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Optimization of municipal solid waste management using fuzzy technique for order of preference by similarity to ideal solution: A multi-criteria evaluation in the Rabat-Salé-Kénitra region (Morocco)

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ABSTRACT

Sustainable municipal solid waste (MSW) management is a major challenge for local authorities in Morocco. This study applies the fuzzy TOPSIS multi-criteria method to evaluate and rank seven MSW management scenarios for the prefectures of Rabat, Salé, and Skhirat-Témara in Morocco. The evaluation is based on 16 sub-criteria classified into five categories: institutional, social, environmental, economic, and technical. The study was based on the results of a survey conducted among experts with knowledge of MSW management (Regional Council, Regional Territorial Administration, Regional Department of the Environment). The survey data was then analyzed in the form of linguistic scales converted into triangular fuzzy numbers. The aggregated decision matrix was normalized, weighted, and compared to ideal positive and negative solutions according to the fuzzy TOPSIS algorithm, allowing the calculation of a proximity coefficient for each alternative. The results obtained indicate that alternative A7, corresponding to mechanical-biological treatment (MBT) coupled with energy recovery and composting, is the most efficient, with a proximity coefficient of 0.9767. It is followed by alternative A6 (sorting, composting, and energy recovery) with a score of 0.7275, then by alternative A5 (mechanical sorting and composting) with 0.6991. The other scenarios perform less well and are ranked in the following order: A3 (simple mechanical sorting, 0.4920), A4 (mechanical sorting, recycling, and landfill, 0.2914), A2 (sorting at source and selective collection, 0.2961), and finally A1 (collection and controlled landfill, 0.2390).

Keywords: municipal solid waste, decision-making, fuzzy TOPSIS, mechanical-biological treatment, Rabat, Salé, Skhirat-Témara, Morocco.

INTRODUCTION

In Morocco, solid waste management remains a major environmental and institutional challenge. Despite progress made over the past two decades, particularly with the implementation of the National Household Waste Program (PNDM) and the National Household Waste Recovery Program (PNVDM, 2023–2034), which primarily aim to close illegal dumps and improve the efficiency of controlled landfill sites, the system is still marked by significant contrasts between urban and peri-urban areas. While these infrastructures reflect a tangible effort toward better waste governance, the persistence of illegal sites has considerable environmental impacts: greenhouse gas emissions (Dahchour et al., 2020), soil degradation (El Fadili et al., 2022; Oubdil et al., 2025), and contamination of surface and groundwater (Chofqi et al., 2004; Ahouach et al., 2023; Benaddi et al., 2022; Mouman et al., 2025). In this context, the city of Salé highlights the untapped potential of biowaste, which represents a significant proportion of the municipal waste stream and can be valorized to produce high-quality compost (Majdouline et al., 2023a; Majdouline et al., 2024). Biological valorization, particularly composting and anaerobic digestion, therefore, appears as a strategic solution to enhance the sustainability of local waste management systems. These challenges, however, reflect a global issue, especially in developing countries where rapid urbanization, population growth, and changing consumption patterns complicate the implementation of integrated, economically viable, and environmentally sustainable management systems (Cervantes et al., 2018; Demesouka et al., 2013; Khan et al., 2018; Olay-Romero et al., 2020). In this context, the development of decision-making models adapted to local realities constitutes a strategic lever to achieve sustainability objectives and strengthen urban resilience in the face of growing waste pressure. The Rabat-Salé-Kénitra region, particularly the prefectures of Rabat, Salé, and Skhirate-Témara, exemplifies this issue. The Oum Azza site, covering 110 hectares, receives nearly 2,000 tons of municipal waste daily (El Jalil et al., 2020). Although designed as a model for sector modernization, this site has been criticized for odor nuisance, soil and groundwater pollution, and the impact of truck traffic associated with waste transport (Ait Errouhi et al., 2018; Touzani et al., 2021; El Fadili et al., 2023). These observations highlight the limitations of current management methods and underscore the need for a structured assessment tool based on objective and measurable criteria to guide the choice of municipal waste treatment and valorization technologies.

This study aims to develop and apply a fuzzy TOPSIS model for the optimal ranking of municipal solid waste treatment technologies in the prefectures of Rabat, Salé, and Skhirate-Témara, integrating technical, economic, environmental, and social criteria simultaneously. To date, no study in Morocco has combined a fuzzy approach with a multicriteria TOPSIS model specifically applied to the selection of municipal waste treatment technologies while accounting for the recently identified strategic importance of bio-waste. The research is based on three main hypotheses: that biological valorization (composting and/or anaerobic digestion) will achieve a higher overall score than landfill options if environmental and social criteria are properly weighted; that the integration of fuzzy logic improves the accuracy and robustness of the ranking by reducing the impact of uncertainties associated with expert judgments; and that a localized decision-making model will lead to recommendations different from those obtained using non-contextualized international standard criteria. By applying the Fuzzy TOPSIS method, this study provides a robust methodological framework to support decision-makers in the optimal selection of municipal solid waste treatment technologies, ensuring a balance between technical efficiency, environmental sustainability, economic viability, and social acceptability in a real Moroccan context.

METHODOLOGY

Study area

The study covers the prefectures of Rabat, Salé, and Skhirat-Témara, located in the Rabat–Salé–Kénitra region on Morocco's Atlantic coast (Figure 1). This agglomeration covers approximately 1,858.5 km² and has a population of 2,134,533 according to the 2014 RGPH (High Commission for Planning, 2024; Boulmani et al., 2023). Annual household waste production reaches 639,071 tons, or 0.85 kg/inhabitant/day (Municipal Council, 2024), which is higher than the national average (0.78 kg/inhabitant/day) (Kammou et al., 2024). Contractors collect waste daily, which is then transferred to transfer centers and the Oum Azza Landfill and Recovery Center (CEV).

As part of this research, seven alternatives for managing solid household waste (DSM), numbered A1 to A7, were established based on an in-depth review of the literature and feedback from comparable experiences. These scenarios were designed based on a combination of factors, including the specific national characteristics of the Moroccan context, lessons learned from international practices, and the specific characteristics of the study area. The evaluation of these alternatives is based on 16 sub-criteria, divided into four main dimensions: social, environmental, economic, and technical (Elhamdouni et al., 2022; Sadessa and Balo, 2025).

Expert opinions were gathered from three representative regional institutions: Regional council (CR), Regional Territorial Administration (ATR/RTA), and Regional Department of the Environment (DRE/RED). Each stakeholder provided linguistic assessments for each alternative and criterion (on a scale of "very low/low/medium/good/very good"), which were converted into triangular fuzzy numbers. First, the assessments of three different experts are considered.

To consider the relative importance of the criteria, the weightings were obtained from the same experts by expressing the relative importance of the criteria (linguistic scale), then converted into fuzzy values and aggregated (inter-institutional consensus). The fuzzy TOPSIS procedure applied includes the standard steps: normalization of fuzzy values (according to benefit/cost type), construction of the weighted matrix, determination of the ideal positive (FPIS) and negative (FNIS) solutions, calculation of the distances of each alternative to FPIS and FNIS, and calculation of the proximity coefficient (Cci) allowing the final ranking.

Description of alternatives studied

Seven alternatives (A1–A7) were developed based on a review of the literature and relevant national and international experiences. These scenarios combine different technical options for municipal solid waste (MSW) treatment, ranging from simple controlled landfilling (A1) to integrated recovery through composting and energy production (A7). Their design considers the specificities of the Moroccan context, available infrastructure, and regional socio-economic conditions (Elhamdouni et al., 2022; Mekan et al., 2013; EPA, 2021). Table 1 summarizes the seven management scenarios studied (A1–A7), developed from a combination of recognized international models and practices observed in Morocco. Each alternative incorporates a different level of treatment, ranging from simple controlled landfill to integrated recovery through composting and energy production. These scenarios form the basis of the multi-criteria decision matrix used in the fuzzy TOPSIS method.

Criteria and sub-criteria for comparative evaluation of alternatives

To rigorously evaluate the various options considered for optimizing DSM management in the main cities of the RSK region, a set of multidimensional criteria was defined. These criteria encompass institutional, social, environmental, economic, and technical aspects, thus providing an integrative and systematic framework for analysis. Table 2 presents the criteria and sub-criteria adopted to quantify and compare the performance of the proposed alternatives. This methodical approach not only ensures the

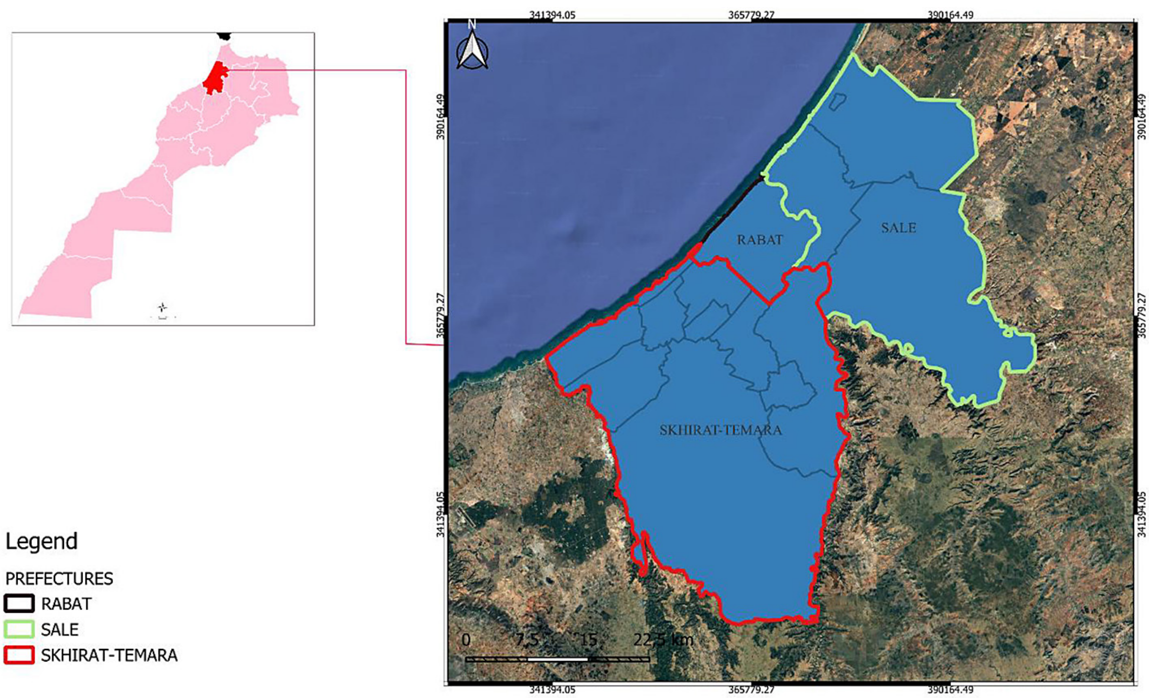

Figure 1. Geographical location of the prefectures of Rabat, Salé, and Skhirat-Temara

Table 1. Description of municipal solid waste management alternatives analyzed in the study (A1–A7)

Alternative	Designation	Technical overview	Main component	Environmental objective / Key benefit
A1	Collection and controlled landfilling	Mixed waste collection without prior sorting, disposal in a regulated landfill	Landfilling	Waste confinement leachate control
A2	Source separation and selective collection	Upstream separation of recyclable and organic fractions	Recycling, Composting	Reduction of landfill input flow
A3	Simple mechanical sorting	Mechanical separation of dry recyclables	Recycling	Material recovery of plastics and metals
A4	Mechanical sorting+ Recycling+ Landfilling	Centralized sorting, recycling of recoverable fractions, landfilling of residues	Recycling/ Landfilling	Reduction of residual waste volume
A5	Mechanical Sorting + Composting	Separation of organic matter followed by controlled composting	Composting	Compost production, reduction of CH_4 emissions
A6	Mechanical Sorting + Energy Recovery from Sorting Refusals (SRF)	Mechanical separation of recyclables, energy recovery	Recycling / SRF	Energy recovery, circular economy
A7	MBT + Energy recovery from sorting refusals (SRF) and Composting	Mechanical-biological treatment with energy and compost production	Integrated MBT	Integrated solution, minimization of final waste

Table 2. Criteria and sub-criteria for multi-criteria evaluation of municipal solid waste (MSW) management alternatives

Criteria	Sub-criteria	Description	Criteria type
Technique	Feasibility and operability (FO)	The technical capability of the system to perform reliably and efficiently in the local context.	Profit
	Appropriation (AP)	Level of experience and competence with similar solutions in Morocco.	Profit
	Qualification (QU)	Skills and expertise required of personnel for operation and maintenance.	Cost
	Urban planning (UP)	System compatibility with existing infrastructure and development constraints.	Profit
Économie	Investment cost (IC)	Total amount of investment required to implement the solution.	Cost
	Operating cost (OC)	Annual expenses related to operation, transportation, and maintenance.	Cost
	Land requirement (LR)	Area and location required to set up the facilities.	Cost
	Profitability (RE)	Potential for creating economic value and generating valuable products.	Profit
Environment	Environmental impact (EI)	Overall level of potential impact on the climate (GHG) and ecosystems.	Cost
	Environmental pollution (ES)	Risks of air, water, and soil pollution associated with the system.	Cost
	Solid residues (SR)	Volume and nature of residues generated after treatment.	Cost
	Visual and olfactory nuisances (VO)	Negative aesthetic and olfactory effects perceived by the population.	Cost
Social	Legislative application (LA)	Compliance of the system with national public policies and regulatory frameworks.	Profit
	Implementing organization (IO)	Clarity of the governance model and institutional coordination.	Profit
	Social acceptance (SA)	Level of engagement and participation of citizens and local stakeholders.	Profit
	Social impact (SI)	Positive effects on employment, quality of life, and social cohesion.	Profit

Note: Adapted from Elhamdouni et al., (2022); EPA (2021), Mekan et al., (2013) and supplemented by local expertise (2024).

transparency and reproducibility of the assessment but also facilitates the identification of the solutions best suited to local specificities, while integrating the operational and contextual constraints of the territory. The criteria and sub-criteria selected (Table 2) cover the four dimensions of sustainable development: technical, economic, environmental, and socio institutional. Each criterion is classified according to its type (benefit or cost) to facilitate the normalization process in the fuzzy TOPSIS method (Kahraman et al., 2015).

Key institutional actors in municipal solid waste management in the RSK region

Three key institutions participated in the validation of the results: the CR, which ensures territorial consistency; the Regional Territorial Administration (ATR), responsible for regulatory implementation; and the Regional Department of the Environment (DRE), responsible for technical monitoring and environmental assessment. Their involvement ensured the territorial and institutional legitimacy of the multi-criteria assessment applied to the RSK region.

Choosing an appropriate method

Decision-making in complex contexts cannot be limited to a single criterion, as this may lead to partial or biased results. A multi-criteria approach that simultaneously integrates technical, economic, environmental, and social dimensions is more appropriate for identifying the optimal solution. When information is imprecise or incomplete, fuzzy logic is a particularly robust decision-making tool, capable of modeling the uncertainty and subjectivity of human judgments. Fuzzy methods, whether they involve multi-attribute or multi-objective decision-making, are now applied in many fields: logistics, engineering, management, environmental, sustainable development and health sciences (Kahraman et al., 2015; Sadessa and Balo, 2025; Stecyk, 2019). However, the choice of a decision support method must be based on a thorough understanding of the problem, the available alternatives, the potential interactions between criteria, and the degree of uncertainty associated with the data (Elhamdouni et al., 2022).

Description of the fuzzy TOPSIS method

Fuzzy TOPSIS (technique for order of preference by similarity to ideal solution) is an extension of TOPSIS that incorporates logic to better represent uncertainty and subjectivity in multi-criteria evaluation. It is used to rank strategic alternatives according to weighted criteria. Normalized fuzzy values are used to determine the distances to the positive ideal solution (FPIS) and the negative ideal solution (FNIS), making it possible to calculate the proximity coefficient (Cci) for each alternative and determine the optimal strategy. The TOPSIS approach ensures accurate and discriminating evaluation of alternatives while incorporating the uncertainty of expert assessments (Sadessa and Balo, 2025; Sagnak et al., 2021; Rani et al., 2020; Sahar et al., 2024). Fuzzy TOPSIS method is an extension of TOPSIS that integrates fuzzy logic to better represent uncertainty and subjectivity in multi-criteria evaluation. To overcome the limitations of the traditional TOPSIS method in dealing with imprecise situations, its fuzzy variant (fuzzy TOPSIS) incorporates cardinal data to analyze issues with a degree of uncertainty (Sadessa and Balo, 2025). The fundamental principle of the method is based on the idea that each alternative has two references (Sagnak et al., 2021; Rani et al., 2020):

- the positive ideal solution (FPIS), corresponding to the best performance on all criteria,
- and the negative ideal solution (FNIS), represents the least favorable performance.

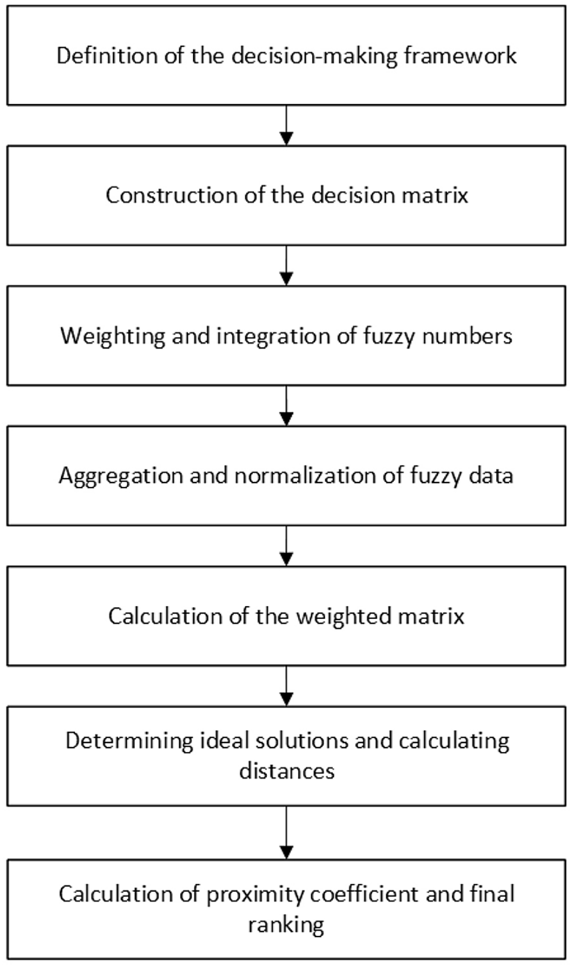

Figure 2. Successive steps in the fuzzy TOPSIS method, from defining criteria to ranking alternatives

The fuzzy TOPSIS method is based on a series of successive steps that allow a set of alternatives to be compared according to several criteria evaluated by experts (Figure 2).

Step 1: Construction of the decision matrix

In an uncertain multi-criteria decision-making problem, a set of alternatives is examined in relation to a set of selected criteria $C = \{C_j \mid j = 1, ..., m\}$based on the judgments made by a set of decision-makers $M = \{M_k \mid k = 1, ... , l\}$. The fuzzy decision matrix can then be represented as follows:

$$DM = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad (1)$$

where: $\tilde{x}_{ij} = (aij, bij, cij)$ represents a triangular fuzzy score assigned to alternative A_i according to criterion C_j, calculated from the experts-s evaluations:

With:

$$a_{ij} = \min\,(a_{ij}^{(k)}),$$

$$b_{ij} = \frac{1}{l}\sum_{k=1}^{l} b_{ij}^{(k)}\,,\; c_{ij} = \max\,(c_{ij}^{(k)})$$

Each fuzzy value (aij, bij, cij) corresponds respectively to the lower limit, the most probable value, and the upper limit of the judgments obtained from the experts, allowing for a more realistic representation of the uncertainty associated with the evaluation of alternatives.

Step 2: Normalization of the fuzzy decision matrix

The normalized fuzzy decision matrix $\tilde{R} = [\tilde{r}_{ij}]_{n\times m}$, is obtained by applying formulas for benefit-type and cost-type criteria.

For benefit criteria, normalization is performed by dividing each triangular fuzzy number $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ by the maximum value of its upper interval (Equation 2):
Benefit criterion:

$$\bar{r}_{ij} = (\frac{a_{ij}}{c_j^+}, \frac{b_{ij}}{c_j^+}, \frac{c_{ij}}{c_j^+})\; With\; c_j^+ = \max{}_i\, c_{ij} \quad (2)$$

However, for cost criteria, normalization is performed by dividing the smallest fuzzy value a_j^- by each element of the triangular fuzzy number, as expressed in the following relation (Eq.3):
Cost criterion:

$$\bar{r}_{ij} = \left(\frac{a_j^-}{a_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{c_{ij}}\right)\; With\; a_j^- = \min{}_i\, a_{ij} \quad (3)$$

Step 3: Construction of the weighted normalized fuzzy decision matrix

After obtaining the normalized fuzzy decision matrix, each criterion is weighted to reflect its relative importance in the decision-making process.

The weighted normalized matrix is given by the following relationship (4).

$$\bar{P} = [\bar{P}_{ij}] = \bar{r}_{ij} \times \bar{w}_j \quad (4)$$

where: $i = 1, 2,\ldots\ldots, n$ and $j = 1, 2,\ldots.., m.$

Step 4: Determining the ideal solutions

In this step, we calculate the distance of each alternative from the positive ideal solution A^+ and the negative ideal solution A^-. The positive and negative solutions are given by the following equations (Equation 5 and Equation 6):

$$A^+ = (p_1^+, p_2^+, \ldots, p_n^+) \quad (5)$$

with

$$p_j^+ = \max_i\,\{p_{ij}^3\}$$

$$A^- = (p_1^-, p_2^-, \ldots, p_n^-) \quad (6)$$

with:

$$p_j^- = \min_i\,\{p_{ij}^1\}$$

Step 5: Calculating the distance of each alternative from the ideal solutions

The distance of each alternative from the positive and negative ideal solutions is calculated as follows:

$$FPIS = S^+(A_i) = \sqrt{\frac{1}{n}\sum_{j=1}^{m}(p_{ij} - p_j^+)^2} \quad (7)$$

$$FNIS = S^-(A_i) = \sqrt{\frac{1}{n}\sum_{j=1}^{m}(p_{ij} - p_j^-)^2} \quad (8)$$

The distance (pi+, pi–) of each alternative i=1,…,m from the FPIS and FNIS is given by the following equations:

$$d_i^+ = \sum_{j=1}^{n} d(p_{ij}, p_j^+) \quad (9)$$

$$d_i^- = \sum_{j=1}^{n} d(p_{ij}, p_j^-) \quad (10)$$

Step 6: Calculation of the proximity coefficient

For each alternative, the proximity coefficient is defined by:

$$CC_i = \frac{S^-(A_i)}{S^-(A_i)+S^+(A_i)}, i = 1, \ldots, n \quad (11)$$

Step 7: Ranking and selection of the best alternative

The alternatives are ranked according to their proximity coefficient CC_i. The highest-ranked option is the alternative with the highest CC_i value.

Identification of fuzzy numbers

Fuzzy multi-criteria evaluation is based on the use of linguistic values converted into triangular fuzzy numbers, allowing the qualitative judgments of decision-makers to be translated into manipulable quantitative values (Fei et al.,

Table 3. Correlation between linguistic variables and their representations in triangular fuzzy numbers

Triangular fuzzy numbers	Alternative assessment	Acronym (Abbreviation)	Weight of criteria	Acronym (Abbreviation)
(1, 1, 3)	Very Poor	VP	Very Low	VL
(1, 3, 5)	Poor	P	Low	L
(3, 5, 7)	Fair	F	Medium	M
(5, 7, 9)	Good	G	High	H
(7, 9, 9)	Very Good	VG	Very High	VH

Note: Adapted from Chen et al., 1992; Kahraman et al., 2015; Neelima et al., 2017; Yu-Jui et al., 2007. These values are used to convert linguistic judgments into triangular fuzzy numbers in the fuzzy TOPSIS method.

Table 4. Results of the evaluation of the different alternatives

Alternative	Experts	Technical				Economical				Environmental				Social			
		FO	AP	QU	UP	IC	OC	LR	PR	EI	ES	SR	VO	LA	IO	SA	SI
A1	RC	(1,1,3)	(1,1,3)	(7,9,9)	(1,1,3)	(7,9,9)	(7,9,9)	(7,9,9)	(1,1,3)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(1,1,3)	(5,7,9)
	RTA	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(1,3,5)	(1,1,3)	(1,1,3)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(1,1,3)	(5,7,9)
	RED	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(1,3,5)	(1,1,3)	(1,1,3)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(5,7,9)	(5,7,9)	(1,1,3)	(5,7,9)
A2	RC	(1,3,5)	(1,3,5)	(5,7,9)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(1,3,5)	(1,3,5)
	RTA	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(1,3,5)	(1,3,5)
	RED	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(1,3,5)	(1,3,5)
A3	RC	(1,3,5)	(1,3,5)	(3,5,7)	(1,3,5)	(3,5,7)	(3,5,7)	(3,5,7)	(1,3,5)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(5,7,9)	(5,7,9)	(1,3,5)	(1,3,5)
	RTA	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,3)	(5,7,9)	(5,7,9)	(1,3,5)	(1,3,5)
	RED	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,3)	(5,7,9)	(5,7,9)	(1,3,5)	(1,3,5)
A4	RC	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(5,7,9)	(5,7,9)	(3,5,7)	(3,5,7)
	RTA	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(5,7,9)	(5,7,9)	(3,5,7)	(3,5,7)
	RED	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(3,5,7)	(5,7,9)	(5,7,9)	(3,5,7)	(3,5,7)
A5	RC	(3,5,7)	(3,5,7)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)	(1,3,5)	(3,5,7)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(3,5,7)	(3,5,7)
	RTA	(5,7,9)	(7,9,9)	(5,7,9)	(7,9,9)	(5,7,9)	(7,9,9)	(5,7,9)	(7,9,9)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(7,9,9)
	RED	(5,7,9)	(7,9,9)	(5,7,9)	(7,9,9)	(5,7,9)	(7,9,9)	(5,7,9)	(7,9,9)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(7,9,9)
A6	RC	(5,7,9)	(5,7,9)	(1,3,5)	(5,7,9)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)
	RTA	(3,5,7)	(5,7,9)	(3,5,7)	(5,7,9)	(3,5,7)	(5,7,9)	(3,5,7)	(5,7,9)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(3,5,7)	(5,7,9)
	RED	(3,5,7)	(5,7,9)	(3,5,7)	(5,7,9)	(3,5,7)	(5,7,9)	(3,5,7)	(5,7,9)	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(5,7,9)	(5,7,9)	(3,5,7)	(5,7,9)
A7	RC	(7,9,9)	(7,9,9)	(1,1,3)	(7,9,9)	(1,1,3)	(1,1,3)	(1,1,3)	(7,9,9)	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)
	RTA	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)
	RED	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)	(1,1,3)	(1,1,3)	(1,1,3)	(1,1,3)	(7,9,9)	(7,9,9)	(7,9,9)	(7,9,9)

Table 5. Aggregate fuzzy decision matrix

Sub-criterion	A1	A2	A3	A4	A5	A6	A7
FO	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,6.33,9)	(3,5.67,9)	(7,9,9)
AP	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,7.67,9)	(5,7,9)	(7,9,9)
QU	(1,3.67,9)	(1,4.33,9)	(1,3.67,7)	(3,5,7)	(1,5.67,9)	(1,4.33,7)	(1,6.33,9)
UP	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,7.67,9)	(5,7,9)	(7,9,9)
IC	(1,3.67,9)	(1,4.33,9)	(1,3.67,7)	(3,5,7)	(1,5.67,9)	(1,4.33,7)	(1,6.33,9)
OC	(1,3.67,9)	(1,4.33,9)	(1,3.67,7)	(3,5,7)	(1,7,9)	(1,5.67,9)	(1,6.33,9)
LR	(1,3.67,9)	(1,4.33,9)	(1,3.67,7)	(3,5,7)	(1,5.67,9)	(1,4.33,7)	(1,6.33,9)
PR	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,7.67,9)	(5,7,9)	(7,9,9)
EI	(5,7.67,9)	(5,7,9)	(1,3.67,7)	(3,5,7)	(1,3,5)	(1,2.33,5)	(1,1,3)
WS	(5,7.67,9)	(5,7,9)	(1,3.67,7)	(3,5,7)	(1,3,5)	(1,2.33,5)	(1,1,3)
SR	(5,7.67,9)	(5,7,9)	(1,3.67,7)	(3,5,7)	(1,3,5)	(1,2.33,5)	(1,1,3)
VO	(5,7.67,9)	(5,7,9)	(1,3.67,7)	(3,5,7)	(1,3,5)	(1,2.33,5)	(1,1,3)
LA	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(7,9,9)
IO	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	(7,9,9)
SA	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	(3,6.33,9)	(3,5.67,9)	(7,9,9)
SI	(5,7,9)	(1,3,5)	(1,3,5)	(3,5,7)	(3,7.67,9)	(5,7,9)	(7,9,9)

2014; Kahraman et al., 2015). These conversion scales, generally based on a rating from 1 to 9, ensure a balanced representation of assessment levels. The numerical intervals associated with each linguistic term (low, medium, high, very high, etc.) facilitate the modeling of fuzzy values and the aggregation of expert judgments (Ekmekçioglu et al., 2010; Neelima et al., 2017). To translate the qualitative judgments of experts into quantitative values that can be used by the model, linguistic terms were associated with triangular fuzzy numbers according to the notation proposed by Chen (1992) and widely used in the literature (Kahraman et al., 2015; Neelima et al., 2017). Table 3 presents the correspondence used for the evaluation of alternatives and the weighting of criteria.

RESULTS

From the literature, seven alternatives were identified to evaluate their performance across sixteen sub-criteria. Three key regional institutional actors were invited to evaluate the performance of the urban waste management strategy in the RSK prefectures using a linguistic scale ranging from "very poor" to "very good." All respondents were asked to give their opinion on the performance evaluation of municipal waste management alternatives according to the evaluation criteria (Table 4) and aggregated by applying the arithmetic means of all experts (see Table 5). Using equations (2–3), a normalized decision matrix can be calculated from an aggregated decision matrix, which depends on the objective of the sub criteria.

The sub-criteria are defined as benefit and cost criteria, depending on whether the objective is to maximize or minimize. Equation 2 is used for criteria identified as benefit or maximization objectives, while Equation 3 is used for criteria considered as cost or minimization objectives, to develop the overall structure of the normalized decision matrix. In this study, eight sub-criteria were determined as cost criteria and eight as benefit criteria. Table 6 presents the corresponding normalized matrix.

After normalizing the decision matrix while considering the weight of each criterion obtained (Table 7), the weighted normalized fuzzy decision matrix was constructed by integrating the criterion weight into the normalized fuzzy matrix, as defined in Equation 4. The final weighted fuzzy matrix is presented in (Table 8). Next, the ranking of each alternative in relation to the positive (A^+) and negative (A^-) ideal solutions was determined using Equations 5 and 6, respectively. The most suitable option corresponds to the alternative that is nearest to the FPIS and most distant from the FNIS.

Once the ideal positive and negative points were established for each sub-criterion related to the selection of a municipal solid waste

Table 6. Normalized decision matrix

Sub-criterion	A1	A2	A3	A4	A5	A6	A7
FO	(0.11, 0.11, 0.33)	(0.11, 0.33, 0.56)	(0.11, 0.33, 0.56)	(0.33, 0.56, 0.78)	(0.33, 0.70, 1.00)	(0.33, 0.63, 1.00)	(0.78, 1.00, 1.00)
AP	(0.11, 0.11, 0.33)	(0.11, 0.33, 0.56)	(0.11, 0.33, 0.56)	(0.33, 0.56, 0.78)	(0.33, 0.85, 1.00)	(0.56, 0.78, 1.00)	(0.78, 1.00, 1.00)
QU	(0.11, 0.27, 1.00)	(0.11, 0.23, 1.00)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.11, 0.18, 1.00)	(0.14, 0.23, 1.00)	(0.11, 0.16, 1.00)
UP	(0.11, 0.11, 0.33)	(0.11, 0.33, 0.56)	(0.11, 0.33, 0.56)	(0.33, 0.56, 0.78)	(0.33, 0.85, 1.00)	(0.56, 0.78, 1.00)	(0.78, 1.00, 1.00)
IC	(0.11, 0.27, 1.00)	(0.11, 0.23, 1.00)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.11, 0.18, 1.00)	(0.14, 0.23, 1.00)	(0.11, 0.16, 1.00)
OC	(0.11, 0.27, 1.00)	(0.11, 0.23, 1.00)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.11, 0.14, 1.00)	(0.11, 0.18, 1.00)	(0.11, 0.16, 1.00)
LR	(0.11, 0.27, 1.00)	(0.11, 0.23, 1.00)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.11, 0.18, 1.00)	(0.14, 0.23, 1.00)	(0.11, 0.16, 1.00)
PR	(0.11, 0.11, 0.33)	(0.11, 0.33, 0.56)	(0.11, 0.33, 0.56)	(0.33, 0.56, 0.78)	(0.33, 0.85, 1.00)	(0.56, 0.78, 1.00)	(0.78, 1.00, 1.00)
EI	(0.11, 0.13, 0.20)	(0.11, 0.14, 0.20)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.20, 0.33, 1.00)	(0.20, 0.43, 1.00)	(0.33, 1.00, 1.00)
WS	(0.11, 0.13, 0.20)	(0.11, 0.14, 0.20)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.20, 0.33, 1.00)	(0.20, 0.43, 1.00)	(0.33, 1.00, 1.00)
SR	(0.11, 0.13, 0.20)	(0.11, 0.14, 0.20)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.20, 0.33, 1.00)	(0.20, 0.43, 1.00)	(0.33, 1.00, 1.00)
VO	(0.11, 0.13, 0.20)	(0.11, 0.14, 0.20)	(0.14, 0.27, 1.00)	(0.14, 0.20, 0.33)	(0.20, 0.33, 1.00)	(0.20, 0.43, 1.00)	(0.33, 1.00, 1.00)
LA	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.78, 1.00, 1.00)
IO	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.56, 0.78, 1.00)	(0.78, 1.00, 1.00)
SA	(0.11, 0.11, 0.33)	(0.11, 0.33, 0.56)	(0.11, 0.33, 0.56)	(0.33, 0.56, 0.78)	(0.33, 0.70, 1.00)	(0.33, 0.63, 1.00)	(0.78, 1.00, 1.00)
SI	(0.56, 0.78, 1.00)	(0.11, 0.33, 0.56)	(0.11, 0.33, 0.56)	(0.33, 0.56, 0.78)	(0.33, 0.85, 1.00)	(0.56, 0.78, 1.00)	(0.78, 1.00, 1.00)

management strategy, the distances between each alternative and these two solutions were calculated. Equations 9 and 10 were applied to compute the distances to the FPIS (Fuzzy positive ideal solution) and FNIS (Fuzzy negative ideal solution), respectively. The results of these calculations are presented in Table 9. Table 9 indicates that the lowest d^{-} values correspond to the alternative located to the negative ideal solution, which corresponds to the best possible performance, whereas the highest d^{-} values indicate the alternative farthest from the ideal solution. Conversely, higher d^{+} values indicate proximity to the positive ideal solution, i.e., the best alternative, while lower d^{+} values correspond to the least performing alternative according to the criterion considered.

Furthermore, the closeness coefficient was derived using Equation 11. The option nearest to the fuzzy positive ideal solution (FPIS) is selected as the best alternative, whereas the alternative farthest from the FPIS is designated as the least favorable. Conversely, the alternatives farthest and closest to the fuzzy negative ideal solution (FNIS) are viewed as the best and worst alternatives, respectively. Table 10 and Figure 3 presents the results of the closeness coefficient and the final ranking of the alternatives.

Table 7. Aggregated fuzzy matrix of criteria weights

Sub-criterion	Value
FO	(7.00, 7.00, 9.00)
AP	(7.00, 7.00, 9.00)
QU	(3.00, 5.67, 9.00)
UP	(3.00, 6.33, 9.00)
IC	(5.00, 7.00, 9.00)
OC	(7.00, 7.00, 9.00)
LR	(1.00, 4.33, 7.00)
PR	(5.00, 7.00, 9.00)
EI	(5.00, 7.00, 9.00)
WS	(5.00, 7.00, 9.00)
SR	(5.00, 7.00, 9.00)
VO	(5.00, 7.00, 9.00)
LA	(5.00, 7.00, 9.00)
IO	(3.00, 5.67, 9.00)
SA	(5.00, 7.00, 9.00)
SI	(5.00, 7.00, 9.00)

Table 8. Results of the decision matrix after normalization and weighting

Sub-criterion	A1	A2	A3	A4	A5	A6	A7
FO	(0.78,0.78,3.00)	(0.78,2.33,5.00)	(0.78,2.33,5.00)	(2.33,3.89,7.00)	(2.33,4.93,9.00)	(2.33,4.41,9.00)	(5.44,7.00,9.00)
AP	(0.78,0.78,3.00)	(0.78,2.33,5.00)	(0.78,2.33,5.00)	(2.33,3.89,7.00)	(2.33,5.96,9.00)	(3.89,5.44,9.00)	(5.44,7.00,9.00)
QU	(0.33,1.55,9.00)	(0.33,1.31,9.00)	(0.43,1.55,9.00)	(0.43,1.13,3.00)	(0.33,1.31,9.00)	(0.43,1.31,9.00)	(0.33,0.90,9.00)
PU	(0.33,1.70,3.00)	(0.33,2.11,5.00)	(0.33,2.11,5.00)	(1.00,3.52,7.00)	(1.00,5.40,9.00)	(1.67,4.93,9.00)	(2.33,6.33,9.00)
CI	(0.56,1.91,9.00)	(0.56,1.62,9.00)	(0.71,1.91,9.00)	(0.71,1.40,3.00)	(0.56,1.24,9.00)	(0.71,1.62,9.00)	(0.56,1.11,9.00)
CF	(0.78,1.91,9.00)	(0.78,1.62,9.00)	(1.00,1.91,9.00)	(1.00,1.40,3.00)	(0.78,1.00,9.00)	(0.78,1.24,9.00)	(0.78,1.11,9.00)
EF	(0.11,1.18,7.00)	(0.11,1.00,7.00)	(0.14,1.18,7.00)	(0.14,0.87,2.33)	(0.11,0.76,7.00)	(0.14,1.00,7.00)	(0.11,0.68,7.00)
RE	(0.56,0.78,3.00)	(0.56,2.33,5.00)	(0.56,2.33,5.00)	(2.33,3.89,7.00)	(1.67,5.96,9.00)	(2.78,5.44,9.00)	(3.89,7.00,9.00)
IE	(0.56,0.91,1.80)	(0.56,1.00,1.80)	(0.71,1.91,9.00)	(0.71,1.40,3.00)	(1.00,2.33,9.00)	(1.00,3.00,9.00)	(1.67,7.00,9.00)
ES	(0.56,0.91,1.80)	(0.56,1.00,1.80)	(0.71,1.91,9.00)	(0.71,1.40,3.00)	(1.00,2.33,9.00)	(1.00,3.00,9.00)	(1.67,7.00,9.00)
RS	(0.56,0.91,1.80)	(0.56,1.00,1.80)	(0.71,1.91,9.00)	(0.71,1.40,3.00)	(1.00,2.33,9.00)	(1.00,3.00,9.00)	(1.67,7.00,9.00)
VO	(0.56,0.91,1.80)	(0.56,1.00,1.80)	(0.71,1.91,9.00)	(0.71,1.40,3.00)	(1.00,2.33,9.00)	(1.00,3.00,9.00)	(1.67,7.00,9.00)
AL	(2.78,5.44,9.00)	(2.78,5.44,9.00)	(2.78,5.44,9.00)	(2.78,5.44,9.00)	(2.78,5.44,9.00)	(2.78,5.44,9.00)	(3.89,7.00,9.00)
OM	(1.67,4.41,9.00)	(1.67,4.41,9.00)	(1.67,4.41,9.00)	(1.67,4.41,9.00)	(1.67,4.41,9.00)	(1.67,4.41,9.00)	(2.33,5.67,9.00)
AS	(0.56,0.78,3.00)	(0.56,2.33,5.00)	(0.56,2.33,5.00)	(1.67,3.89,7.00)	(1.67,4.93,9.00)	(1.67,4.41,9.00)	(3.89,7.00,9.00)
IS	(2.78,5.44,9.00)	(0.56,2.33,5.00)	(0.56,2.33,5.00)	(1.67,3.89,7.00)	(1.67,5.96,9.00)	(2.78,5.44,9.00)	(3.89,7.00,9.00)

Table 9. Distance between alternatives and ideal positive and negative solutions

Parameter	Distance from positive ideal (d^+)	Distance from negative ideal(d^-)
A1	52.176	16.387
A2	48.955	20.596
A3	38.460	37.250
A4	49.324	20.284
A5	23.894	55.520
A6	20.799	55.521
A7	1.622	67.903

Table 10. Closeness coefficients (Cci)

Parametr	CC_i	Score
A1	0.2390	6
A2	0.2961	5
A3	0.4920	4
A4	0.2914	7
A5	0.6991	3
A6	0.7275	2
A7	0.9767	1

DISCUSSION

Based on the results presented in Figure 2, obtained using the fuzzy TOPSIS method, the highest-ranked alternative is mechanical-biological treatment (MBT) with energy recovery and composting (A7), which achieved a proximity coefficient (Cci) of 0.9767. It is followed by mixed collection combined with mechanical sorting and material recovery with RDF production (A6, Cci = 0.7275), and by mixed collection, mechanical sorting, material recovery, and composting (A5, Cci = 0.6991). The remaining alternatives, particularly those involving source separation and anaerobic digestion (A4), obtained lower scores, reflecting their limited suitability for municipal solid waste management in the Rabat–Salé–Kénitra region. These results underline the effectiveness of integrated waste management systems that simultaneously treat mixed waste streams while combining material and energy recovery processes, such as mechanical-biological treatment (MBT). This approach distinguishes itself by significantly reducing landfill disposal, recovering energy in the form of solid recovered fuel (SRF), lowering greenhouse gas emissions, and stabilizing the organic fraction of waste (Mathlouthi et al., 2024). Moreover, MBT supports a gradual

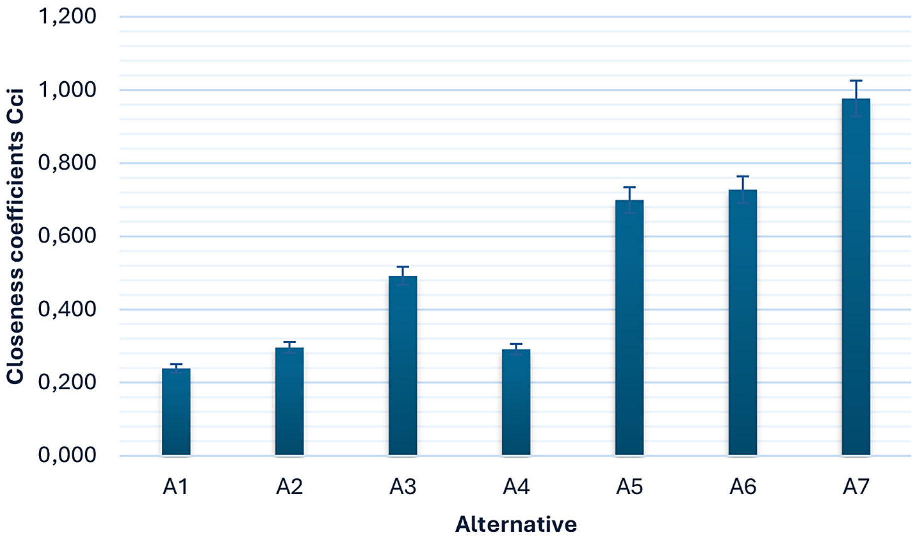

Figure 3. Graphical representation of Closeness coefficients

transition toward a circular economy without requiring full source separation, a measure that remains challenging to implement in developing urban contexts (Fan et al., 2018).

Alternative A6, which combines mechanical sorting, material recovery, and SRF production, ranks second. This finding highlights the growing potential of energy recovery from residual waste, which reduces landfill dependency and contributes to alternative energy production (Ouigmane et al., 2021). However, the feasibility and sustainability of this option depend on the presence of compatible industrial facilities, notably cement plants and on the quality and calorific value of the produced fuel, both of which are influenced by the level of contamination in the collected waste (Hasib et al., 2020).

In third position, alternative A5 (mechanical sorting and composting) illustrates the importance of biological recovery of the organic fraction of municipal solid waste, in line with several studies that have demonstrated the high environmental, economic, and agronomic potential of composting in Moroccan cities, where organic matter represents more than 50% of the total waste stream (El Hallab et al., 2025).

This option derives its relevance from its capacity to reduce landfill disposal, stabilize the biodegradable fraction, and produce nutrient-rich compost, thereby contributing to soil fertility restoration and reducing dependence on chemical fertilizers.

The results obtained align with recent research conducted in Morocco, particularly in the city of Salé, which confirmed the effectiveness of controlled thermophilic composting applied to household biowaste, as well as the physicochemical and agronomic quality of the resulting compost (Majdouline et al., 2023a; Majdouline et al., 2024).

These studies, carried out on different organic substrates, also emphasized the need for seasonal monitoring, control of thermal parameters, and optimization of the initial input composition, which are key factors for ensuring the biological stability and fertilizing quality of locally produced compost.

However, the quality of the final compost remains strongly dependent on the level of pre-sorting and the purity of the organic fraction, which constitutes a major limitation in the region studied. These challenges are comparable to those observed in the management of animal waste, where the lack of regulatory oversight and persistent microbiological risks continue to represent significant barriers to safe and sustainable recovery (Ajmani et al., 2025).

However, anaerobic digestion, integrated into alternative A4, ranks lower, despite its theoretical advantages in terms of biogas generation and greenhouse gas emission reduction (Ibarra-Esparza et al., 2023). This result can be attributed to technological complexity, high investment and operational costs, and the sensitivity of the process to input quality—particularly in developing countries, where source separation practices remain limited (Ibarra-Esparza et al., 2023).

Alternatives primarily based on source separation and recycling also occupy lower positions in the ranking. The effectiveness of these strategies largely depends on citizen participation, the availability of adequate infrastructure, and the stability of the recyclable materials market (Kaza et al., 2018). The Moroccan experience demonstrates that selective sorting initiatives yield substantial results only over the long term, when public awareness, institutional coordination, and local governance mechanisms are effectively strengthened (Konrad Adenauer Foundation, 2022).

Overall, these findings highlight that the most effective waste management solutions for the RSK region are those that combine technological flexibility, integrated material and energy recovery, and a significant reduction of residual waste sent to landfill. The fuzzy TOPSIS method has proven to be particularly suitable for identifying such priorities, as it integrates technical, economic, and environmental dimensions under conditions of uncertainty. It therefore provides a robust and transparent decision-support framework to guide regional authorities toward integrated and circular municipal solid waste management models.

CONCLUSIONS

The quantitative analysis conducted in this study establishes that Alternative A7 (mechanical-biological treatment coupled with energy recovery and composting) constitutes the optimal strategy for municipal solid waste management in the Rabat-Salé-Kénitra region. With a proximity coefficient of 0.9767, this integrated approach significantly outperforms simple mechanical sorting and landfill-based scenarios, confirming our initial hypothesis that hybrid systems are best suited to the region's specific waste composition (high organic and moisture content). This research successfully achieved its objective by revealing that the sustainability of waste management in this context depends less on the adoption of a single high-tech solution than on the balance between biological stabilization and energy recovery. Unlike previous descriptive studies, this work fills a specific gap by providing a robust hierarchical ranking of scenarios under uncertainty, demonstrating that energy recovery from sorting refusals is a critical component for viability, provided it is coupled with rigorous composting.

These findings offer a new scientific basis for regional decision-making, shifting the focus from mere sanitary landfilling to integrated valorization. However, the implementation of the identified optimal strategy opens new perspectives for future research: it requires a detailed feasibility study on the industrial absorption capacity of sorting refusals (e.g., by local cement plants) and analysis of the governance mechanisms needed to ensure the quality of the organic input flow. Future works should therefore focus on the life cycle assessment of the A7 scenario to further quantify its long-term environmental benefits.

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