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Multi-Criteria Decision-Making for Fluorescent Lamp Disposal using Extended Group Fuzzy TOPSIS and Two-Tuple Linguistic Representation

Mohammad Ali Bagherzadeh[1]✉ | Mahboubeh Afzali[1] | Hossein Vahidi[2]

1. Department of Electrical and Computer Engineering, Graduate University of Advanced Technology, Kerman, 7631818356, Iran.
2. Department of Environment, Institute of Science and High Technology and Environmental Sciences, Graduate University of Advanced Technology, Kerman, 7631818356, Iran.

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ABSTRACT

The improper disposal of used fluorescent lamps poses serious environmental and public health risks because of their mercury content and other hazardous materials. Despite growing awareness, the absence of a structured and sustainable disposal strategy remains a major challenge for many developing countries. This study aims to evaluate and prioritize alternative disposal scenarios for fluorescent lamp waste in Iran, taking into account environmental, economic, and social dimensions. To achieve this, a multi-criteria decision-making (MCDM) approach was adopted, combining an extended group fuzzy TOPSIS method with the 2-tuple linguistic representation model to handle expert opinions under uncertainty. Four practical scenarios were analyzed: long-term storage, recycling with residue disposal, landfilling, and cement co-processing. The results revealed that the scenario involving crushing, processing, washing, recycling, and disposal of residue achieved the highest sustainability score, offering a balanced performance across all criteria. Its ranking is supported by prior studies emphasizing integrated recovery systems and circular economy benefits. The findings not only validate the proposed hybrid decision-making model but also provide a replicable framework to guide policymakers, environmental regulators, and waste management stakeholders in developing sustainable e-waste strategies.

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INTRODUCTION

The rapid production of electronic products has increased electronic waste (e-waste), which contains hazardous materials such as mercury and poses serious environmental risks (Rivera et al., 2018). Proper disposal of e-waste, particularly fluorescent lamps, is critical to mitigate the release of toxic substances. Neutralizing, recycling, and reusing e-waste have become priorities compared to landfill disposal (Pant & Singh, 2013). In Iran, the disposal of used fluorescent lamps is a pressing issue due to mercury pollution risks and the accumulation of these lamps in warehouses (Takaoka, 2014). Despite existing regulations, managing the fluorescent lamp e-waste supply chain remains challenging for regional supervisors and contractors. Classified as hazardous waste due to their mercury content, fluorescent lamps require specific methods for

*Corresponding Author Email: *ma.bagherzadeh@kgut.ac.ir*

temporary storage, transfer, and disposal, which differ across countries (Morais et al., 2012). Iranian environmental laws mandate proper temporary storage and disposal of these lamps, but challenges persist among households and small-scale industries, where lamps often end up in general waste, collected by municipalities and disposed of in landfills (Kosai et al., 2021). This lack of infrastructure and public awareness exacerbates the problem, as lamps frequently break in transit, making recycling impractical (Taghipour et al., 2014). In contrast, Iranian organizations and industries—subject to stricter environmental oversight and generating large volumes of used fluorescent lamps—are required to adopt appropriate collection, storage, and disposal practices. Nevertheless, despite the recognized hazards, a structured framework for evaluating and selecting the most sustainable disposal scenarios in Iran remains lacking.

Mercury management is the most critical challenge in handling used fluorescent lamps. Techniques such as shredding lamps and applying sealed vacuum systems with activated carbon filters are essential for safe disposal. Shredded lamps consist of 94% glass, 5% plastic and metal, and 1% fluorescent dust and mercury. While activated carbon filters absorb most mercury, residual hazardous materials remain in glass, plastic, and metal fragments (Gaitanelis et al., 2018). Improper disposal risks releasing mercury, cadmium, and lead, contaminating soil and water, as highlighted by studies on leaching under acid rain and landfill conditions (Lecler et al., 2018; Viana & Saint'Pierre, 2024).

The primary waste product from fluorescent lamps is glass cullet, which has been studied for reuse in asphalt, concrete, and ceramics (Cenci et al., 2020; Grigoropoulos et al., 2020; Novais et al., 2016; Pavón et al., 2018; Rahman et al., 2017; Wu et al., 2014; Zamprogno Rebello et al., 2020). For example, incorporating glass cullet into asphalt mixtures improves performance, with 10-15% glass content enhancing stiffness and moisture resistance (Androjić & Marović, 2019; Arabani & Kamboozia, 2013; Salem et al., 2017; Shafabakhsh & Sajed, 2014). However, larger glass particles (>4.75 mm) can negatively impact tire interactions and skid resistance (Arabani, 2011). In cement-based materials, reducing cullet particle size increases pozzolanic activity, allowing up to 40% sand replacement (Idir et al., 2010; Mohajerani et al., 2017; Terro, 2006). The use of amorphous fine glass enhances pozzolanic activity, with 20% glass in samples showing no adverse Alkali-Silica reaction (Shi et al., 2005; Topçu & Canbaz, 2004). Additionally, glass cullet could safely constitute up to 70% of the aggregate in some applications (Corinaldesi et al., 2005; Rajabipour et al., 2010).

Glass cullet has also shown benefits in ceramic production, where it improves mechanical properties, enhances energy efficiency, reduces water absorption and linear shrinkage, and maintains compressive strength (Abdelzaher, 2023; Andreola et al., 2016; Loryuenyong et al., 2009; Morais et al., 2016; Saparuddin et al., 2020; Silva et al., 2017). Factors such as particle diameter, chemical composition, and morphology are critical in recycling and utilizing glass cullet, as they affect the quality of final products (Karayannis et al., 2017). For example, in the asphalt industry, the morphology of glass cullet impacts slip resistance, affecting vehicle stability during acceleration or braking (Topçu & Canbaz, 2004). Furthermore, recent studies have demonstrated the potential of waste-derived ceramic fillers (such as ultra-fine ceramic waste in cementitious matrices) for enhancing durability, reducing porosity, and contributing to circular economy practices in construction (Abdelzaher et al., 2023). However, unpulverized glass fragments pose injury risks to workers, especially during transportation, underscoring the need for safe handling practices (Jang et al., 2022).

In situations involving complex trade-offs, the effective management of fluorescent lamp waste necessitates synthesizing expert opinions across quantitative and qualitative criteria. Multi-criteria decision-making (MCDM) methods are thus employed to evaluate disposal scenarios while accounting for regional infrastructure capacities and constraints (Ma et al., 2010; Rodríguez & Martínez, 2013).

This study employs linguistic variables to capture expert opinions and incorporates them into a structured and transparent framework for evaluating disposal scenarios. To address the uncertainty and vagueness inherent in group decision-making, the 2-tuple linguistic representation model is applied (Martinez & Herrera, 2000), outputs remain both precise and interpretable (Li et al., 2017; Martı´nez & Herrera, 2012; Rodríguez & Martínez, 2013; Ruan et al., 2010). Prior studies have applied either fuzzy TOPSIS or the 2-tuple model individually in decision-making contexts—for example, in healthcare waste treatment (Dursun et al., 2011a) or linguistic group evaluations (Cheng et al., 2017). Moreover, (Vuckovic et al., 2022) employed a classical AHP-TOPSIS method to select disposal sites for mercury-containing lamps without incorporating fuzzy or linguistic components. Similarly, (Dursun et al., 2011b) combined fuzzy AHP and fuzzy TOPSIS for municipal waste technology selection in Istanbul, but their method relied solely on expert judgment without linguistic modeling. To the best of our knowledge, no prior study has integrated both fuzzy TOPSIS and the 2-tuple linguistic method within a unified framework for evaluating fluorescent lamp disposal scenarios.

This research represents the first attempt to combine an extended group fuzzy TOPSIS approach with the 2-tuple linguistic representation model to evaluate sustainable disposal scenarios for used fluorescent lamps. This methodological contribution fills a critical gap in both decision-support tool development and its practical application to environmental management. The proposed framework explicitly addresses subjectivity and uncertainty in expert assessments and facilitates nuanced comparison across environmental, economic, and socio-cultural criteria. Four practical scenarios—ranging from long-term storage to integrated recycling and co-processing in cement kilns—were selected in accordance with Iran's regulatory and infrastructure context. By combining qualitative expert input with structured linguistic uncertainty analysis, the study offers a novel and flexible decision-support tool for policymakers, industrial stakeholders, and environmental authorities.

The objectives of this research are threefold: (1) to develop an MCDM framework incorporating environmental, economic, and socio-cultural dimensions; (2) to apply a combined fuzzy TOPSIS and 2-tuple linguistic approach to account for uncertainty in expert evaluations; and (3) to assess four realistic disposal scenarios for used fluorescent lamps in Iran. This integrated methodology aims to support evidence-based policy, strategic planning, and regulatory practices for hazardous e-waste. Its adaptability also positions it as a valuable tool for addressing similar waste management challenges in other developing contexts with limited infrastructure and regulatory oversight.

MATERIALS AND METHODS

This section outlines the core methodologies used in this study, focusing on the 2-tuple fuzzy linguistic representation model and the fuzzy TOPSIS technique, which form the analytical foundation for identifying the most sustainable fluorescent lamp disposal scenario. Given the complexity of balancing environmental, economic, and socio-cultural criteria, the problem is framed as an MCDM challenge.

The analysis considers a set of disposal scenarios $A = \{A_1, A_2, ..., A_m\}$ and evaluation criteria $C = \{C_1, C_2, ..., C_n\}$, with expert assessments expressed using linguistic variables. These qualitative inputs are processed using the 2-tuple linguistic model and fuzzy TOPSIS to derive a consistent ranking of alternatives. The proposed framework addresses uncertainty in expert judgment while ensuring systematic comparison across scenarios.

Traditional fuzzy sets (Zimmermann, 2010), though effective for handling imprecision, face challenges in linguistic contexts where direct numerical translation of terms is limited. To address this, the 2-Tuple Linguistic Representation Model (2TLRM) (Martinez & Herrera, 2000) provides a more precise mechanism. In this model, each term in the linguistic set $S = \{s_0, s_1, s_2, \ldots, s_{2n}\}$ is represented as a 2-tuple (h_i, α_i), where $h_i \in S$ and $\alpha_i \in [-0.5, 0.5)$

denotes the symbolic translation capturing deviation from h_i. The following expression describes how a numerical value is converted into a 2-tuple representation for consistent integration in the decision-making process.

Definition 1: (2-Tuple Linguistic Expression (2TLE) (Li et al., 2014; Martinez et al., 2010)) *Given a linguistic term set* $S=(s_0,s_1,s_2,\ldots,s_{2n})$ *and a numerical value* $\beta\in[0\ ,2n]$, *the function* $\Delta:[0\ ,2n]\to S\times[-0.5\ ,0.5)$ *converts* β *into a 2-tuple* (s_i,α_i), *where* $i=Round(\beta)$ *and* $\alpha_i=\beta-i$. *Here* s_i *is the linguistic term nearest to* β *and* α_i *captures the symbolic deviation. The inverse function* $\Delta^{-1}:S\times[-0.5\ ,0.5)\to[0,2n]$ *reconstructs the original numeric value as* $\beta=i+\alpha_i$, *preserving the fidelity of the linguistic assessment throughout the aggregation process.*

The negative form of a 2TLE is calculated by converting it into its numerical equivalent, computing the negative, and converting it back into the 2-tuple form, ensuring effective handling of contrasting evaluations.

Definition 2: (Negative Form of a 2TLE (Martinez & Herrera, 2000; Tao et al., 2014)) *Given a 2TLE* (s_i,α_i), *its negative is calculated as:*

i. Conversion to Numerical Value: $\beta=\Delta^{-1}(s_i\ ,\alpha_i)=i+\alpha_i$,

ii. Calculation of Negative Value: $Neg(\beta)=2n-\beta$,

iii. Conversion Back to 2-Tuple: $\Delta(Neg(\beta))=(s_k,\alpha_k)$.

Thus, $Neg(s_i\ ,\alpha_i)=(s_k,\alpha_k)$.

To compare linguistic values, symbolic deviation and term order are both considered.

Definition 3: (linguistic comparison operator (Martinez & Herrera, 2000)) For two 2TLEs (s_i,α_i) and (s_j,α_j),

$$\begin{cases}(S_i;\alpha_i)\prec(S_j;\alpha_j) & if\ i<j\\ (S_i;\alpha_i)\equiv(S_j;\alpha_j) & if\ i=j\ and\ \alpha_i=\alpha_j\\ (S_i;\alpha_i)\prec(S_j;\alpha_j) & if\ i=j\ and\ \alpha_i<\alpha_j\end{cases} \tag{1}$$

Definition 4: (2-tuple linguistic arithmetic mean (Ren et al., 2019)) The arithmetic mean is $(\bar{s}\ ,\bar{\alpha})=\Delta(\bar{\beta})$, where $\bar{\beta}=\frac{1}{n}\sum_{i=1}^{k}\Delta^{-1}(s_i,\alpha_i)$ and $\bar{\alpha}=\bar{\beta}-Round(\bar{\beta})\in[-0.5\ ,0.5)$.

Definition 5: (Linguistic Weighted Average (Ren et al., 2019)) *Given 2TLEs* $\mathbb{S}=\{(s_i,\alpha_i)\}$ *with weights* $\mathbb{W}=\{(w_i,\alpha_i^{w_i})\}$, *the weighted average is* $\Delta\left(\frac{\left(\sum_{i=1}^{n}\beta_i\beta_{w_i}\right)}{\left(\sum_{i=1}^{n}\beta_{w_i}\right)}\right)$, *where* $\beta_i=\Delta^{-1}(s_i,\alpha_i)$ *with* $\beta_{w_i}=\Delta^{-1}(w_i,\alpha_i^{w_i})$

The similarity between two 2TLEs is measured as the absolute difference between their numerical equivalents, quantifying proximity within the defined linguistic scale.

Definition 6: (Similarity between Two 2-Tuples (Li et al., 2014; Sohaib et al., 2019)) *Given a linguistic term set* $S=(S_0,S_1,\ldots,S_{2n})$ *as, and a derived similarity set* $S'=(S_0^{'}\ ,S_1^{'}\ ,\ldots,S_{2m}^{'})$ *in which* $S_i^{'}$ *denotes the similarity level between two terms* S_k *and* S_l *with* $|k-l|=2m-i$, *the similarity between two 2-tuple linguistic terms* (S_k,α_k) *and* (S_l,α_l) *is given by:*

$$Sim\left((S_k,\alpha_k),(S_l,\alpha_l)\right)=\Delta_{S'}\left((2m+1)-\frac{m\cdot\left|\Delta_S^{-1}(S_k,\alpha_k)-\Delta_S^{-1}(S_l,\alpha_l)\right|}{n}\right)$$

Definition 7: (Distance between two 2-Tuples (Delgado et al., 2002; Zimmermann, 2010)) *Similarly, using a distance set* $S'' = \left(S''_0, S''_1, \ldots, S''_{2m}\right)$*, where* S''_i *represents the distance between* S_k *and* S_l *with* $|k-l| = 2m - i$*, the distance between two 2-tuples is computed as:*

$$Distance\left((S_k, a_k), (S_l, a_l)\right) = \Delta_{S''}\left(2m - \frac{(2m-1)\cdot\left|\Delta_S^{-1}(S_k, \alpha_k) - \Delta_S^{-1}(S_l, \alpha_l)\right|}{(2n-1)}\right)$$

The fuzzy TOPSIS technique, as a widely adopted MCDM method (Sohaib et al., 2019), is applied to handle uncertainty in evaluating fluorescent lamp disposal scenarios. The process begins by constructing a fuzzy decision matrix for each decision maker k:

$$\tilde{X}^k = \left[\tilde{x}_{ij}^k\right]_{m\times n}, \quad \tilde{W}^k = \left[\tilde{w}_j^k\right]_{1\times n}$$

with $i \in \{1,2,\ldots,m\}$, $j \in \{1,2,\ldots,n\}$, and $k \in \{1,2,\ldots,h\}$, where $\tilde{x}_{ij}^k$ and $\tilde{w}_j^k$ represent the fuzzy score and weight for scenario i and criterion j, respectively. These are aggregated using the fuzzy arithmetic mean:

$$\tilde{x}_{ij} = \frac{1}{h}\sum_{k=1}^{h}\tilde{x}_{ij}^k \quad \text{and} \quad \tilde{w}_j = \frac{1}{h}\sum_{k=1}^{h}\tilde{w}_j^k. \tag{2}$$

The decision matrix is then normalized to ensure comparability across criteria, transforming fuzzy values into a non-fuzzy scale $\tilde{N} = \left[\tilde{n}_{ij}\right]_{m\times n}$, where

$$\tilde{n}_{ij} = \begin{cases} \dfrac{\tilde{x}_{ij}}{\max\left(\tilde{x}_{ij}\right)} & ; \quad \text{if the criterion j is a benefit} \\[2ex] \dfrac{\min\left(\tilde{x}_{ij}\right)}{\tilde{x}_{ij}} & ; \quad \text{if the criterion j is a cost} \end{cases}$$

The normalized values are then weighted as

$$\tilde{r}_{ij} = w_j \otimes \tilde{n}_{ij} \tag{3}$$

where $\otimes$ denotes fuzzy multiplication. Fuzzy ideal $\left(\tilde{r}_j^+\right)$ and negative-ideal $\left(\tilde{r}_j^-\right)$ solutions for benefit and cost criteria are identified as:

$$\tilde{r}_j^+ = \max_{i\in\{1,2,\ldots,m\}} \tilde{r}_{ij} \text{ and } \tilde{r}_j^- = \min_{i\in\{1,2,\ldots,m\}} \tilde{r}_{ij}\ ; \text{ (for benefit criteria),} \tag{4-a}$$

$$\tilde{r}_j^+ = \min_{i\in\{1,2,\ldots,m\}} \tilde{r}_{ij} \text{ and } \tilde{r}_j^- = \max_{i\in\{1,2,\ldots,m\}} \tilde{r}_{ij}\ ; \text{ (for cost criteria).} \tag{4-b}$$

Distances of each alternative from ideal (d_i^+) and anti-ideal (d_i^-) solutions are calculated:

$$d_i^+ = \sum_{j=1}^{n} Distance\left(\tilde{r}_j^+, \tilde{r}_{ij}\right), \tag{5-a}$$

$$d_i^- = \sum_{j=1}^{n} Distance\left(\tilde{r}_j^-, \tilde{r}_{ij}\right). \tag{5-b}$$

The relative closeness of each alternative is then computed as:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{6}$$

To integrate fuzzy TOPSIS with the 2-tuple linguistic model for sustainable selection of disposal scenarios, a two-phase approach is applied.

In Phase I, the decision framework is structured: experts, alternatives, and criteria are identified, and evaluations are expressed in linguistic terms modeled as triangular fuzzy numbers. The similarity and distance measures are defined as:

- *Similarity:* $S' = \{S_0'$: completely dissimilar, S_1': mostly dissimilar, S_2': somewhat dissimilar, S_3': neutral, S_4': somewhat similar, S_5': mostly similar, S_6': completely similar$\}$.
- *Distance:* $S'' = \{S_0''$: equal, S_1'': almost equal, S_2'': somewhat close, S_3'': neutral, S_4'': somewhat far, S_5'': far, S_6'': very far$\}$.

In Phase II, the 2-tuple fuzzy TOPSIS method is executed. Expert scores and weights are transformed into 2-tuples linguistic forms:

$$\tilde{X} = \left[\left(\tilde{x}_{ij}, 0\right)\right]_{m\times n}, \quad \tilde{W} = \left[\left(\tilde{w}_j, 0\right)\right]_{1\times n}.$$

Aggregating expert evaluations using Definition 4 results in:

$$\tilde{W} = \Delta_S\left(\frac{1}{K}\sum_{k=1}^{K}\Delta_S^{-1}\left(\tilde{w}_j^k, 0\right)\right) \tag{7}$$

$$\tilde{X} = \Delta_S\left(\frac{1}{K}\sum_{k1}^{K}\Delta_S^{-1}\left(\tilde{x}_{ij}^k, 0\right)\right) \tag{8}$$

The weighted normalized decision matrix $\left(\tilde{r}_{ij}, \tilde{\rho}_{ij}\right)$ is also formulated as

$$\left(\tilde{r}_{ij}, \tilde{\rho}_{ij}\right) = \Delta_S\left(\frac{\Delta_S^{-1}\left(\tilde{w}_j, \tilde{\alpha}_j\right)\Delta_S^{-1}\left(\tilde{x}_{ij}, \tilde{\alpha}_{ij}\right)}{\sum_{i=1}^{m}\Delta_S^{-1}\left(\tilde{x}_{ij}, \tilde{\alpha}_{ij}\right)}\right), \tag{9}$$

Distances from the ideal and negative ideal solutions are also calculated as:

$$\left(\gamma_j^+, \rho_j^+\right) = \Delta_S\left(\frac{1}{n}\sum_{j=1}^{n}\Delta_{S''}^{-1}\left(Distance\left(\left(\tilde{x}_{ij}, \tilde{\alpha}_{ij}\right), \left(\tilde{r}_j^+, \tilde{\rho}_j^+\right)\right)\right)\right) \tag{11-a}$$

$$\left(\gamma_j^-, \rho_j^-\right) = \Delta_S\left(\frac{1}{n}\sum_{j=1}^{n}\Delta_{S''}^{-1}\left(Distance\left(\left(\tilde{x}_{ij}, \tilde{\alpha}_{ij}\right), \left(\tilde{r}_j^-, \tilde{\rho}_j^-\right)\right)\right)\right) \tag{11-b}$$

Finally, the closeness coefficient for each alternative is computed as

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{12}$$

for ranking them, where

$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(\Delta_S^{-1}\left(\tilde{r}_j^-, \tilde{\rho}_j^-\right) - \Delta_S^{-1}\left(\tilde{r}_{ij}, \tilde{\alpha}_{ij}\right)\right)^2}, \tag{13-a}$$

$$d_i^+ = \sqrt{\sum_{j=1}^{n}\left(\Delta_S^{-1}\left(\tilde{r}_j^+, \tilde{\rho}_j^+\right) - \Delta_S^{-1}\left(\tilde{r}_{ij}, \tilde{\alpha}_{ij}\right)\right)^2}. \tag{13-b}$$

Finally, the scenario closeness measure (γ_j, ρ_j) is computed as

$$(\gamma_j, \rho_j) = \Delta_S\left(\left(\frac{\Delta_S^{-1}(\gamma_j^+, \rho_j^+)}{\Delta_S^{-1}(\gamma_j^+, \rho_j^+) + \Delta_S^{-1}(\gamma_j^-, \rho_j^-) - 1}\Delta r^n\right)\right) \tag{14}$$

This hybrid approach—combining fuzzy TOPSIS and 2TLRM—offers a robust methodology for navigating technical, economic, and social trade-offs in fluorescent lamp disposal, enabling informed, transparent, and sustainable decision-making.

v Disposal Scenario Classification

To support regulatory and industry decision-making, four disposal scenarios for used fluorescent lamps were identified through expert consultation and current practices in Iran, representing feasible approaches to managing this hazardous waste:

- **Scenario 1 (Storage):** Long-term storage of used lamps within organizations due to inadequate infrastructure or budget. This poses environmental risks, notably mercury leakage, and incurs ongoing maintenance costs and liabilities.
- **Scenario 2 (Crushing, Processing, Washing, Recycling, and Residue Disposal):** A multi-stage process that captures hazardous vapors, processes recyclable components, and sends remaining residues to landfills. Though initially costly, this scenario offers strong long-term benefits in waste reduction, compliance, and material recovery.
- **Scenario 3 (Crushing, Processing, Storage, and Landfill):** Lamps are crushed, sorted, temporarily stored, and finally disposed of in engineered landfills. While compliant with regulations, this method is less economical due to high transport and disposal costs and presents environmental risks such as mercury leachate.
- **Scenario 4 (Crushing, Processing, and Use in Cement Plant):** Crushed glass is reused in cement kilns, where high temperatures neutralize hazardous compounds. This reduces raw material demand and offers economic benefits but requires stringent emission controls to manage mercury exposure.

These scenarios were evaluated using the proposed fuzzy MCDM framework.

- Evaluation Criteria

To ensure a balanced assessment, sixteen evaluation criteria were defined across environmental, economic, and socio-cultural dimensions, based on expert input:

Environmental criteria: toxic gas emissions (C11), hazardous solid waste (C12), toxic effluents (C13), recycling efficiency (C14), green supply chain support (C15), occupational risks (C16), and compliance with environmentally sound practices (C17).

Economic criteria: capital investment (C21), transport costs (C22), storage/maintenance needs (C23), operational resource use (C24), and income from recycling (C25).

Social and cultural criteria: environmental responsibility (C31), public participation (C32), industrial collaboration (C33), and process safety (C34).

Each scenario was assessed against these criteria using expert judgments expressed via linguistic variables and analyzed through the proposed fuzzy 2-tuple TOPSIS model.

RESULTS AND DISCUSSION

The four predefined disposal scenarios and their corresponding evaluation criteria, previously detailed in the Materials and Methods section, were assessed using the extended group fuzzy TOPSIS method combined with the two-tuple linguistic representation model. This hybrid approach facilitated the aggregation of expert opinions under uncertainty and enabled consistent ranking of alternatives across environmental, economic, and social dimensions.

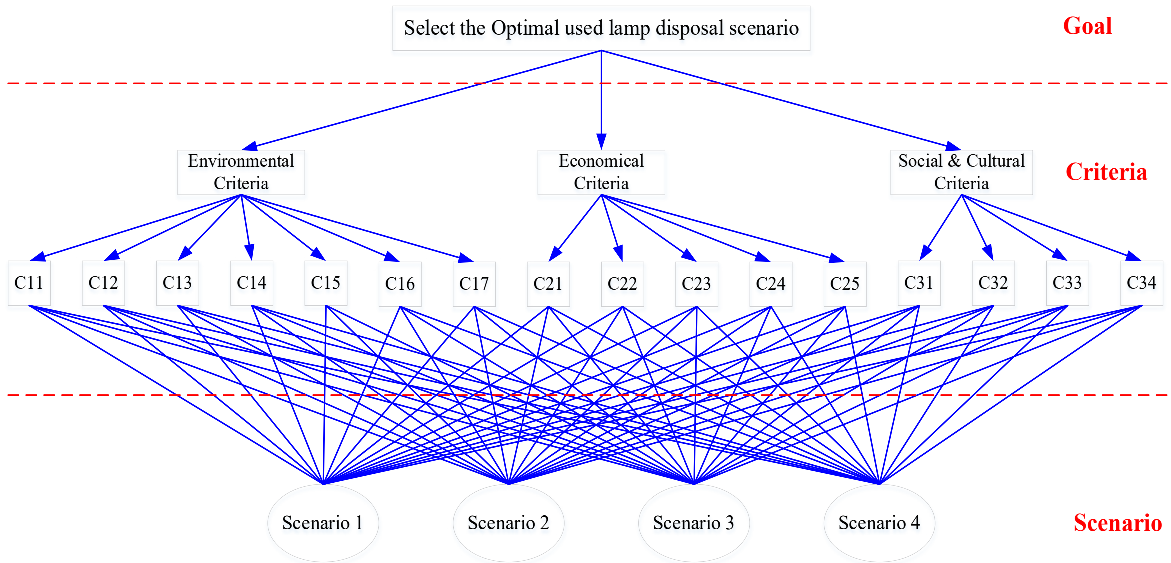

Fig. 1. The relationship among criteria and scenarios

Table 1. Importance weight of each criterion assigned by decision makers

Decision Makers	Criteria															
	Environmental							Economical					Social & cultural			
	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{31}	C_{32}	C_{33}	C_{34}
D_1	VHI	MHI	MLI	MHI	MHI	MI	MHI	MHI	MI	MHI	MHI	MHI	MHI	MHI	MHI	MHI
D_2	HI	HI	MLI	MI	MHI	MHI	MI	MHI	MI	MHI	MHI	MI	MHI	MHI	MHI	MHI
D_3	HI	MHI	MI	MHI	MHI	MI	MHI	MHI	MHI	MHI	MHI	MHI	MHI	MI	MHI	MHI

Figure 1 illustrates the relationship between the evaluation criteria and the disposal scenarios analyzed in this study.

Each scenario was evaluated against the defined criteria to determine the most sustainable disposal option for Iran. As shown in Table 1, the criteria weights were assigned by three environmental and waste management experts using linguistic terms—$\{W_1$: Very Low Importance (VLI), W_2: Low Importance (LI), W_3: Moderately Low Importance (MLI), W_4: Medium Importance (MI), W_5: Moderately High Importance (MHI), W_6: High Importance (HI), W_7: Very High Importance (VHI)$\}$— which were then converted into numerical values using triangular membership functions (Figure 2). The 2-tuple linguistic model translated these subjective assessments into precise values, ensuring consistency and accuracy in constructing the decision matrix for scenario ranking.

Selecting three decision-makers ensures a balance between expert diversity and practical manageability. While involving more experts could enhance precision by incorporating broader perspectives, it would also complicate consensus-building and opinion aggregation. This streamlined setup preserves methodological rigor without added complexity. Alternative ratings were expressed using the linguistic scale $S = \{S_1$: Very Poor (VP), S_2: Poor (P), S_3: Fair (F), S_4: Average (A), S_5: Above Average (AA), S_6: Good (G), S_7: Very Good (VG)$\}$, with corresponding triangular representations shown in Figure 3.

The importance weights assigned by decision-makers are presented in Table 1 and were aggregated to form the comprehensive decision matrix shown in Table 2, reflecting collective

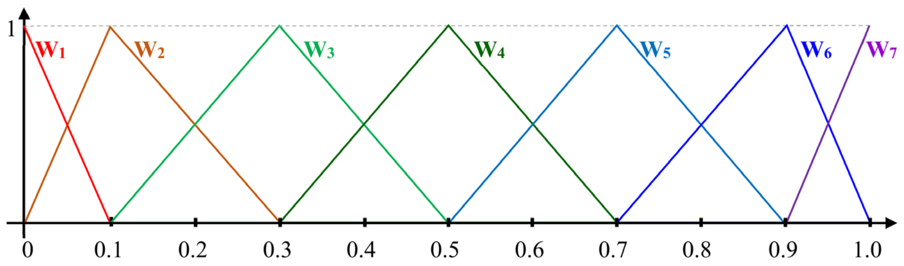

Fig. 2. Linguistic term set for weight importance of criteria

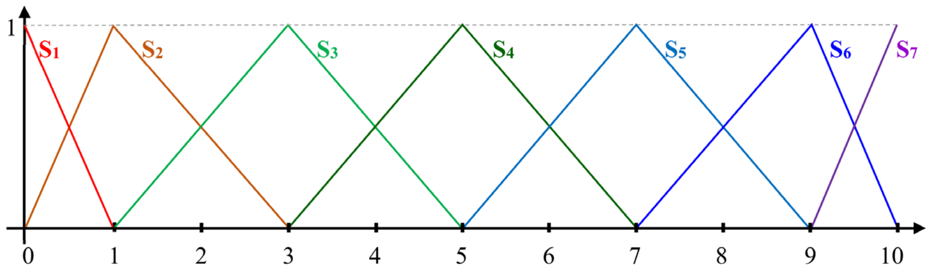

Fig. 3. Linguistic term set for weight importance of alternative for each criterion

Table 2. Decision makers' importance weights for each alternative and criterion

Alternatives	Decision Makers	Criteria															
		Environmental							Economical					Social & cultural			
		C11	C12	C13	C14	C15	C16	C17	C21	C22	C23	C24	C25	C31	C32	C33	C34
	D1	A	G	AA	F	VP	VG	P	VG	F	AA	P	P	P	P	F	G
A1	D2	A	AA	G	A	P	G	F	G	P	A	A	F	F	F	A	AA
	D3	VG	VG	A	F	VP	VG	P	AA	A	A	AA	VP	P	VP	A	G
	D1	P	F	G	G	VG	AA	AA	P	G	P	AA	G	AA	VG	AA	A
A2	D2	P	P	VG	VG	VG	F	G	P	AA	F	A	AA	A	VG	G	F
	D3	VP	A	AA	G	G	A	G	VP	VG	F	AA	G	G	G	AA	A
	D1	P	A	AA	F	F	F	F	A	AA	P	A	A	AA	AA	AA	AA
A3	D2	F	F	G	F	A	AA	F	F	A	F	A	A	A	G	G	G
	D3	P	AA	A	A	F	A	F	F	G	P	A	F	A	A	A	A
	D1	P	AA	AA	AA	AA	F	A	F	AA	P	F	AA	AA	AA	AA	A
A4	D2	P	A	G	G	A	A	AA	F	A	F	F	AA	AA	AA	G	A
	D3	F	G	A	AA	AA	F	A	P	G	P	VP	A	AA	A	A	F

expert judgment. Assigning weights through linguistic variables introduces inherent subjectivity and potential bias; thus, experts were carefully selected based on their experience in environmental management and hazardous waste disposal. To mitigate individual biases, fuzzy logic was employed to translate linguistic terms into nuanced numerical values, and expert inputs were validated through iterative assessments. While some degree of arbitrariness remains, the structured and transparent approach enhances the credibility and reliability of the evaluation process.

Following the assignment of importance weights, the decision matrix was constructed by combining these weights with expert evaluations of each disposal scenario. Assessments were initially provided using linguistic variables and then translated into numerical values using a fuzzy scale to enable objective comparison. To ensure precision in processing qualitative data, linguistic inputs were further converted into 2-tuple linguistic representations $\left(S_i, \alpha_i\right)$, where S_i denotes the linguistic term and α_i its symbolic translation. This approach preserves the qualitative nature of expert judgments while allowing for accurate quantitative analysis.

Normalization was applied to the transformed decision matrix to enable comparability across criteria by scaling values between 0 and 1 while preserving their relative importance. The weighted normalized matrix was then obtained by multiplying normalized values with their respective weights, allowing for a balanced evaluation of scenario performance. Table 3 summarizes the aggregated 2-tuple weights for each criterion, derived from expert opinions using the linguistic scale in Figure 2. Table 4 presents the resulting decision matrix, showing how each scenario performs against the weighted criteria.

To finalize the decision-making process, the normalized weighted aggregated 2-tuple matrix (Table 5) incorporates both positive and negative ideal solutions, calculated using Equations

Table 3. Aggregated Average 2-Tuple Weights for Each Criterion

Criteria	**C11**	**C12**	**C13**	**C14**	**C15**	**C16**	**C17**
Type	N	N	N	P	P	N	P
Weight	$(W_4; -0.2)$	$(W_3; 0.2)$	$(W_2; 0)$	$(W_3; -0.2)$	$(W_3; 0)$	$(W_3; -0.4)$	$(W_3; -0.2)$
Criteria	C21	C22	C23	C24	C25		
Type	P	N	N	N	P		
Weight	$(W_3; 0)$	$(W_3; -0.4)$	$(W_3; 0)$	$(W_3; 0)$	$(W_3; -0.2)$		
Criteria	C31	C32	C33	C34			
Type	P	P	P	P			
Weight	$(W_3; 0)$	$(W_3; -0.2)$	$(W_3; 0)$	$(W_3; 0)$			

Table 4. Aggregated 2-Tuple Weights for Each Alternative by Criterion

Criteria		**Alternatives**			
		A1	**A2**	**A3**	**A4**
Environmental	C11	$(S_3; 0)$	$(S_1; 0)$	$(S_1; 0.4)$	$(S_2; -0.4)$
	C12	$(S_4; -0.4)$	$(S_2; -0.2)$	$(S_2; 0.4)$	$(S_3; 0)$
	C13	$(S_3; 0)$	$(S_4; -0.4)$	$(S_3; 0)$	$(S_3; 0)$
	C14	$(S_2; 0)$	$(S_4; -0.2)$	$(S_2; 0)$	$(S_3; 0.2)$
	C15	$(S_1; -0.2)$	$(S_4; 0)$	$(S_2; 0)$	$(S_3; -0.2)$
	C16	$(S_4; 0)$	$(S_2; 0.4)$	$(S_2; 0.4)$	$(S_2; 0)$
	C17	$(S_1; 0.4)$	$(S_3; 0.4)$	$(S_2; -0.2)$	$(S_3; -0.4)$
Economical	C21	$(S_4; -0.4)$	$(S_1; 0)$	$(S_2; 0)$	$(S_2; -0.4)$
	C22	$(S_2; -0.2)$	$(S_4; -0.4)$	$(S_3; 0)$	$(S_3; 0)$
	C23	$(S_3; -0.4)$	$(S_2; -0.4)$	$(S_1; 0.4)$	$(S_1; 0.4)$
	C24	$(S_1; 0.4)$	$(S_3; -0.2)$	$(S_2; 0.4)$	$(S_1; 0.4)$
	C25	$(S_1; 0.2)$	$(S_3; 0.4)$	$(S_2; 0.2)$	$(S_3; -0.2)$
Social & cultural	C31	$(S_1; 0.4)$	$(S_3; 0)$	$(S_3; -0.4)$	$(S_3; 0)$
	C32	$(S_1; 0.2)$	$(S_4; 0)$	$(S_3; 0)$	$(S_3; -0.2)$
	C33	$(S_2; 0)$	$(S_3; 0.2)$	$(S_3; 0)$	$(S_3; 0)$
	C34	$(S_3; 0.4)$	$(S_2; 0.2)$	$(S_3; -0.4)$	$(S_2; 0.2)$

Table 5. Normalized aggregated decision matrix, including positive and negative ideal solutions.

Criteria		Alternatives				Positive ideal	Negative ideal
		A1	A2	A3	A4		
Environmental	C_{11}	$(S_2; -0.37)$	$(S_1; -0.45)$	$(S_1; -0.24)$	$(S_1; -0.13)$	$(S_1; -0.45)$	$(S_2; -0.37)$
	C_{12}	$(S_1; 0.06)$	$(S_1; -0.46)$	$(S_1; -0.28)$	$(S_1; -0.11)$	$(S_1; -0.46)$	$(S_1; 0.06)$
	C_{13}	$(S_0; 0.47)$	$(S_1; -0.42)$	$(S_0; 0.47)$	$(S_0; 0.47)$	$(S_0; 0.47)$	$(S_1; -0.42)$
	C_{14}	$(S_1; -0.49)$	$(S_1; -0.04)$	$(S_1; -0.49)$	$(S_1; -0.18)$	$(S_1; -0.04)$	$(S_1; -0.49)$
	C_{15}	$(S_0; 0.25)$	$(S_1; 0.25)$	$(S_1; -0.37)$	$(S_1; -0.12)$	$(S_1; 0.25)$	$(S_0; 0.25)$
	C_{16}	$(S_1; -0.03)$	$(S_1; -0.42)$	$(S_1; -0.42)$	$(S_0; 0.48)$	$(S_0; 0.48)$	$(S_1; -0.03)$
	C_{17}	$(S_0; 0.42)$	$(S_1; 0.03)$	$(S_1; -0.45)$	$(S_1; -0.20)$	$(S_1; 0.03)$	$(S_0; 0.42)$
Economical	C_{21}	$(S_1; 0.31)$	$(S_0; 0.36)$	$(S_1; -0.26)$	$(S_1; -0.41)$	$(S_1; 0.31)$	$(S_0; 0.36)$
	C_{22}	$(S_0; 0.41)$	$(S_1; -0.17)$	$(S_1; -0.31)$	$(S_1; -0.31)$	$(S_0; 0.41)$	$(S_1; -0.17)$
	C_{23}	$(S_1; 0.11)$	$(S_1; -0.31)$	$(S_1; -0.4)$	$(S_1; -0.4)$	$(S_1; -0.4)$	$(S_1; 0.11)$
	C_{24}	$(S_1; -0.47)$	$(S_1; 0.05)$	$(S_1; -0.1)$	$(S_1; -0.47)$	$(S_1; -0.47)$	$(S_1; 0.05)$
	C_{25}	$(S_0; 0.35)$	$(S_1; 0)$	$(S_1; -0.35)$	$(S_1; -0.18)$	$(S_1; 0)$	$(S_0; 0.35)$
Social & cultural	C_{31}	$(S_0; 0.42)$	$(S_1; -0.1)$	$(S_1; -0.22)$	$(S_1; -0.1)$	$(S_1; -0.1)$	$(S_0; 0.42)$
	C_{32}	$(S_0; 0.30)$	$(S_1; 0.01)$	$(S_1; -0.23)$	$(S_1; -0.28)$	$(S_1; 0.01)$	$(S_0; 0.30)$
	C_{33}	$(S_1; -0.46)$	$(S_1; -0.14)$	$(S_1; -0.19)$	$(S_1; -0.19)$	$(S_1; -0.46)$	$(S_1; -0.19)$
	C_{34}	$(S_1; -0.01)$	$(S_1; -0.36)$	$(S_1; -0.25)$	$(S_1; -0.36)$	$(S_1; -0.01)$	$(S_1; -0.36)$

Table 6. Distances from positive and negative ideal solutions using the 2-tuple model.

Distance of Each Alternative from Positive ideal			
A_1	A_2	A_3	A_4
$(S_1''; 0.40)$	$(S_1''; 0.17)$	$(S_1''; 0.28)$	$(S_1''; 0.22)$
Distance of Each Alternative from Negative ideal			
A_1	A_2	A_3	A_4
$(S_1''; 0.16)$	$(S_1''; 0.39)$	$(S_1''; 0.28)$	$(S_1''; 0.34)$

(10-a) and (10-b). These benchmarks support objective ranking of the disposal alternatives. This structured approach ensures consistency, transparency, and reliability by combining expert consensus with systematic analysis. Scenario evaluation continues with the calculation of distances from the ideal solutions using Equations (11-a) and (11-b); shorter distances indicate stronger performance. Table 6 presents these distances, enabling a clear comparison and identification of the most suitable disposal scenario.

The relative closeness of each scenario to the ideal solutions was calculated by combining the distances from the positive and negative ideals. This measure ranks the scenarios based on their overall performance. Table 7 presents the relative closeness of each scenario, determined by (14), highlighting their suitability for implementation.

We systematically evaluated aggregated judgments and scenario outcomes to identify the most balanced and sustainable disposal method for used fluorescent lamps in Iran.

The analysis revealed uncertainties stemming from subjective evaluations, data variability, and potential bias in linguistic assessments. Differences in expert experience and data sources affect reliability, while the qualitative nature of linguistic terms further emphasizes the need for robust methods to mitigate bias and enhance decision-making accuracy.

Scenario 2—crushing, processing, washing, recycling, and residue disposal—ranked highest, with the farthest distance from the negative ideal $\left(S_6^{''}; -0.153\right)$. It outperformed other

Table 7. The Relative closeness of alternatives from the positive and negative ideal solutions.

Alternatives	A_1	A_2	A_3	A_4
Relative closeness	$(S_3''; -0.002)$	$(S_6''; -0.153)$	$(S_5''; -0.465)$	$(S_5''; 0.278)$

options across all criteria by reducing environmental harm, enabling efficient hazardous waste treatment, and providing economic value through material recovery. These results align with (Taghipour et al., 2014), who highlighted the importance of integrated mercury recovery systems. Further studies (Abbas et al., 2024; Abbas et al., 2021; Morais et al., 2016; Novais et al., 2016) support the reuse of processed lamp materials in industrial applications, reinforcing Scenario 2's relevance to circular economy goals.

The findings support both practical policy development and the theoretical advancement of MCDM in environmental management. The integration of fuzzy TOPSIS with the 2-tuple linguistic model improves upon conventional approaches by better addressing uncertainty and subjectivity in group decisions.

Scenario 4 (co-processing in cement kilns) ranked second $\left(S_5''; 0.278\right)$, offering economic value and material reuse but with environmental drawbacks due to possible mercury release during high-temperature treatment—an issue raised by (Gaitanelis et al., 2018).

Scenario 3 (landfilling) showed moderate performance $\left(S_5''; -0.465\right)$, hindered by high costs and long-term risks such as mercury leakage. Scenario 1 (long-term storage) scored lowest $\left(S_3''; -0.002\right)$, reflecting its poor environmental and economic impact—consistent with (Vuckovic et al., 2022), who noted risks associated with prolonged storage under limited infrastructure.

Compared to classical AHP-TOPSIS approaches, our integrated model introduces linguistic flexibility and addresses uncertainty in expert input—an improvement over deterministic models that ignore variability in linguistic judgment.

These results validate the proposed fuzzy decision-making framework while reinforcing empirical knowledge on disposal strategies. Scenario 2 offers the greatest potential for promoting circular economy principles by reducing resource dependency, supporting waste reuse, and minimizing emissions. To harness these benefits, integrated disposal systems with strong regulatory support should be prioritized.

By uniting fuzzy logic and linguistic modeling, this study contributes a flexible, context-sensitive decision-support tool, particularly suited for infrastructure-limited and evolving regulatory environments in developing regions.

CONCLUSION

This study applied a multi-criteria decision-making framework that integrates fuzzy TOPSIS with the 2-tuple linguistic representation model to evaluate sustainable disposal options for fluorescent lamps in Iran. By addressing the inherent uncertainties in expert judgment, the analysis identified Scenario 2—crushing, processing, washing, recycling, and residue disposal—as the most sustainable and practical option. It effectively reduces hazardous emissions, promotes resource efficiency, and supports circular economy goals, despite requiring higher initial investment. In contrast, Scenario 1 (long-term storage) was the least favorable due to poor environmental and economic performance, while Scenarios 3 (landfilling) and 4 (cement kiln co-processing) offered only moderate viability, with environmental concerns associated with mercury emissions. The findings contribute theoretically by advancing the application of fuzzy decision-making models in environmental management. The combined use of fuzzy TOPSIS and the 2-tuple linguistic model enhances the interpretability of expert input and provides a more resilient framework for managing subjective judgments in complex decision-making processes. From a practical perspective, the results offer guidance for policymakers and waste management authorities, highlighting strategies that align with green management and sustainability goals. A key lesson is the importance of integrating multiple expert perspectives and balancing environmental, economic, and social criteria. The study demonstrates that recycling-oriented solutions, although initially cost-intensive, offer substantial long-term benefits and support strategic policy development over reactive or short-term planning. Nonetheless, the research is not without limitations. The evaluation was limited to a predefined set of scenarios based on Iran's infrastructure, regulations, and available data, excluding broader stakeholder participation such as public opinion. Moreover, the economic assessments reflect current cost structures that may evolve with technological or market changes. While the proposed framework is adaptable, its findings are context-specific and may require adjustment for application in other regions or waste streams. Future work should broaden the range of scenarios, include diverse stakeholder inputs, and explore innovative technologies to support sustainable hazardous waste management globally.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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