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An ideal plastic waste management system based on an enhanced MCDM technique

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Abstract
The Fermatean probabilistic hesitant fuzzy set (FPHFS) concept is a method that combines Fermatean fuzzy sets and PHFS to provide detailed MCDM problem solutions. The management of solid waste is facing challenges in disposing of environmentally harmful plastic products. The study primarily focuses on plastic waste from the packaging industry, as it is the primary contributor to overall waste generation. The packaging sector has proposed a concept for the recycling of waste at various levels. This study aims to assess the effectiveness of the hybrid analytic hierarchy process and the combinative distance-based assessment (AHP-CODAS) method FPHFS in determining the most suitable plastic waste collection system. The AHP analysis identified the most effective methods for collecting plastic waste for recycling, emphasizing successful segregation for efficient recycling. A deposit and refund system promotes waste collection and a circular economy by facilitating efficient waste management. The research offers valuable insights into selecting packaging waste collection (PWC) technology in uncertain environments and enhances decision-making methods in the field.

Keywords Decision making · Fermatean probabilistic hesitant fuzzy set · Combinative distance-based assessment · Packaging waste collection

1 Introduction

The global challenge of managing municipal solid waste effectively and sustainably at the end of its life cycle is significant (Jang et al. 2023). The focus is shifting towards end-of-life care and circularity, particularly in the realm of plastics. Consumer plastic packaging waste collection and recycling systems are less developed compared to other materials like paper, glass, and metal (Ozkır et al. 2015). Strategies have been implemented to enhance plastic recycling and promote a circular economy (De Tandt et al. 2021).

The European Union (EU) is advocating for stricter legislation to enhance plastic waste management and promote environmentally friendly end-use options like reuse and recycling (Huysman et al. 2017). Extended Producer Responsibility (EPR) is a crucial

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waste management policy tool that aids in implementing the European waste hierarchy (Roosen et al. 2020). The expansion of the collection system is aimed at reducing post-consumer plastic litter, but it also increases the complexity of curbside collection (Toraman et al. 2014). Polyethylene terephthalate (PET) bottles are more effective for recycling due to their lower contamination rate (Tang et al. 2023). The optimal approach to handling and recycling mixed waste streams, or highly contaminated waste streams, requires further investigation (Mahari et al. 2018).

The literature uses the term "quantity-quality trade-off hypothesis" to describe this. Real measurable facts and universally accepted, science-based arguments remain challenging to obtain (Belahcéne et al. 2023). To optimize recycling techniques and meet recycling targets by 2025 and 2030, more detailed data on sorted waste fraction quantity and quality is required (Thoden van Velzen et al. 2020). The use of holistic assessment methods such as MFA and performance indicators is used to assess the quantity and quality of waste fractions. The study of EPR systems, sorting procedures, and recycling technologies is gaining significant attention (Larrain et al. 2021).

Consumer plastic packaging waste collection and recycling systems are less developed compared to other materials like paper, glass, and metal (Chakraborty and Saha 2022). These processes are frequently described using various statistical and mathematical frameworks (Alao et al. 2022). Making decisions involves selecting one of several actions that people or organizations can take to accomplish a particular objective.

Research indicates that intuitive judgments are insufficient for making complex decisions, despite their widespread use in everyday judgments. MCDM is a method that employs analytical techniques to assess various options based on various factors (Yuksel et al. 2024) and (Bozanic et al. 2023). Decision-makers evaluate options based on various qualities and criteria before ranking them (Belahcéne et al. 2023). Probability information is crucial in Decision Making (DM) for accurate predictions due to uncertainty in events with multiple outcomes without clear probabilities (Almeida and Nagano 2023).

Fuzzy logic theory offers a reliable method for logical inference in the context of vague and imperfect knowledge (Zadeh 1965). Fuzzy logic theory is a computer science concept that aids in processing linguistic input and incorporating individual perspectives. This skill is honed through symbolic expressions, rather than expressing numerical data. Fuzzy sets are charts that assign membership degrees to each possibility, rather than values to probabilities, to create a more realistic representation of probabilities. Atanasov introduced IFS, a generalization of fuzzy set theory. The offset of IFSs in [0, 1] is determined by the membership degrees (MD) and non-membership degrees (ND) (Mishra et al. 2023). The abstract set PFS was defined as being more comprehensive than IFS (Yadegaridehkordi et al. 2018). The calculation of MD and ND squares is defined as a PFS in the interval [0, 1] (Peng and Selvachandran 2019).

The proposed a new decision-support method and specified new integral operators in relation to FFS (Shahzadi and Akram 2021). A new FFS-type integral operator described by the t-norm and t-conorm was defined by Garg et al. (2019). Although various fuzzy set theories, such as complex intuitionistic fuzzy sets, have received significant attention in the literature for their ability to capture uncertainty and ambiguity, our study focuses on Fermatean fuzzy sets. It is important to note that Fermatean fuzzy sets differ in their mathematical representation, operational rules, and interpretative frameworks. Unlike complex intuitionistic fuzzy sets, which extend traditional fuzzy set theory by introducing additional parameters to represent both membership and non-membership degrees, Fermatean fuzzy sets emphasize. Biswas et al. (2023) generalised the FS concept to the HFS concept. New

FS sets have been developed to overcome the challenges of MD construction and random selection of prospective values.

The PHFS accurately represents people's reluctance to express their preferences on items compared to the FS and its other generalizations (Tesic and Marinkovic 2023). The study will introduce a new FPHFS and investigate its properties. A new score function has been introduced to compare the Fermatean probabilistic hesitancy numbers (FPHN). Table 1 provides a comprehensive overview of the nomenclature utilized in this paper. This analysis will emphasize fundamental differences in their mathematical frameworks, criteria weighting approaches, and relevance to different decision-making contexts.

The AHP-CODAS fuzzy MCDM method provides a robust, flexible, and comprehensive approach for multi-criteria decision-making, especially suitable for complex problems with uncertainty and diverse stakeholder perspectives (Saaty 1990). The method, which integrates AHP, CODAS, and fermatean probabilistic hesitant fuzzy set theory, improves decision-making efficiency, reliability, and stakeholder satisfaction. In particular, it discusses how the BWM component allows decision-makers to capture preferences by identifying the best and worst criteria or alternatives within a set. MULTIMOORA, a hierarchical structure, combines multiple criteria using specific aggregation techniques like Borda, thereby enhancing the accuracy of the results (Liu et al. 2021).

The study explores integration operators and introduces the MCDM technique for FPHFS. The approach will be demonstrated through an examination of decision-making in packaging waste management. The suggested approach will be compared to the previous method used in the study.

Table 1 Nomenclature

DM	Decision Making
MCDM	Multi Criteria Decision Making
FPHFS	Fermatean Probabilistic Hesitant Fuzzy Set
IFS	Intuitionistic Fuzzy Set
PFS	Pythagorean Fuzzy Set
HFS	Hesitant Fuzzy Set
FFS	Fermatean Fuzzy Set
PHFEs	Probabilistic Hesitant Fuzzy Elements
FUPHFS	Fermatean Unified Probabilistic Hesitant Fuzzy Set
CODAS	Combinative Distance-based Assessment
AHP	Analytic Hierarchy Process
CCM	Curbside Collection Method
DORM	Drop Off Recycling Method
D/RP	Deposit / Refund Programme
VC	Vehicular Collection
BBC	Buy Back Centre

2 Literature review

The methods and solutions used for decision problems vary. The MCDM process is suitable for identifying innovative solutions when multiple criteria or levels are present. MCDM is a method that aids in identifying the most suitable solution based on pre-established criteria. Traditional MCDM problems often include alternatives and criteria weights (Badi et al. 2024).

The research has shown significant interest in the application of PHFS to the MCDM problem. The FFS and PHFS combo can effectively manage the complex and ambiguous nature of MCDM situations (Senapati and Yager 2019). The CODAS technique is widely utilized by notable academics in case research on MCDM challenges. Numerous original MCDM approaches have been extensively studied in many popular pieces of literature, including the AHP model (Moslem et al. 2023), ELECTRE model (Jagtap and Karande 2023), MOORA model (Jafarzadeh Ghoushchi and Sarvi 2023), MABAC model (Salimian et al. 2022), COPRAS model (Mishra et al. 2022), and ARAS model (Gocer and Sener 2022).

MCDM methods such as DematEL, Structural Equation Modelling, Dynamic Analysis, and General Linear Modeling are commonly utilized for dependent research (Pamucar and Biswas 2023). AHP assesses the impact of a goal on its components by comparing only those within the goal's hierarchy when comparing different MCDMs (Kou et al. 2014). VIKOR and TOPSIS are methods used to determine the shortest distance between ideal and non-ideal solutions (Opricovic and Tzeng 2007). Yager introduced the q-step OFS, which was based on the FFS, and its basic features were studied (Yager 2017). The definition of new transactions for FFS, such as the Fermatean arithmetic operator, is provided, along with an exploration of their properties (Senapati and Yager 2019). The new weighted aggregated operators related to FFSs are defined in PFS (Wang et al. 2021). The study employs FPHFS to enhance AHP-CODAS based on its distinctive features.

Researchers have adapted the classical AHP method to incorporate fuzzy sets, expanding its scope. Fuzzy AHP (Zyoud et al. 2016), intuitionistic AHP (Liao and Xu 2015), Pythagorean AHP (Ilbahar et al. 2018), and hesitant AHP (Jeon et al. 2023) are proposed methods for solving decision problems in various situations. Fuzzy AHP methods offer a more comprehensive structure than traditional AHP due to their combination of quantitative and qualitative criteria. For example, fuzzy AHP to investigate methods to minimize water loss and the consistency of AHP preference relationships in intuitionistic fuzzy environments (Zyoud et al. 2016) and (Wang et al. 2023). The study suggests combining risk assessment with fuzzy AHP to assess occupational health (Jeon et al. 2023). Researchers are increasingly combining various forms of information with the fuzzy extended-AHP method due to its ability to handle human subjective consciousness ambiguity, aligning with decision-making situations.

The CODAS method, developed by Pamucar et al. (2023), utilizes crisp sets and the Hamming distance to evaluate alternatives. The researchers utilized CODAS to select an industrial robot based on its operation criteria and extended it to evaluate market segmentation using linguistic variables and trapezoidal fuzzy numbers (Alkan 2023). The results were analyzed using Fuzzy EDAS and Fuzzy TOPSIS methods. The study suggests a multi-criteria decision-making approach for industrial maintenance problems, employing the geometric mean method to calculate the weights of criteria and subcriteria (Akram et al. 2023). The weights were utilized to determine the ranking of strategy maintenance alternatives.

Pamucar et al. (2023) employed pairwise criteria selection and CODAS crisp to select wave energy technology. Roy successfully validated IVIF-CODAS by adjusting criteria weights, resulting in high stability. Ilhan and Gundogdu (2023) developed a case study for personnel selection using hesitant Fuzzy linguistic term sets (HFLTS). The information type was used to evaluate the organizational and technological aspects of Industry 4.0. These studies have demonstrated the efficacy of these methods in various settings.

The best and worst (BWM) method was utilized to assess criteria and linguistic variables in a cloud computing system (Ma et al. 2023). The team created a unique application using interval-valued intuitionistic fuzzy CODAS for multi-attribute decision-making in Tehran. The study compared MOORA and CODAS methods under Pythagorean Fuzzy sets to evaluate their advantages and disadvantages (Rani et al. 2023).

The CODAS method is a statistical technique that uses Euclidean distance (ED) and hamming distance (HD) to generate analytic estimates of alternatives. The ED is calculated using the negative-ideal point as the primary metric distance, indicating the attractiveness of the alternative (Keshavarz Ghorabaee at al. 2016). The CODAS method was proposed as a fuzzy application to address uncertainty in DM problems, specifically applied to a consumer market choice method (Keshavarz Ghorabaee et al. 2017). The fuzzy CODAS method utilizes linguistic variables, while AHP's key advantage lies in its capacity to detect and minimize errors in professional judgment. The AHP is utilized to determine the most effective method for collecting plastic waste and analyzing the gathered data (Venkatalaxmi et al. 2004).

The analysis of bio-plastic production processes and their superiority over conventional plastics has been based on performance measures (Jaideep Balwada et al. 2021). Black plastic, containing organic solvents, significantly harms natural and marine wildlife due to its harmful effects. Reprocessed disposable containers must pass laboratory tests and criteria before they can be used with fruits and vegetables (Wang et al. 2024). The researchers proposed thermogravimetry as a method to assess the degradation of plastic waste (Cristina Mora et al. 2013). Social sustainability and health and safety must be integrated in resource recovery, particularly for plastics, ensuring their safe use in grocery stores (Pamucar et al. 2023). This work introduces a hybrid AHP-CODAS method for FPHFs, which effectively selects the most sustainable technology for packaging waste collection methods within the F-MCDM technique framework. The fermatean probabilistic hesitant fuzzy number is utilized for handling various types of information, while a pairwise comparison matrix is suggested for selecting key criteria.

2.1 Motivation and objective of the study

Motivated by recent research, we present a technique based on AHP and fuzzy CODAS to evaluate the best PWC technology, taking into account the correlation and reliability between DMs rationality and evaluation criteria. Fuzzy set theory is applied to decision-making frameworks and integrated with decision-making techniques to handle fuzzy information more effectively, resolve ambiguity in decision-making processes (DMs), and reduce information loss. Consequently, the concept of PHFE serves as the motivating force behind this study. An integrated PHFE can be created from FFS. A case study of an efficient packaging waste collection system demonstrates the effectiveness of research methods in implementation. It is significant to examine the selection of PWC technology that integrates the criteria of the four standard features with the psychological and behavioral aspects of DMs. The proposed technique combines MCDM and fuzzy AHP methods to determine literature review criteria weights. In the scope of this study, decision systems with fermatean-integrated probabilistic hesitation components are proposed. The comparative and sensitivity analyses compared the two strategies in terms of their impact on criteria.

2.2 Contribution of the study

The primary contributions of our study are divided into two categories: theoretical and practical, as indicated below:

Theoretical aspect

- The goal of this contribution is to introduce segmentation functionality for FPHFs, and the performance is compared with the proposed aggregate functionality for FPHFEs.
- An MCDM framework for PWC is proposed based on AHP and fuzzy CODAS, in which fuzzy set theory is used to obtain linguistic information in FPH fuzzy numbers.
- The strategy is demonstrated by selecting and finding an appropriate packaging waste collection system using the MCDM technique. It uses HFS with the AHP weighting technique in the critical weighting section in the application of the MCDM method. The CODAS method in the ranking of the MCDM system uses FUPHFS.
- Compared with other methods, the hybrid method proposed in this paper is a reasonable method for selecting PWC technology, considering the psychological factors of DMs.
- A sensitivity analysis is performed to establish the stability of the technique, and the accuracy of the proposed approach is demonstrated by comparing the performance of five existing MCDM methods.
- Fuzzy set theory has been introduced into decision-making modeling, which has advantages in dealing with the vagueness and uncertainty of human judgments, as well as false or insufficient information about quantitative and qualitative data.

Practical aspect

- The PWC technology selection system includes four criteria: environmental effect, social impact, material cost, and simplicity of sorting.
- The recommended decision framework evaluates and selects five alternative PCW technologies, providing appropriate reference for managers.
- By analyzing the suggested method's findings, various management implications on environmental effect, social impact, material cost, and sorting ease are proposed to achieve sustainable environmental development and prevent resource waste.

The paper is structured as follows: Sections 1 and 2 provide an introduction and review of the literature. Sections 3 and 4 provide a comprehensive overview of FFS and PHFS, their functions, objectives, and proposed methodology. Sections 5 and 6 detail the application of the CODAS method for determining the most suitable packaging waste. The discussion and results related to Section 7 are provided. Section 8 provides a summary of our work's conclusion and all potential future investigations.

3 Preliminaries

This section delves into the definition, operation rules, scoring functions, and normalization operator between two random PHFSs.

Definition 1 Senapati and Yager (2019) Let $\mathfrak{I}$ is a universal set. A FFS M in $\mathfrak{I}$ is a representation, $M = \left\{ \langle x, \zeta_M(\mathrm{x}), \eta_M(\mathrm{x}) \rangle : \mathrm{x} \in \mathfrak{I} \right\}$, where $\zeta_M(\mathrm{x}), \eta_M(\mathrm{x}) : \mathfrak{I} \to [0, 1]$ among the state of affairs $0 \le \left(\zeta_M(\mathrm{x})\right)^3 + \left(\eta_M(\mathrm{x})\right)^3 \le 1$. To simplify matters, $\left(\zeta_M(\mathrm{x}), \eta_M(\mathrm{x})\right)$ a FFN defined by $M = \left(\zeta_M, \eta_M\right)$. The Fermatean membership grades are the membership grades associated with FFS.

Definition 2 Liao et al. (2023) A FFS $\left(\zeta_M(x), \eta_M(x)\right)$, which must be satisfied $0 \le \zeta_M^3(x) + \eta_M^3(x) \le 1$, it can be converted into a PHFE using the steps outlined below. Once the bijective mapping has been established,

$$\phi : \left(\zeta_M(x), \eta_M(x)\right) \longrightarrow \left(\zeta_M^3(x), \eta_M^3(x)\right)$$

The result is obtained by normalizing it,

$$\hat{\phi}\left(\zeta_M(x), \eta_M(x)\right) = \left(\hat{\zeta}_M(x), \hat{\eta}_M(x)\right) = \left(\frac{\zeta_M^3(x)}{\zeta_M^3(x) + \eta_M^3(x)}, \frac{\eta_M^3(x)}{\zeta_M^3(x) + \eta_M^3(x)}\right)$$

It's clear now that $\hat{\zeta}_M(\mathrm{x}) + \hat{\eta}_M(\mathrm{x}) = 1$ and hence, $\hat{\eta}_M(\mathrm{x}) = 1 - \hat{\zeta}_M(\mathrm{x})$. Regarding this, any FFS $\left(\zeta_M(\mathrm{x}), \eta_M(\mathrm{x})\right)$ can be considered a single PHFE in the manner of

$$\begin{aligned} {}^{\gamma}\dot{g}(\mathrm{x}) &= \bigcup_{\langle \dot{g}(\mathrm{x}), \dot{\gamma}(\mathrm{x}) \rangle \in {}^{\gamma}\dot{h}(\mathrm{x})} \{\langle \dot{g}(x), \dot{\gamma}(\mathrm{x}) \rangle\} = \left\{ \left\langle \hat{\zeta}_M(\mathrm{x}), 0.5 \right\rangle, \left\langle \hat{\eta}_M(\mathrm{x}), 0.5 \right\rangle \right\} \\ &= \left\{ \left\langle \frac{\zeta_M^3(\mathrm{x})}{\zeta_M^3(\mathrm{x}) + \eta_M^3(\mathrm{x})}, 0.5 \right\rangle, \left\langle \frac{\eta_M^3(\mathrm{x})}{\zeta_M^3(\mathrm{x}) + \eta_M^3(\mathrm{x})}, 0.5 \right\rangle \right\} \end{aligned}$$

Definition 3 Liao et al. (2023) Let ${}^{\gamma}\dot{g}_1 = \bigcup_{\langle \dot{g}_1, \dot{\gamma}_1 \rangle \in {}^{\gamma}g_1} \{\langle \dot{g}_1, \dot{\gamma}_1 \rangle\}$ and ${}^{\gamma}\dot{g}_2 = \bigcup_{\langle \dot{g}_2, \dot{\gamma}_2 \rangle \in {}^{\gamma}g_2} \{\langle \dot{g}_2, \dot{\gamma}_2 \rangle\}$, are two UPHFEs. Then, the following division operations of PHFEs can be introduced.

$${}^{\gamma}\dot{g}_1 \oslash {}^{\gamma}\dot{g}_2 = \left\{ \left\langle \min\left\{1, \frac{\dot{g}_1^1}{\dot{g}_2^1}\right\}, \gamma_*^1 \right\rangle, \ldots \left\langle \min\left\{1, \frac{\dot{g}_1^{p^*}}{\dot{g}_2^{l^*}}\right\}, \gamma_*^{p^*} \right\rangle \right\}$$

Definition 4 Li and Wang (2019) Suppose that ${}^{\gamma}g(x) = \left\{\gamma_i\left(g_i\right) \mid i = 1, 2, \ldots, \#s\right\}$ a PHFE, its scoring function is as follows:

$$S({}^{\gamma}g(x)) = \sum_{i=1}^{\#s} \gamma_i g_i$$

If ${}^{\gamma}g(x)$ satisfying $\sum_{i=1}^{\#s} \gamma_i = 1$.

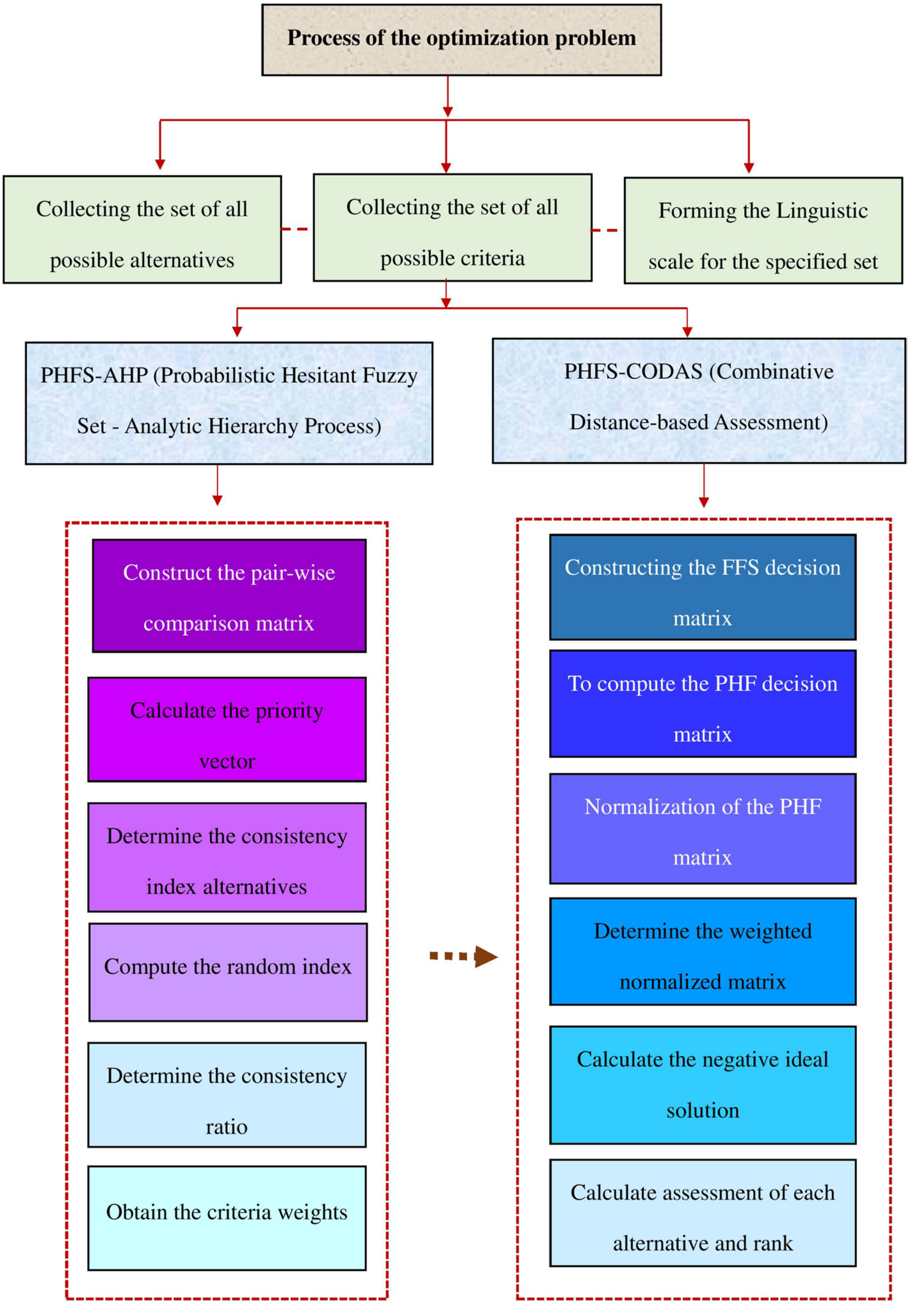

Fig. 1 A flowchart depicting the steps involved in solving an optimization problem

4 Proposed methodology

MCDM methods were used in this research and the results are summarized below. More precisely, we outline the process for solving the optimization problem in Fig. 1.

4.1 Algorithm of fuzzy AHP method

Complex judgments are broken down into a series of pairwise comparisons using AHP. The generated pairwise comparison matrices take the following form,

$$\mathbb{C} = \begin{bmatrix} 1 & \mathbb{C}_{12} & \cdots & \mathbb{C}_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbb{C}_{n1} & \mathbb{C}_{n2} & \cdots & 1 \end{bmatrix}.$$

Step 1 Normalized matrix; Each row sum in the pairwise comparison matrix should be divided by each element.
Step 2 A preference vector was created by averaging the matrix ranks normalized by decimal transformation.
Step 3 Depending on how important each criterion is, groups are created within the weighted total vector. The values' average is then calculated and denoted by λ_{max}.
Step 4 The n alternatives can be determined using the Consistency Index (CI).

$$CI = \left(\lambda_{\max} - n\right)/(n-1)$$

Step 5 As shown in Table 2, Random Index (RI) values should be determined.
Step 6 Calculate consistency ratio CR = CI/RI. If $CI/RI < 0.1$ the degree of CR is acceptable, otherwise AHP is not meaningful.

4.2 Algorithm of fuzzy CODAS method

The Fuzzy CODAS technique is a method used to solve MCDM problems by following specific steps (Keshavarz Ghorabaee at al. 2016). Generate the fuzzy decision matrix in the mode $\bar{\mathcal{D}} = \left[\bar{\mathcal{D}}_{ij}\right]_{m\times n}$. The fuzzy performance score for the alternative M_i is represented by $\bar{\mathcal{D}}_{ij}$, corresponding to the decision maker's criteria.

Step 1. Compute the normalised decision matrix.

$$\overline{\mathcal{D}}_{ij} = \begin{cases} \mathcal{D}_{ij} \oslash \max_i\{\mathcal{D}_{ij}\} & \text{for beneficial criteria} \\ \min_i\{\mathcal{D}_{ij}\} \oslash \mathcal{D}_{ij} & \text{for non- beneficial criteria} \end{cases} \tag{1}$$

where $\max_i\mathcal{D}_{ij}$ is determined as $\max_i\mathcal{D}_{ij} = \left(\max_i\zeta_{ij}, \min_i\eta_{ij}\right)$ and $\min_i\mathcal{D}_{ij}$ is determined as $\max_i\mathcal{D}_{ij} = \left(\min_i\zeta_{ij}, \max_i\eta_{ij}\right)$.

Step 2. Calculate the weighted normalised decision matrix $\widetilde{C} = \left[c_{ij}\right]_{m\times n}$, as follows:

$$\widetilde{C}_{ij} = v_j\tilde{\mathcal{D}}_{ij} \tag{2}$$

Step 3. Calculate the non ideal solution $\widetilde{NS} = \left[\tilde{ns}_j\right]_{1\times m}$ as follows:

Table 2 RI values

Number of Alternatives (n)	RI	Number of Alternatives (n)	RI
3	0.58	6	1.24
4	0.9	7	1.32
5	1.12	8	1.41

$$\overline{ns}_j = \min_i \bar{c}_{ij} \tag{3}$$

Step 4. Calculate each alternative's *Euclidean distance* $\left(\mathcal{ED}_i\right)$ and *Hamming distance* $\left(\mathcal{HD}_i\right)$ from the fuzzy non ideal solution using distance measures (He and Xu 2019).

$$\mathcal{ED}_i = \sum_{j=1}^{m} d_E\left(\bar{c}_{ij}, \overline{ns}_j\right) \tag{4}$$

$$\mathcal{HD}_i = \sum_{j=1}^{m} d_H\left(\bar{c}_{ij}, \overline{ns}_j\right) \tag{5}$$

Step 5. Create an evaluation matrix for comparative assessments $\mathcal{RA} = \left[q_{is}\right]_{m\times n}$ as follows:

$$q_{is} = \left(\mathcal{ED}_i - \mathcal{ED}_s\right) + \left(T\left(\mathcal{ED}_i - \mathcal{ED}_s\right) \times \left(\mathcal{HD}_i - \mathcal{HD}_s\right)\right) \tag{6}$$

The threshold function, denoted by θ, is a key component in the decision threshold generator.

$$\mathbb{T}(\mathrm{x}) = \begin{cases} 1, & \text{if } |\mathrm{x}| \geq \theta \\ 0, & \text{if } |\mathrm{x}| < \theta \end{cases}$$

Step 6. The process of calculating the assessment score for each alternative can be summarized as follows:

$$AS_i = \sum_{s=1}^{m} q_{is} \tag{7}$$

Step 7. Sort the alternatives in order of decreasing value settings AS_i. The preferred alternative should be chosen based on the highest evaluation score.

4.3 Similarity coefficients

Similarity coefficients are a method used to compare two distinct ranking values. The differences are distinguished by the ranking values provided by different methods or the performance of the same method. The coefficients are frequently utilized in research to provide insights into the differences between MCDM and other methodologies (Amman et al. 2023).

Weighted Spearman coefficient:

$$r_w = 1 - \frac{6\sum_{i=1}^{n}\left(P_i - Q_i\right)^2\left(\left(n - P_i + 1\right) + \left(n - Q_i + 1\right)\right)}{n^4 + n^3 - n^2 - n} \tag{8}$$

WS coefficient:

$$WS = 1 - \sum_{i=1}^{N}\left(2^{-S_{xi}} \cdot \frac{\left|S_{xi} - Q_{yi}\right|}{\max\left\{\left|1 - S_{xi}\right|, \left|N - S_{xi}\right|\right\}}\right) \tag{9}$$

Two coefficients were selected: weighted Spearman's coefficient and the Weighted WS coefficient. Both WS and weighted Spearman's coefficients are utilized for ranking values, with the WS coefficient focusing more on ranking than the other.

5 Case study: selection of the optimal packaging waste collection method

Plastic consumption has skyrocketed in the last decade as polypropylene has become ubiquitous in all facets of society. Because of its biodegradability, plastic's management of solid waste has become a significant environmental struggle, and packaging has become a bottleneck.

The fuzzy MCDM method allows experts to make informed decisions on packaging plastic waste collection systems across various domains. Experts offer insights into the environmental impacts of various packaging plastic waste collection methods, including factors like recyclability, biodegradability, energy consumption, greenhouse gas emissions, and ecological footprint. Their expertise ensures that the chosen method aligns with sustainability goals and environmental regulations. These experts possess extensive knowledge and experience in waste collection, sorting, processing, recycling, and disposal technologies. Their expertise ensures that the chosen method is in line with economic viability, profitability, and financial sustainability. The community can collect plastic containers for recycling in five different ways: curbside recycling, drop-off recycling, deposit/refund programmes, buy-back centres, and vehicle collection.

- Curbside Recycling Method (CRM) (M_1): CRM is the most commonly used method for collecting recycling bins. Curbside collection is a modest method of reducing waste and promoting recycling. Bulky bins, colored backpacks, or small plastic bins are commonly used for collecting materials, making them more efficient. Recycling bins are more convenient for neighborhood members to use. Curbside collection communities require residents to separate limited recyclable waste from household waste and store it in special containers, which are then placed in the CRM by municipal contracted personnel.
- Drop-Off Recycling Method (DORM) (M_2): The method involves installing approved composting equipment at key community entry points such as public spaces, religious sites, colleges, universities, shopping malls, and other institutions. Food waste should be properly labeled for easy disposal in containers. Residents are encouraged to bring their waste to the designated recycling drop-off point, where it will be segregated and placed in appropriate containers for proper disposal. DORM processes are beneficial

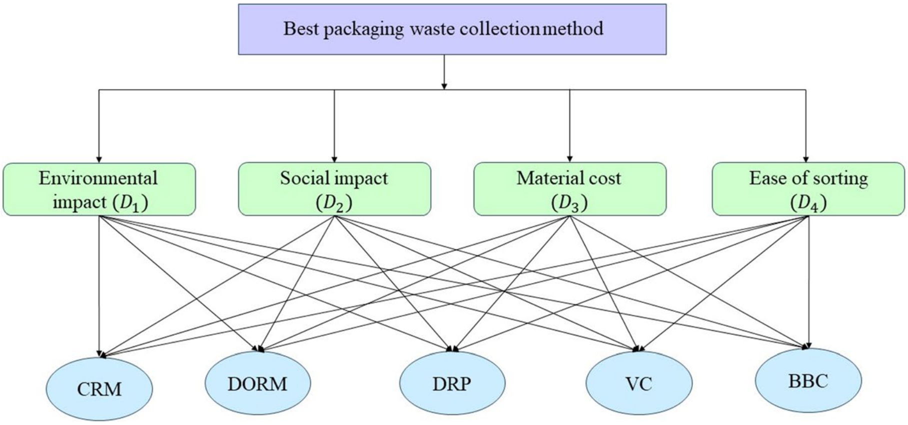

Fig. 2 Selecting the most suitable waste collection method

Table 3 Pairwise comparison of criteria

	Environmental impact	Social impact	Material costs	Ease of sorting
Environmental impact	1	3	7	9
Social impact	1/3	1	5	7
Material cost	1/7	1/5	1	3
Ease of sorting	1/9	1/7	1/3	1

when waste is transported to a central collection point or waste transfer station by occupiers.

- Deposit/Refund Programs (DRP) (M_3): These schemes necessitate the collection of cash deposits and the purchase of plastic containers. The deposit is either explicitly or implicitly returned to the community contributors when the container is recovered from an authorized recovery center. Americans who have consumed a drink from a soda bottle are familiar with the various uses of such containers.
- Vehicular Collection (VC) (M_4): Daily collection of household waste is mandatory. Garbage collection systems in densely populated cities cause unpleasant odors and sight from single-place waste collection, making solid waste disposal problematic.
- Buy-Back Centre (BBC) (M_5): Most buy-to-let recycling facilities are operated by private providers who charge customers for the recycling of their waste. Consumers are typically required to provide separate recycled products for sale at the PBC to meet purchase performance requirements. The proposed consumer purchasing specifications could significantly decrease pollution and enhance the BBC's capacity to process recyclable materials. Consumers are increasingly buying products based on financial incentives, similar to how buy-back centers earn waste turbines based on product market value. Figure 2 presents the hierarchical decision of the four proposed criteria and five waste collection methods.

5.1 The PHFE-based AHP method

The most feasible collection method can be evaluated by developing a hierarchy. The pairwise comparison procedure, as described in Saaty (1990), is utilized to achieve this goal. The goal's relative importance in Table 3 was determined by comparing the four criteria pairwise. The weight of the criterion is $w_j = (0.5739{,}0.2913{,}0.0902{,}0.0444)$, as depicted in Fig. 3.

The consistency of decision-makers' judgments is assessed through the calculation of CI and CR values. The calculated CI and CR values are 0.0561 and 0.0623, respectively.

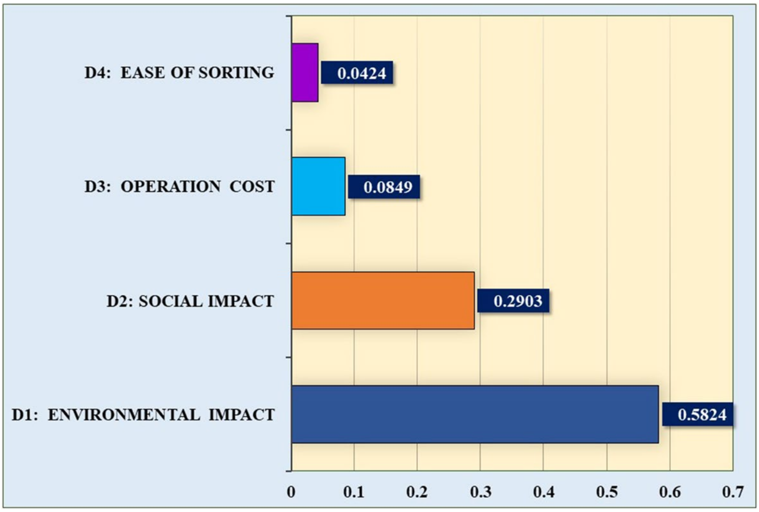

Fig. 3 Weights of criteria

Decision-makers' assessments are considered reliable due to their CR values being less than 0.1.

5.2 The PHFE-based CODAS method

The normalized production model for the FFS environment was developed using an FFS definition (1), considering the segmentation function (Senapati and Yager 2019). The decision matrix D was emphasized as a crucial factor.

$$D = \begin{bmatrix} & D_1 & D_2 & \cdots D_n \\ M_1 & (\zeta_{11}, \eta_{11}) & (\zeta_{12}, \eta_{12}) & (\zeta_{1n}, \eta_{1n}) \\ M_2 & (\zeta_{21}, \eta_{21}) & (\zeta_{22}, \eta_{22}) & (\zeta_{2n}, \eta_{2n}) \\ \vdots & \vdots & \vdots & \vdots \\ M_m & (\zeta_{m1}, \eta_{m1}) & (\zeta_{m2}, \eta_{m2}) & (\zeta_{mn}, \eta_{mn}) \end{bmatrix}$$

The linguistic conversion scale was utilized to determine the optimal approach in Table 4, prioritizing factors influencing the decision-making goal.

Table 4 Linguistic conversion scale

Linguistic term	Fermatean fuzzy set values
Very highest	{0.85, 1.0}
Highest	{0.78, 0.86}
Medium	{0.54, 0.73}
Lowest	{0.36, 0.59}
Very lowest	{0.15, 0.35}

Table 5 The fermatean fuzzy decision matrix

	D_1	D_2	D_3	D_4
M_1	$\{\langle(0.76, 0.83)\rangle\}$	$\{\langle(0.53, 0.68)\rangle\}$	$\{\langle(0.54, 0.68)\rangle\}$	$\{\langle(0.63, 0.70)\rangle\}$
M_2	$\{\langle(0.85, 0.92)\rangle\}$	$\{\langle(0.76, 0.92)\rangle\}$	$\{\langle(0.73, 0.78)\rangle\}$	$\{\langle(0.26, 0.35)\rangle\}$
M_3	$\{\langle(0.23, 0.45)\rangle\}$	$\{\langle(0.73, 0.83)\rangle\}$	$\{\langle(0.25, 0.38)\rangle\}$	$\{\langle(0.65, 0.72)\rangle\}$
M_4	$\{\langle(0.53, 0.76)\rangle\}$	$\{\langle(0.25, 0.43)\rangle\}$	$\{\langle(0.73, 0.78)\rangle\}$	$\{\langle(0.26, 0.35)\rangle\}$
M_5	$\{\langle(0.19, 0.28)\rangle\}$	$\{\langle(0.19, 0.26)\rangle\}$	$\{\langle(0.18, 0.25)\rangle\}$	$\{\langle(0.72, 0.80)\rangle\}$

The FFS decision matrix allows consultants to prioritize waste collection, as detailed in Table 5. Table 6 displays the PHFS result matrix after applying the Definition (2) correction law.

Step 1. The decision matrix with normalization $(\widetilde{ND}) = [\tilde{D}_{ij}]$ is calculated using Equation (1) and Definition (3). Table 7 displays the outcome of the value.

Step 2. The weighted normalised decision matrix $(\widetilde{R})$ is calculated using Equation (2), with the results displayed in Table 8.

Step 3. The solution for a negative ideal $\widetilde{NS} = [\tilde{ns}_j]_{1\times m}$ is given by Equation (3). $\overline{ns}_j =$ {0.2623712, 0.16219061, 0.05084661, 0.0252492}

Step 4. Calculate the (ED_i) and (HD_i) of each alternative to the optimal solution using Equations (4) and (5). ED_i={0.060418126, 0.069402117, 0.325773164, 0.184625686, 0.152053425} HD_i={0.04695439, 0.03611209, 0.35408219, 0.25554579, 0.20439341}

Step 5. The matrix of relative assessment $\widetilde{RA}$ is calculated using Equation (6), as illustrated in Table 9.

Step 6. Eq. 7 displays the assessment scores for each option. AS_i= {−0.4877, −0.4428, 0.8407, 0.1322, −0.0309} Fig. 4 displays a visual representation of various possible values.

$$M_3 > M_4 > M_5 > M_1 > M_2$$

Table 6 The probabilistic hesitant fuzzy decision matrix

	D_1	D_2	D_3	D_4
M_1	$\{\langle 0.4343, 0.5\rangle, \langle 0.5657, 0.5\rangle\}$	$\{\langle 0.3213, 0.5\rangle, \langle 0.6787, 0.5\rangle\}$	$\{\langle 0.3337, 0.5\rangle, \langle 0.6663, 0.5\rangle\}$	$\{\langle 0.4216, 0.5\rangle, \langle 0.5784, 0.5\rangle\}$
M_2	$\{\langle 0.4409, 0.5\rangle, \langle 0.5590, 0.5\rangle\}$	$\{\langle 0.3605, 0.5\rangle, \langle 0.6395, 0.5\rangle\}$	$\{\langle 0.4126, 0.5\rangle, \langle 0.5874, 0.5\rangle\}$	$\{\langle 0.1997, 0.5\rangle, \langle 0.8003, 0.5\rangle\}$
M_3	$\{\langle 0.1178, 0.5\rangle, \langle 0.8822, 0.5\rangle\}$	$\{\langle 0.4049, 0.5\rangle, \langle 0.5951, 0.5\rangle\}$	$\{\langle 0.2216, 0.5\rangle, \langle 0.7784, 0.5\rangle\}$	$\{\langle 0.4239, 0.5\rangle, \langle 0.5761, 0.5\rangle\}$
M_4	$\{\langle 0.2532, 0.5\rangle, \langle 0.37467, 0.5\rangle\}$	$\{\langle 0.1642, 0.5\rangle, \langle 0.8358, 0.5\rangle\}$	$\{\langle 0.4505, 0.5\rangle, \langle 0.5495, 0.5\rangle\}$	$\{\langle 0.2907, 0.5\rangle, \langle 0.7093, 0.5\rangle\}$
M_5	$\{\langle 0.2381, 0.5\rangle, \langle 0.7619, 0.5\rangle\}$	$\{\langle 0.2807, 0.5\rangle, \langle 0.7193, 0.5\rangle\}$	$\{\langle 0.2718, 0.5\rangle, \langle 0.7282, 0.5\rangle\}$	$\{\langle 0.4216, 0.5\rangle, \langle 0.5784, 0.5\rangle\}$

Table 7 The normalized PHF decision matrix

	D_1	D_2	D_3	D_4
M_1	0.4562	0.6615	0.76	0.5982
M_2	0.4505	0.6103	0.6458	1
M_3	1	0.5587	1	0.5955
M_4	0.6554	1	0.5989	0.7866
M_5	0.6792	0.7227	0.8754	0.5982

Table 8 The weighted normalized PHF decision matrix

	D_1	D_2	D_3	D_4
M_1	0.265691	0.192033	0.064524	0.025364
M_2	0.262371	0.17717	0.054828	0.0424
M_3	0.5824	0.162191	0.0849	0.025249
M_4	0.381705	0.2903	0.050847	0.033352
M_5	0.395566	0.2098	0.074321	0.025364

Table 9 Relative assessment matrix

	M_1	M_2	M_3	M_4	M_5
M_1	0	−0.00899	−0.26373	−0.12369	−0.09135
M_2	0.00899	0	−0.25475	−0.11472	−0.08237
M_3	0.26373	0.25475	0	0.14087	0.1732
M_4	0.12369	0.11472	−0.14087	0	0.03254
M_5	0.09135	0.08237	−0.1732	−0.03254	0

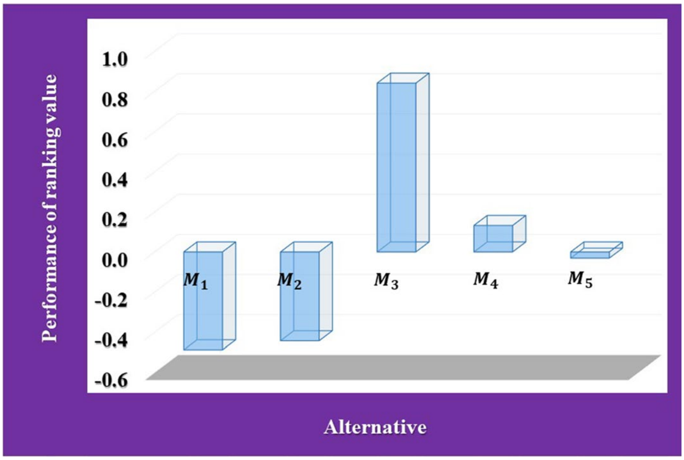

Fig. 4 The proposed CODAS method

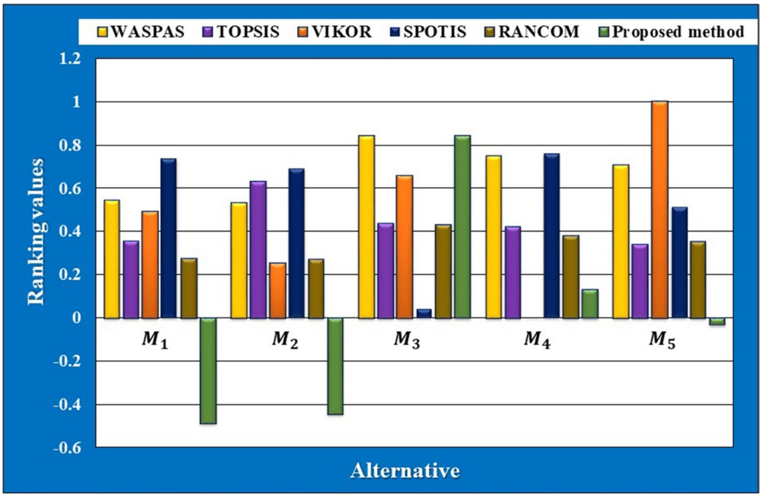

Fig. 5 Comparison of ranking results

Table 10 Comparative ranking of the results

Alternative	VIKOR	TOPSIS	WASPAS	SPOTIS	RANCOM	Proposed Method
M_1	0.4901	0.4901	0.5422	0.7369	0.2738	−0.4877
M_2	0.2514	0.6294	0.5307	0.6913	0.2683	−0.4428
M_3	0.6559	0.4354	0.8404	0.0424	0.4273	0.8406
M_4	0	0.4214	0.7486	0.7628	0.3781	0.1321
M_5	1	0.3378	0.7039	0.5163	0.3525	−0.0308

6 Results and discussion

The study's findings are summarized in the following section. The Deposit/Refund Programmes (M_3) have been ranked as the top strategy for managing packaging plastic waste. The study presents a hybrid fuzzy MCDM approach for determining the most suitable plastic waste collection methods using AHP-CODAS. The case study identified the best plastic waste collection methods based on four criteria and five waste collection methods.

The deposit-refund system (M_3) is a device that encourages package reuse, thereby reducing the need for landfills. This recycling method offers significant advantages to the economy, environment, and society. Plastic's superior performance in the vehicular collection (M_4) is due to its reduced weight, cost, environmental compliance, and recycling capabilities, setting it apart from aluminum. Buy-back centres (M_5) charge garbage collectors a fee for delivering recyclables in their operating areas. The curbside recycling method (M_1) is satisfactory as it reduces land and water contamination. Minimizing littering in landfills not only helps in reducing environmental degradation but also prevents the erosion of fertile soils. Drop-off recycling (M_2) is a recycling plan where designated locations collect various recyclables and drop them in marked containers.

This study explores various collection methods that align with India's integrated plastic waste management system. This study explores various collection methods that align with India's integrated plastic waste management system. The suggested methods can be applied to other developing or industrialized nations.

6.1 Comparative analysis

The FPHFS-CODAS approach is a distinctive method for determining the most suitable alternatives. The study compares five popular MCDM techniques: F-TOPSIS (Kumar et al. 2022), F-VIKOR (Khan et al. 2022), F-WASPAS (Rao and Sujatha 2023), F-SPOTIS (Abdel-aziem et al. 2023), and F-RANCOM (Wieckowski et al. 2023). The mean score of the evaluated fuzzy techniques was real, as per the performance evaluations set by the instructors for each ranking result, as shown in Table 10.

The proposed method has chosen five PWC technologies with a sequence that differs significantly from the VIKOR sequence but is compatible with the TOPSIS sequence. The fuzzy VIKOR and SPOTIS strategies prioritize options with the smallest final value, while the proposed CODAS strategy considers absolute ratings and relative performance balance, making it a superior choice for sustainability prioritization. The proposed fuzzy MCDM strategies show (M_3) is the best approach, as illustrated in Fig. 5.

The distance-based comparative analysis method involves adjusting the ranking value of alternatives by adding and averaging scores based on minor changes. The proposed method, which is more effective than other MCDM methods, has yielded more feasible results.

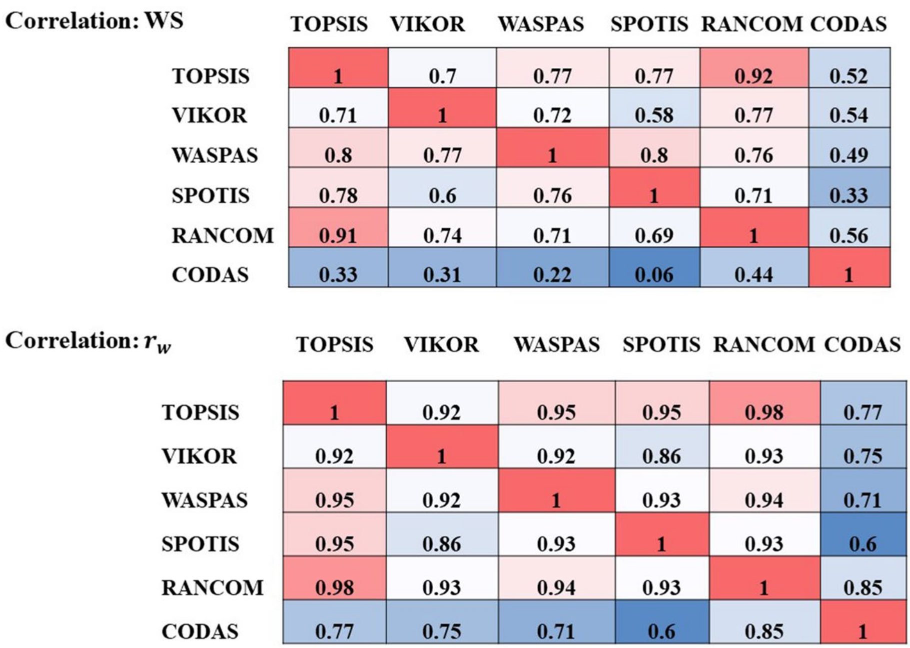

Fig. 6 Correlation of rankings

The rankings were compared using two previously discussed similarity coefficients, Eqs. 8 and 9, to assess their accuracy. The VIKOR method demonstrated the lowest correlation with other methods used in this study, as depicted in Fig. 5. The CODAS and VIKOR methods show the lowest correlation in weighted Spearman's correlation coefficient, following the TOPIS method and VIKOR method. The spectrum of CODAS, WASPAS, SPOTIS, and RANCOM exhibits high similarity, as shown in Fig. 6, as they promote similar alternatives. The WS correlation coefficient is asymmetrical. The coefficient rewards higher-ranked alternatives for the referenced one. The VIKOR method exhibits a slight resemblance to other methods, with the rest falling between 0.7 and 0.94. A value of 0.8 indicates a similarity between ranking values but can favor some alternatives differently, while a 0.94 value indicates highly similar rankings. The proposed method, which is more successful than existing MCDM methods, provided more realistic results.

6.2 Sensitivity analysis

The effectiveness of the developed method is evaluated through two cases.

Case I: The proposed method is used to consider equal weights for criteria, resulting in the optimal solution being M_3.

Case II: The optimal solution is obtained by assigning zero weights to the weights D_1, D_2, and D_4, and using the developed methodology for alternative M_3. Table 11 and Fig. 7 display the results obtained.

Table 11 Sensitivity ranking of the results

Alternative	Case I	Rank	Case II	Rank
M_1	0.057738	3	−0.23401	4
M_2	0.26069	1	−0.53636	5
M_3	0.096259	2	0.291032	2
M_4	−0.04675	4	0.391761	1
M_5	−0.15345	5	0.09187	3

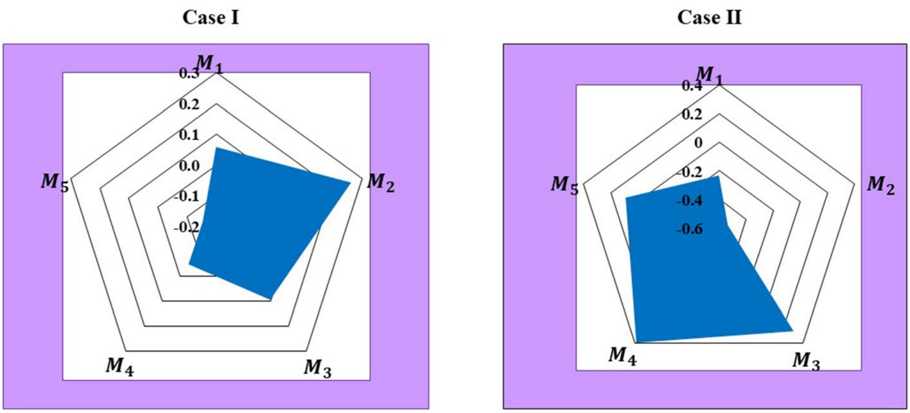

Fig. 7 Sensitivity analysis results

Sensitivity analysis is a crucial tool in decision-making, helping to select the best alternative among competing options. It involves evaluating each alternative based on evaluative criteria, determining how much variation in input values affects the results of a mathematical model. This method can help identify the best data for evaluating and selecting a plastic waste collection method.

7 Conclusion

The FFS and unified PHFS were combined to form the FPHE, offering procedures and comparison methods for FPHEs. The novelty of this paper is to extend CODAS using FPHFS in applications involving decision problems in ambiguous and complex environments. The fuzzy CODAS approach is combined with the provided operators to address various MCDM challenges.

The study presents a probabilistic strategy based on the best resalable trash collection system to highlight the applicability and benefits of new technologies. The growing use of plastic is causing a significant increase in plastic waste, which is a major issue in the developing world. The environmental issue of plastic waste has sparked research on sustainable energy. The circular economy is crucial for recycling plastic waste and repurposing it without causing harm to natural resources. This study utilizes a fuzzy MCDM model to evaluate criteria, rank them in importance, and choose the most suitable recycling options for packaging trash. Recycling should be conducted in municipal facilities rather than private ones, as it boosts public awareness and generates revenue from recycled garbage. The government should increase incentives for effective packaging waste management policies. The government should promote the recycling of packaging waste in localities.

The AHP is primarily utilized to compare the key factors and objectives among the various trash collection techniques being investigated. AHP-CODAS is a valuable method for addressing complex MCDM issues. A more efficient garbage collection system minimizes negative impacts on society and the environment, providing lower operating costs. The results indicate that the deposit or return method is the most suitable option. The D/R system effectively manages waste collection, potentially offering financial benefits. This research contributes to the creation of a sustainable economic model for reducing plastic waste. This paper presents a decision-making method that effectively addresses PWC technology selection issues in uncertain environments, potentially extending to other waste management problems like MSW treatment and sewage treatment.

In the future, we can perform further in-depth studies on the three probable avenues listed below. First of all, in the actual decision-making process, there is not just choice information in the form of linguistic concepts but also real numbers and interval numbers. Therefore, in the future, a hybrid MADM technique that can handle multiple types of decision information can be used to choose an optimal packaging waste collection system. Second, the approach suggested in this research is feasible and practical; therefore, it may be implemented in various industries. Finally, packaging and plastic waste can be investigated in a spherical, fuzzy environment to address more complex and precise problems. Additionally, it improves the accuracy of the method in unpredictable settings and will provide criteria for a more effective hierarchy and selection process.

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Declarations

Competing interests The authors declare no competing interests.

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