alternatives based on their relative closeness to the ideal solution. The values P_i^+ and P_i^- represent the distances of each alternative from the ideal best and ideal worst solutions, respectively. The relative closeness indicating how close each alternative is to the ideal option. The alternatives are then ranked in descending order, where Rank 1 is the most preferred option.

Step 8: Discussion.

This research employs AHP and TOPSIS to evaluate effective sustainable techniques in waste management for smart cities within NSS environment. Table 12 and Fig. 3 show the ranking of strategy about criterion. Following the results, the A2 is the highest-performing strategy in the considered alternative, then A1, and A4, and A3 will remain the fourth-best strategy. The findings provide a clear summary of the potential of each strategy to deal with the SWM issue in smart cities. As compared to existing literature,[34] the Hybrid Fuzzy AHP-TOPSIS approach had slightly different ranking of waste management strategies of smart cities. The alternatives were ranked according to the closeness coefficients and they were as follows: A2 > A3 > A4 > A1. Nevertheless, A2, or a A pay-as-you-throw system based on blockchain, is still continuously ranked among the most effective SWM to be used in smart cities.

Fig. 3 shows the position of the alternatives (A1, A2, A3, and A4) in terms of their relative closeness to each other. The ranking values are shown on the y-axis, which is the relative performance of the alternative. A2 (0.632) is the most desirable since it is ranked highest among the alternatives. The second-best alternative is A1 (0.509), while the third-best alternative is the A4 (0.352), and the least desirable score, is A3 (0.261). These rankings were identified based on AHP-TOPSIS methodology in a NSS environment, as presented in this paper.

Sensitivity analysis

In MCDM, sensitivity analysis helps with assessing the consistency and strength of results which makes the rankings reliable in different conditions. Sensitivity analysis was conducted in this study in five different scenarios which also included varying the criteria weights. In Scenario 1, the weight of benefit criterion was also increased by 25% and in Scenario 2, the weight of each cost criterion was also increased by 25%. Scenario 3 was a 50% decrease in the weight of benefit criterion and Scenario 4 a 75% decrease in the weight of benefit criterion. Lastly, Scenario 5 applied equal weights to all criteria to evaluate a balanced weighting approach. The values of the closeness coefficient (C_i) of the alternatives were recalculated in each case. The findings indicated that in Scenario 5 where equal weights had been considered on all criteria, though rankings were generally stable, slight change in the rankings had been observed. But the ranking in the first four cases (1–4) did not vary. Even with such slight adjustments in Scenario 5, the alternative that was selected as first was not changed in all scenarios. It is worth noting that the A pay-as-you-throw system with the use of blockchain technology (A2), secured the top place in all five cases, and always obtained the largest value of the closeness coefficient. Table 13 provides a summary of the obtained C_i values of the alternatives. The results indicate that the AHP-TOPSIS approach is robust and stable in a neutrosophic environment, which makes this approach reliable even when significant changes in the criteria weights.

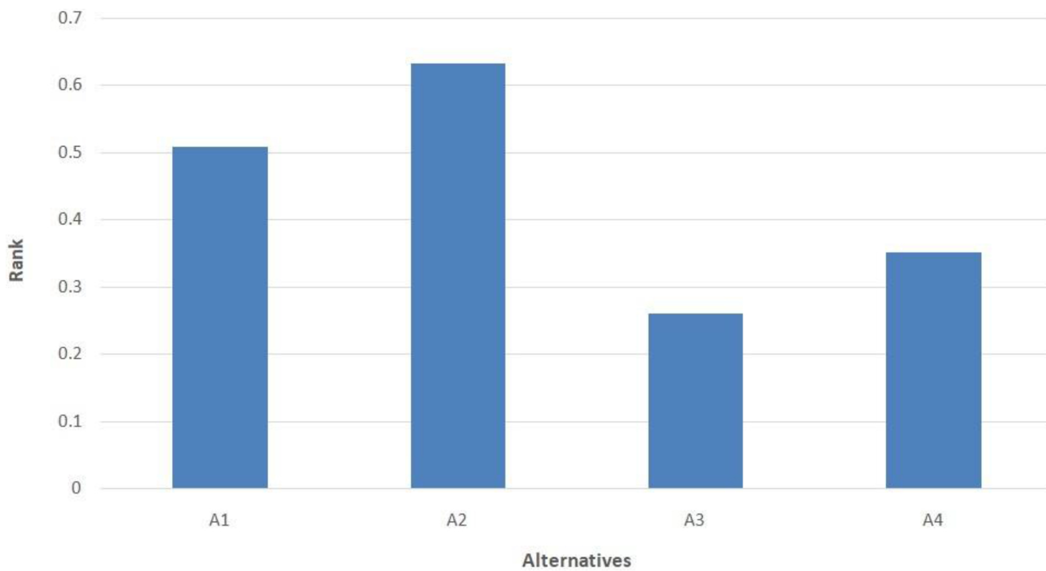

Fig. 3. Ranking of alternatives.

Table 13. Updated C_i values for the alternatives following the sensitivity analysis.

Scenario	C_i (A1)	C_i (A2)	C_i (A3)	C_i (A4)
1	0.49074	0.65404	0.25649	0.38706
2	0.52317	0.61575	0.26434	0.32307
3	0.54126	0.59412	0.26882	0.28144
4	0.52651	0.61179	0.26516	0.31583
5	0.37965	0.65505	0.35306	0.47641

Table 13 shows the new C_i under different alternatives after the sensitivity analysis under five different scenarios. Under each of the scenarios, the table records the C_i values of four alternatives (A1, A2, A3 and A4). The different scenarios (1–5) were represented by each row, and the weights of the criteria were changed. Such C_i values represent the performance of one alternative compared to another.

Conclusion

Waste management plays a critical role in sustaining a healthy environment, safeguarding health of the public and enhancing economic stability. By effectively managing waste, it can able to control pollution, save natural resources, curb climate change, and improve the living standards in our society. The most effective SWM technique is determined in this proposed work with the help of MCDM methods, AHP, and TOPSIS in an NSS environment. NSS is dealing with vagueness and uncertainty. Consequently, A2 (0.632) is the most effective and then A1 (0.509), A4 (0.352), and A3 (0.261). The results indicate the usefulness of the proposed methodology in the process of ranking and choosing waste management approaches. Nevertheless, the inconsistency in outcomes, which is affected by the variation of the opinions of the experts, emphasizes the characteristic of dynamism and flexible character of such evaluation. The study has a theoretical contribution as it shows that the NSS is applicable in addressing the complex multi-criteria problems in decision-making. On a practical level, it facilitates SWM practices. This study can be improved in future by adding alternative options and evaluation criteria, and using more sophisticated computational methods, including machine learning, to increase accuracy and flexibility. More than that, the potential of the framework is not limited to waste management, which is why it can be used in other areas where sustainable and evidence-based decision-making processes are required.

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Authors' declaration

- Conflicts of Interest: None.

- We hereby confirm that all the Figures and Tables in the manuscript are ours. Furthermore, any Figures and images, that are not ours, have been included with the necessary permission for republication, which is attached to the manuscript.
- No animal studies are present in the manuscript.
- No human studies are present in the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee at Vellore Institute of Technology, Vellore, India.

Authors' contribution statement

Conception, design, acquisition of data, analysis, interpretation, drafting the MS, revision and proofreading: S. B. Conceptualized and Computations E. D. Conceptualized and Verified the Accuracy.

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تقييم كمي للإدارة المستدامة الفعالة للنفايات باستخدام منهجية AHP-TOPSIS في بيئة نيوتروسوفية (في الهند)

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الخلاصة

تعتبر الإدارة الفعالة للنفايات أمرًا بالغ الأهمية للتنمية المستدامة وحماية البيئة، لا سيما في سياق المدن الذكية سريعة النمو. يقدم هذا البحث إطارًا مبتكرًا لاتخاذ القرار مصممًا للمساعدة في اختيار تقنيات مستدامة فعالة في إدارة النفايات للمدن الذكية. ويقوم بتقييم أربعة تقنيات مختلفة لإدارة النفايات مقابل سبعة معايير. يتم استخدام طريقتين لصنع القرار متعدد المعايير (MCDM): 1) عملية التسلسل الهرمي التحليلي (AHP) و 2) تقنية تفضيل الترتيب عن طريق التشابه مع الحل المثالي (TOPSIS) في بيئة المجموعة اللينة النيوتروصوفية. توفر المجموعات اللينة النيوتروصوفية إطارًا أكثر مرونة للتعامل مع حالة عدم اليقين وعدم الدقة الكامنة في صنع القرار بشأن إدارة النفايات. في هذه المنهجية، تحدد AHP أوزان معايير القرار، بينما تصنف TOPSIS استراتيجيات إدارة النفايات الفعالة للاختيار النهائي. قدم فريق من عشرة مهنيين من الجامعات والصناعة والقطاعات الحكومية آراء ذاتية من خلال استبيانات منظمة لهذا التقييم. ونتيجة لذلك، تم ترتيب البدائل على أساس قيم معامل التقارب على النحو التالي: A2 (0.632) > A1 (0.509) > A4 (0.352) > A3 (0.261)). يشير هذا الترتيب إلى أن A2 أكثر فعالية من A1 و A4 و A3.

الكلمات المفتاحية: AHP، صنع القرار، إدارة النفايات الفعالة، مجموعات لينة نيوتروسوفيك، TOPSIS.