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An appropriate artificial intelligence technique for plastic materials recycling using bipolar dual hesitant fuzzy set

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Plastic recycling has become more important than ever as the globe struggles with growing environmental issues. This research explores the significant environmental impact of recycling plastic and its growing relevance. The pervasive material known as plastic presents a complex risk to both human health and ecosystems in contemporary life. It exacerbates problems including marine pollution, habitat damage, and wildlife entanglement because of its persistence in landfills and seas, which leads to serious ecological deterioration. In addition, producing plastic uses a lot of energy and produces a lot of greenhouse gas emissions, which exacerbate climate change. Through the use of multi-criteria decision making (MCDM), this study emphasizes how vital it is to support recycling activities in order to protect the environment and promote a sustainable future. The elimination and choice ex-pressing reality (ELECTRE) approach is used to rank the alternatives in this proposed research study that employs bipolar dual hesitant fuzzy sets (BDHFs). The most efficient and versatile outranking method for making decisions is the BDHF-ELECTRE approach. The weights of environment, economic, social, technical, and finally safety is computed using the entropy distance metric. The economic factor received the highest score of 0.2945 among the other factors since economic considerations are crucial in choosing the most efficient plastic recycling method, as they ensure sustainability, cost-effectiveness, resource allocation, and overall feasibility in managing plastic waste. The decision-makers determined that the mechanical recycling approach ought to be prioritized over all others for the efficient recycling of plastic waste. The robustness of the system is examined in the sensitive and comparative analyses. The proposed MCDM technique thus presents a viable solution, mitigating the adverse effects of plastic waste by conserving resources, reducing energy consumption, and curbing pollution.

Keywords Bipolar dual hesitant fuzzy set, ELECTRE method, Entropy distance measure, Plastic recycling techniques, MCDM

Plastic pollution, stemming from the widespread use and improper disposal of plastic materials, poses a grave threat to the Earth's ecosystems. Despite increased knowledge of the harmful effects, the careless disposal of plastics in landfills is still a common practice. Since plastics are made of non-biodegradable polymers, they can linger in landfills for hundreds or even thousands of years, releasing dangerous chemicals into the groundwater and surrounding soil. Methane is one of the greenhouse gases released by these materials during their degradation, which exacerbates climate change. Balancing the production, recycling, and reuse of plastics presents a formidable challenge in contemporary environmental stewardship[1]. Once considered a rare commodity, plastics have emerged as a pervasive menace, finding utility in a myriad of applications ranging from

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bottles to industrial equipment. Their ubiquity generates vast quantities of waste, necessitating urgent adoption of sustainability principles to safeguard resources. Compounding the issue, plastics endure for thousands of years without biodegrading, underscoring the critical importance of effective waste management strategies. Recycling, the process of converting waste materials into new resources, emerges as a pivotal focus in addressing plastic waste. This study delves into plastic recycling methods (PRM) and their intricacies, offering insights into sustainable approaches for mitigating plastic pollution. The nomenclature is given inTable 1.

Numerous researchers have significantly extended the concept of fuzzy sets, leveraging its dependence on membership degrees to address uncertainty. Fuzzy sets serve as a valuable tool in navigating conditions of uncertainty, with scientists continuously innovating new extensions. These extensions encompass various types such as intuitionistic fuzzy sets, Pythagorean fuzzy sets, interval-valued fuzzy sets, and type-2 fuzzy sets, each elucidated through distinct multi-criteria decision-making methods. In accommodating decision makers' hesitations and ambiguities, hesitant fuzzy sets play a pivotal role. Through hesitant fuzzy sets, decision makers can arrive at clearer and more informed decisions. Moreover, hesitant fuzzy sets have been further extended by several variations, each tailored to different applications within multi-criteria decision-making frameworks. In this context, we introduce a novel extension of hesitant fuzzy sets known as bipolar hesitant fuzzy sets. We propose the advancement from bipolar hesitant fuzzy sets to bipolar dual hesitant fuzzy sets, aiming to enhance decision-making processes in complex and uncertain environments. Over the past few years, there has been a growing interest among many scientists in combining bipolar values with volatile and ambiguous collections, resulting in favorable outcomes. These models, considering the bipolar and heterogeneous nature of element participation scales, offer advantages over other complex mathematical tools used to describe possibilities. However, there are still challenges related to the lack of configuration tools, similar to those available for other mathematical tools. To address this, the concept of ambiguous bipolar value sets and the theory of ambiguous bipolar value soft sets have been introduced, aiming to compensate for the deficiency of structural tools. Classical sets prove to be highly suitable for defining uncertainty problems. The bipolar dual hesitant fuzzy set (BDHFs) is an extension of hesitant fuzzy sets, with hesitant fuzzy sets representing decision makers' thoughts of hesitation. In contrast, BDHF sets deal with decision makers' hesitation thoughts by incorporating both positive and negative information. Positive information signifies what is deemed possible, while negative information denotes what is considered impossible. The BDHF set, therefore, defines both membership and non-membership degrees, offering a valuable tool for addressing various uncertainty problems. It enables decision makers to incorporate both positive and negative ideas as membership and non-membership degrees, respectively. Through this proposed set, we aim to define mutually inclusive membership and non-membership values based on positive and negative thoughts. In multi-criteria decision-making, there are numerous unique techniques available for consideration. Each method possesses its own unique specialization. In our proposed research, we have opted to utilize the ELECTRE method for ranking alternatives. ELECTRE is a multi-criteria decision-making (MCDM) method grounded in the concept of outranking, wherein alternatives are compared against each other based on relevant criteria. It employs pairwise comparisons of alternatives to determine their superiority. However, ELECTRE methods are typically applicable to traditional MCDM problems with independent criteria, despite the existence of interdependencies among criteria in real-world scenarios. The advantage of utilizing ELECTRE methods lies in their ability to streamline decision-making processes by applying another MCDM method with a limited set of alternatives, thereby saving considerable time. The criteria in ELECTRE methods are characterized by two distinct sets of parameters: importance coefficients and threshold values. The existing studies on plastic recycling methods (PRM) highlight a notable research gap, particularly concerning the persistence of plastic

MCDM	Multi criteria decision making
BDHF	Bipolar dual hesitant fuzzy
BDHFs	Bipolar dual hesitant fuzzy set
BDHFN	Bipolar dual hesitant fuzzy number
ELECTRE	ELimination and choice ex-pressing reality
TOPSIS	Technique for order preference by similarity to ideal solution
VIKOR	Vlsekriterijumska Optimizacija I Kompromisno Resenje
ARAS	A new additive ratio assessment
SECA	Simultaneous evaluation of criteria and alternatives
MARCOS	Measurement of alternatives and ranking according to compromise solution
MAIRCA	Multi-attributive ideal-real comparative analysis
COCOSO	Combined coromise solution
COPRAS	Complex proportional assessment
WASPAS	Weighted aggregated sum product assessment
AHP	Analytic hierarchy process
SWARA	Stepwise weight assessment ratio analysis
EDAS	Evaluation based on distance from average solution
PF	Pythagorean fuzzy
PROMETHEE	Preference ranking organization method for enrichment and evaluations

Table 1. Nomenclature.

litter in developing countries despite significant investments and efforts by governments to promote recycling. Despite these endeavors, various constraints significantly impact the success of PRM initiatives, leading to project and policy failures. Unforeseen events such as pandemics or economic downturns can exacerbate these challenges, making it difficult or even impossible to implement effective recycling strategies. Developing countries, in particular, require sustainable recycling techniques resilient to such uncertain constraints. While researchers have explored diverse applications and proposed solutions, none have ventured into the realm of bipolar dual hesitant fuzzy (BDHF) set environments. Given the inherent uncertainty and barriers in plastic recycling processes, selecting the optimal recycling method proves to be a daunting task, as each method possesses unique characteristics. Consequently, effective analysis of this specific application necessitates the development of appropriate mathematical models. Numerous researchers have articulated their concepts using multi-criteria decision making (MCDM) methods. In this research article, we introduce plastic recycling techniques employing the bipolar dual hesitant fuzzy MCDM method. While hesitant fuzzy sets address decision-makers' hesitations and ambiguities, bipolar hesitant fuzzy sets handle hesitation with both positive and negative information. The Bipolar Dual Hesitant Fuzzy set incorporates decision-maker hesitation thoughts in both membership and non-membership functions, considering positive and negative information. Additionally, we propose an effective weight-finding method utilizing an indicator called entropy distance measure, which evaluates similarity using distance and information using entropy. The ELECTRE method, a widely utilized MCDM approach, ranks alternatives based on outranking relations, making it a renowned outranking method. The subsequent sections of this study are structured as follows: The related work is covered in detail in section "Related work". The basic concepts will be clarified in "Preliminaries" section. A brief summary of the different kinds of plastic will be given in "Description of the significance of plastic recycling" section. Section "Research methodology" will contain an outline of the methodology. The case study itself will be presented in "Numerical analysis: recycling techniques for plastic to proposed method" section. In Sect. 7, the findings will be reported along with additional commentary and then will deal with result validation. Section "Result and discussion" will conclude with a summary of the findings and opportunities for further research.

Related work

in terms of mass manufacture, lightweight, and ease of use, with global production reaching 8.3 billion metric tonnes[2]. Injection molding has emerged as a pioneering way to advance technology and plastic production methods[3]. High-tech automation-controlled injection machines reduce production errors[4]. Other reasons for the growing interest in injection molding include the demand for too many items in a short period as product life cycles shrink[5]. The raw material, in the form of granules or pellets, is turned into the end product at a precise temperature and pressure via injection molding[6]. Aghajani Mir et al.[7] assessed the municipal solid waste treatment system by the modified TOPSIS method, and VIKOR was used for sensitivity analysis. Akram et al.[8] elaborated on the ELECTRE-II method under the hesitant Pythagorean fuzzy set (HPFs) with appropriate application. The most effective advanced treatment method for reusing and treating plastic waste is washing water. The treatment reduces the sludge production from 1.00 to 0.21[9]. The supplier section problem was explained by a new group decision-making methodology of intuitionistic fuzzy sets (IFS) with ELECTRE I and the extended VIKOR method[10]. The case of Brazil's waste recycling techniques selection process in two different scenarios, waste recycling facilities to construction and performance evaluation and different kinds of plastic waste disposal techniques[11]. Chaurasiya and Jain[12] discussed the various kinds of health care waste treatment through consuming multi-criteria decision-making techniques, COPRAS, and also entropy measures for evaluating the importance of criteria. Chen et al.[13] developed the hesitant fuzzy-ELECTRE I method and also determined an innovative concept of hesitant fuzzy concordance set and hesitant fuzzy discordance set. A developing country faces rapidly increasing pollution. A case study of Turkish municipal solid waste disposal techniques is selected using MCDM. TOPSIS, PROMETHEE I, and PROMETHEE II methods determine the ranking[14]. Cruz Sanchez et al.[15] focus on thermoplastic recycling processes in current advances by using additive manufacturing technologies. MCDM helps decision-makers and enterprises obtain reasonable conclusions, both quantitatively and qualitatively. It provides recommendations for enhancing options in the direction of a specific goal or utility, utilising a number of analytical approaches[16] and tools to examine how all relevant data influences the decision-making process. MCDM is a goal-oriented procedure that provides the support needed to achieve this objective. While the traditional approach seeks to find a single optimal solution, real-world situations frequently involve several solutions and evaluation criteria, rendering this goal impossible[17]. In actuality, many problems necessitate the examination of multiple criteria before a final conclusion can be made. Unfortunately, the number of assessment criteria increases, making decision-making more difficult[18]. Evaluate the different six stages of distributed recycling via the additive manufacturing chain. The review focuses on developing a life cycle assessment modelling of plastic chemical recycling methods[19]. The literature review of the ELECTRE method and the bipolar hesitant fuzzy set is given in Table 2.

Demets et al.[33], developed the complex plastic waste matrices before and after the washing procedure to analyse volatile contaminants in the technique qualitatively and semi-quantitatively. Ebner and Iacovidou[34] assessed the operational and universal inadequacies of the plastics classification; a sustainable plastics economy in COVID-19 threatens society's commitment to transition. Fei et al.[35]investigated the selection of the optimal supply. A problem of supply chain management deals with the ELECTRE MCDM method, which is handled by the Dempster-Shafer theory. Geetha et al.[36] determine the hesitant Pythagorean fuzzy ELECTRE-III method for testing the plastic recycling problem. The research determined the various kinds of plastic recycling techniques. Gu et al.[37] investigated the Taguchi method and primary constituent investigation to recuperate the mechanical belongings of recycled polypropylene. Marazzi et al.[38], work hard to investigate the pollution of plastic waste reduction in rivers by using one of the methods in MCDM techniques, the SWOT method. The case study of Nis City examined the best sustainable situation for composting organic and inorganic waste recycling to belong

Authors / Year	Method	Problem
Akram et al.[20]	BF-TOPSIS and BF-ELECTRE-I	To evaluate the complexity and uncertainty of diagnostic process
Alghamdi et al.[21]	BF-TOPSIS and BF-ELECTRE-I	To develop new methodology in MCDM problems expressed by bipolar fuzzy information
Al-Quran et al.[22]	HBVNWAO(Hesitant bipolar-valued neutrosophic weighted averaging) and the HBVNWGO(hesitant bipolar-valued neutrosophic weighted geometric operator)	To evaluate the best option to invest a money of an investment company
Fatih Ecer[23]	ARAS, SECA, MARCOS, MAIRCA, COCOSO and COPRAS	To select a battery electric vehicles
Gao et al.[24]	Hamacher prioritized weighted average operator and Hamacher prioritized weighted geometric operator	To select the outstanding teacher
Komsiyah et al.[25]	Fuzzy ELECTRE	To select best cement vendors by Fuzzy ELECTRE.
Liu et al.[26]	SWARA and WASPAS	To select the application of optimal talent by using bipolar hesitant fuzzy set
Mahmood and Rehman [27]	Weighted generalized trigonometric similarity measures	To integrate pattern recognition and medical diagnosis application in bipolar complex fuzzy set
Mandal and Ranadive[28]	Aggregation operators	To determine hesitant bipolar valued fuzzy set under some operators
Özçelik and Nalkıran[29]	EDAS, TOPSIS and VIKOR	To select a medical device in health care system
Pandey et al.[30]	Domination degree of BVHFs(bipolar valued hesitant fuzzy set)	To evaluate the impact power of a person
Qi et al.[31]	Entropy measure and TOPSIS	To analyze influence of weapon system-of-systems, display better cogency and distinguish ability than any other methods
Ruojue et al.[32]	ELECTRE	To determine the prioritization of hydrogen pathways under hybrid information.

Table 2. Literature review of ELECTRE method and bipolar hesitant fuzzy set.

to their selected four waste treatments. The AHP method is used for selecting sustainable waste treatment[39]. Mojaver et al.[40] focus on the relationship between biomass and plastic waste type air gasification. Using the AHP and TOPSIS methods to choose the greatest feedstock gasification. Nik et al.[41] exploited the mechanical properties of invention since recycled plastics are developed by the Taguchi optimisation method. Rani et al.[42] examine the assortment process of renewable energy using the PF-VIKOR method in novel divergence and entropy measures. Senthil et al.[43] Investigate the contractor assessment and assortment in third-party converse logistics applications in a hybrid way of MCDM. Again, he develops the risk of a reverse supply chain with hybrid MCDM models[44]. Shumaiza et al.[45] evaluate the method BF-ELECTRE II in the selection process for business location area and the best supplier selection, evaluating the result by bipolar uncertainty. Thao[46] investigated a new similarity measure including an entropy measure and improved a new entropy measure for picture fuzzy sets in the application of supplier selection problems. Ugduler et al.[47], focus on two removal methods for additives, for example, solid-liquid amputation and dissolution-drizzle. Vinodh et al.[48] develop the evaluation model for choosing the superlative plastic recycling process via the AHP and TOPSIS methods. Wang et al.[49] examined the separation of aluminium from waste pharmaceutical blisters, which include polyvinyl chloride plastic. An industrial case study related to aerospace has tested and focused on generic decision methodology under MCDM techniques for additive manufacturing products[50]. In the China study, various techniques were expended to recycling business prototypes for characteristic peripheral fragments of traveller vehicles and analysed by strengths, weaknesses, opportunities, and threats (SWOT) strategies[51].

Motivation of the research

The motivation for undertaking research on plastic recycling using Multi-Criteria Decision Making (MCDM) methods stems from the urgent need to address the environmental impact of plastic waste. Ecosystems, wildlife, and human health are all severely impacted by plastic pollution. Developing efficient recycling strategies is essential to reducing these consequences. But there are so many different ways to recycle plastic that it takes a methodical effort to find the best ones. A systematic framework for assessing and choosing the best recycling techniques based on a variety of factors, including practicality, cost-effectiveness, and environmental impact, is offered by MCDM. Researchers hope to lessen plastic pollution, promote sustainable waste management techniques, and save the environment for coming generations by utilizing MCDM.

Contribution of the research

The contribution of this research article is described below:

- An MCDM framework for recycling plastic waste is proposed based on entropy distance measure and ELECTRE under BDHF environment.
- The BDHFs emerges as a promising solution, offering clear and unambiguous insights into plastic recycling techniques. This set stands out as a confident and effective problem-solving tool, serving as an extension of hesitant fuzzy sets.
- The BDHF theory is used to obtain linguistic information in BDHF numbers.
- The suggested hybrid MCDM method makes use of fuzzy methodologies and linguistic variables to make it easier for the practitioner to gather evaluation data from the expert panel.
- The defuzzification process of the BDHFs is facilitated by a novel score function.
- The relative significance of each criterion utilized to select the optimal PRM is determined using the BDHF based entropy method.

- The ranking of various PRM alternatives is accomplished through BDHF-ELECTRE, an outranking method known for delivering highly accurate results.
- 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 our proposed paradigm with the existing MCDM methods.

Preliminaries

Definition 3.1 A fuzzy set *X* in *U*. Here u denote the reference set. The fuzzy set A represent as

$$A = \{\langle u, \alpha_x(u)\rangle \, u \in U\} \tag{1}$$

Then, $\alpha_x : U \to [0,1]$ is denotes membership value of fuzzy set. Every fuzzy set is depended on membership function. Each membership function is belongs to the value [0, 1], its represented as $\alpha_x(u) \in [0,1]$. The membership value is $u \in U$ in *X*.

Definition 3.2 An intuitionistic fuzzy set *X* in *U*. The mathematical representation of intuitionistic fuzzy set S is given as

$$S = \{\langle u, \alpha_x(u), \beta_x(u)\rangle \, u \in U\} \tag{2}$$

Here, $\alpha_x(u)$ is represent membership value and $\beta_x(u)$ is represent non-membership value. Each membership and non-membership value is belongs to [0, 1]. Its represent as, $\alpha_x : U \to [0,1]$ and $\beta_x : U \to [0,1]$. The intuitionistic fuzzy set which satisfies one condition that is $0 \leq \alpha_x(u) + \beta_x(u) \leq 1$,for every $u \in U$. The numbers of membership and non-membership $\alpha_x(u), \beta_x(u) \in [0,1]$

Definition 3.3 Let a fixed set is *U*. where the HFS(hesitant fuzzy set) on *U*. the subset of [0, 1] is hesitant fuzzy set *U*. The HFS(hesitant fuzzy set) X_H represent by following form

$$X_H = \{\langle u, h(u)\rangle / u \in U\} \tag{3}$$

The hesitant fuzzy element is represent as *h*(*u*) in the above equation. The set [0, 1] having the same value of hesitant fuzzy element. It is denote a possible membership degree of the element $u \in U$ to the set X_H.

Definition 3.4 An IHFs(intuitionistic hesitant fuzzy set) *H* on *U*. Basically membership and non-membership included in intuitionistic hesitant fuzzy set. In general, mathematical representation of intuitionistic hesitant fuzzy set is given below,

$$X_H = \{\langle u, H_1(u), H_2(u)\rangle \, u \in U\} \tag{4}$$

Here, $H_1(u)$, $H_2(u)$ denotes the membership, non-membership degree. The set *H* contains each element in membership and non-membership degree. The IHFs satisfies, below condition. that is,$\mu \geq 0, \nu \leq 1, 0 \leq \mu + \nu \geq 1$ for every $\mu \in H_1(u), \nu \in H_2(u)$.Then μ and ν are defined as follows,

$$\mu \in H_1(u) = \bigcup_{\mu \in H_1(u)} max(\mu) \quad \forall \; u \in U \tag{5}$$

$$\nu \in H_2(u) = \bigcup_{\nu \in H_2(u)} max(\nu) \quad \forall \; u \in U \tag{6}$$

Definition 3.5 The BFs(bipolar fuzzy) set X_B on U. The membership degree of bipolar fuzzy set is consuming both positive and negative. Mathematically, BFs(bipolar fuzzy set) represent as,

$$X_B = \{\left\langle u, \mu_B^P(u), \mu_B^N(u)\right\rangle u \in U\} \tag{7}$$

In above equation, Both membership degree and non- membership degree is represent as $\mu_B^P(u)$. The degree of membership each element is belongs to [0, 1]. The degree of non-membership each element is belongs to $[-1, 0]$. Where $\mu_B^P :\to [0,1]$ and $\mu_B^N :\to [-1,0]$.

Definition 3.6 A BDFs(bipolar dual fuzzy set) X_B on *U*. Basically membership and non-membership value includes in intuitionistic fuzzy set. BDFs mathematical notation is follows,

$$X_{BDF} = \{\left\langle u, \mu_B^P(u), \mu_B^N(u), \nu_B^P(u), \nu_B^N(u)\right\rangle u \in U\} \tag{8}$$

Here, $\mu_B^P(u)$ and $\mu_B^N(u)$ is represent both positive and negative membership value. Each element of $\mu_B^P : U \to [0,1]$ and $\mu_B^N : U \to [-1,0]$.Then, $\nu_B^P(u)$ and $\nu_B^N(u)$ is define positive and negative non-membership degree. Each element of $\nu_B^P : U \to [0,1]$ and $\nu_B^N : U \to [-1,0]$. The following condition which is fulfills the bipolar intuitionistic fuzzy set, $0 \le \mu_B^P(u) + \nu_B^P(u) \le 1$ and $-1 \le \mu_B^N(u) + \nu_B^N(u) \le 0$. Here, we mainly consider, positive non-membership degree ν^P, where $\nu^P(u) = 1 - \mu^P(u)$, negative non-membership degree ν^n , where $\nu^n(u) = 1 - \mu^n(u)$.

Definition 3.7 Let us consider any two bipolar dual fuzzy set,

$$P = \left\{ \left\langle u, \mu_{B_1}^P(u), \mu_{B_1}^N(u), \nu_{B_1}^P(u), \nu_{B_1}^N(u) \right\rangle u \in U \right\} \tag{9}$$

and

$$R = \left\{ \left\langle u, \mu_{B_2}^P(u), \mu_{B_2}^N(u), \nu_{B_2}^P(u), \nu_{B_2}^N(u) \right\rangle u \in U \right\} \tag{10}$$

The operation of union and intersection are defined below,

$$(A \cap B)(u) = \left\{ \mu_{B_1}^P(u) \cap \mu_{B_2}^P(u), \mu_{B_1}^N(u) \cap \mu_{B_2}^N(u), \nu_{B_1}^P(u) \cap \nu_{B_2}^P(u), \nu_{B_1}^N(u) \cap \nu_{B_2}^N(u) \right\} \tag{11}$$

$$(A \cup B)(u) = \left\{ \mu_{B_1}^P(u) \cup \mu_{B_2}^P(u), \mu_{B_1}^N(u) \cup \mu_{B_2}^N(u), \nu_{B_1}^P(u) \cup \nu_{B_2}^P(u), \nu_{B_1}^N(u) \cup \nu_{B_2}^N(u) \right\} \tag{12}$$

Definition 3.8 Let U is a fixed set , the HBFs on U is described bellow,

$$B^* = \{ \langle u, h_B^*(u) \rangle \, u \in U \} \tag{13}$$

Here, $h_B^*(u)$ is define the hesitant bipolar fuzzy set. The hesitant bipolar fuzzy set $h_B^*(u)$ which is contain the membership degree. Here, positive membership degree is $\mu_{B^*}^P(u)$. then $\mu_{B^*}^N(u)$ is negative membership degree. Where, the positive membership degree element is $\mu_{B^*}^P(u) : U \to [0,1]$ and the negative membership degree element is $\mu_{B^*}^N(u) : U \to [-1,0]$. All the element is correspondingly aimed at each $u \in U$, that is fulfills the below requirement

$$0 \le \mu_{B^*(u)}^P \le 1, -1 \le \mu_{B^*(u)}^N \le 0$$

The pair $\hat{h}(x) = \left\{ \left\langle \mu^P(u), \mu^N(u) \right\rangle \right\}$ is represent as hesitant bipolar fuzzy number is named through $\hat{h} = \left(\mu^P, \mu^N \right)$. Which is satisfies the condition, $0 \le \mu_1^P \le 1, -1 \le \mu_1^N \le 0$, $\left(\mu_1^P, \mu_1^N \right) \in \left(\mu^P, \mu^N \right)$

Definition 3.9 Consider $\hat{h}_i = \left(\mu_i^P, \mu_i^N \right)$ where $(i = 1, 2, 3)$.Let take any two bipolar hesitant fuzzy number is $S(\hat{h}_i) = \frac{1}{\#\hat{h}_i} \sum_{i=1}^{\#\hat{h}_i} \frac{1 + \mu_i^P + \mu_i^N}{2}$ is the score function of $\hat{h}_i = \left(\mu_i^P, \mu_i^N \right)$, Then the accuracy function is $a(\hat{h}) = \frac{1}{\#h} \sum_{i=1}^{\#h} \frac{\mu_i^P - \mu_i^N}{2}$ as $\hat{h}_i = \left(\mu_i^P, \mu_i^N \right)$. The HFE(hesitant fuzzy element) is denoted as $\#\hat{h}_i$. The score function is satisfies the following condition that is,

(i) if $S\left(\hat{h}_1\right) > S\left(\hat{h}_2\right)$, formerly $\hat{h}_1$ is greater to $\hat{h}_2$ represented by $\hat{h}_1 > \hat{h}_2$;
(ii) if $S\left(\hat{h}_1\right) = S\left(\hat{h}_2\right)$,The accuracy function is satisfies the following condition that is

(i) if $a(\hat{h}_1) = a(\hat{h}_2)$, formerly $\hat{h}_1$ is equivalent to $\hat{h}_2$, represent by $\hat{h}_1 \sim \hat{h}_2$;
(ii) if $a(\hat{h}_1) > a(\hat{h}_2)$, formerly $\hat{h}_1$ is superior to $\hat{h}_2$, represent by $\hat{h}_1 > \hat{h}_2$.

Definition 3.10 Let,consider $\hat{h}_i = \left(\mu_i^P, \mu_i^N \right)$ and $\hat{h}'_i = \left(\nu_i^P, \nu_i^N \right)$ where $(i = 1, 2, 3...)$, let take any two bipolar dual hesitant fuzzy number score function is

$$S_{BDHF} = a_{BDHF} = \frac{1}{2} \left(1 + \frac{1}{\#\mu^+} \sum_{\alpha^+ \in \mu^+} \alpha^+ + \frac{1}{\#\nu^-} \sum_{\beta^- \in \nu^-} \beta^- \right) \tag{14}$$

and the accuracy function is

$$a_{BDHF} = \frac{1}{2} \left(\frac{1}{\#\mu^+} \sum_{\alpha^+ \in \mu^+} \alpha^+ - \frac{1}{\#\nu^-} \sum_{\beta^- \in \nu^-} \beta^- \right) \tag{15}$$

Properties and operations

Let, we defined certain new operations for hesitant bipolar fuzzy numbers $\hat{h}, \hat{h}_1$ and $\hat{h}_2$:

1. $\hat{h}^{\delta} = \bigcup_{(\mu_i^P,\mu_i^N)\in(\mu^P,\mu^N)} \left\{ \left((\mu_i^P)^{\delta}, -1 + |1 + \mu_i^N|^{\delta} \right) \right\}, \delta > 0;$
2. $\delta\hat{h} = \bigcup_{(\mu_i^P,\mu_i^N)\in(\mu^P,\mu^N)} \left\{ \left(1 - (1 - \mu_i^P)^{\delta}, -|\mu_i^N|^{\delta} \right) \right\}, \delta > 0;$
3. $\hat{h}_1 \oplus \hat{h}_2 = \bigcup_{(\mu_i^P,\mu_i^N)\in(\mu_1^P,\mu_1^N),(\mu_i^P,\mu_i^N)\in(\mu_2^P,\mu_2^N)} \left\{ \left(\mu_1^P + \mu_2^P - \mu_1^P\mu_2^P, -|\mu_1^N||\mu_2^N| \right) \right\}$
4. $\hat{h}_1 \otimes \hat{h}_2 = \bigcup_{(\mu_i^P,\mu_i^N)\in(\mu_1^P,\mu_1^N),(\mu_i^P,\mu_i^N)\in(\mu_2^P,\mu_2^N)} \left\{ \left(\mu_1^P\mu_2^P, \mu_1^N + \mu_2^N - \mu_1^N\mu_2^N \right) \right\}$

Definition 3.11 Let a fixed set *U*, the BDHFs on *U* is denoted below,

$$B^*_{DHFS} = \{\langle u, h_{B^*}(u), h'_{B^*}(u)\rangle\, u \in U\} \tag{16}$$

Here, $h_{B^*}(u), h'_{B^*}(u)$ represent the membership and non-membership degree. Here, the membership degree and non-membership degree that is contain together positive membership degree and negative membership degree. $\mu^P_{B^*(u)}$ is represent as positive membership degree, $\mu^N_{B^*(u)}$ is represent as negative membership degree. $\nu^P_{B^*}(u)$ is represent as positive non-membership degree, $\nu^N_{B^*}(u)$ is represent as negative non-membership degree. The membership degree every element is $h_{B^*}(u) \in U$. The positive and negative membership degree is define $\mu^P_{B^*}(u) : U \to [0, 1]$ and $\mu^N_{B^*}(u) : U \to [-1, 0]$. As well as the non-membership degree every element is $h'_{B^*}(u) \in U$. In addition to the positive and negative non-membership degree is define $\nu^P_{B^*}(u) : U \to [0, 1]$ and $\nu^N_{B^*}(u) : U \to [-1, 0]$. The BDHFs is fulfills below provision as in, $0 \le \mu^P_{B^*(u)} + \nu^P_{B^*(u)} \le 1$ and $-1 \le \mu^N_{B^*(u)} + \nu^N_{B^*(u)} \le 0$. Here, we strongly consider positive non-membership degree $\nu^P_{B^*(u)} = 1 - \mu^P_{B^*(u)}$ and negative non-membership degree $\nu^N_{B^*(u)} = 1 - \mu^N_{B^*(u)}$.

Definition 3.12 Let consider the two element in bipolar dual hesitant fuzzy set on $U = \{u_1, u_2, ..., u_n\}$ as $\mu = \{\mu^P, \mu^N\}$ and $\nu = \{\nu^P, \nu^N\}$,formerly $d(\mu, \nu)$ is describe to the distance measure between μ and ν ,this is satisfies the below properties:

- $0 \le d(\mu, \nu) \le 1;$
- $d(\mu, \nu) = 0 iff d(\mu = \nu)$
- $d(\mu, \nu) = d(\nu, \mu)$
- Here, we consider a three element in bipolar dual hesitant fuzzy as $\mu \le \nu \le \gamma$, formerly $d(\mu, \nu) \le d(\mu, \nu)$ and $d(\nu, \gamma) \le d(\nu, \gamma)$

Description of the significance of plastic recycling

Plastic has shown to be a substance that has both positive and negative effects on human life. By nature, plastic is not biodegradable. Numerous materials, including poly-lactic acid and petrochemicals, are used to make plastic. The environmental impact of old plastic materials made them bio-non-perishable or non-perishable, which turned plastic into a barrier. Burning plastic usually results in increased air and land pollution. Burning some types of plastic releases the deadly poisonous chemical dioxin, leaving it exposed to the elements. Recycling it is a better option than destroying it in this manner. The best strategy to get rid of plastic's menace is to recycle. In addition to lowering pollution and plastic waste, recycling plastic can also lessen the amount of community resources and energy required to create unique plastics. This would be a more efficient way to release ozone damaging compounds than mixing identical materials with virgin raw materials. Depending on their properties, plastics with various qualities and specializations are employed for various purposes. is where the majority of polyethylene and polypropylene are produced. Together, the two are responsible for half of the output. This is due to the fact that around 40% of plastic use is found in construction sheets, bags, cling film, and building materials that are best suited for polyethylene and polypropylene. Thermoplastic and thermosetting plastics come in two varieties. These polymers are divided into two main categories according to their heating reaction.

- *Thermoplastic plastics* These plastics exhibit strong molecular movement when subjected to heat, resulting in a softening effect. Consequently, they become malleable. Upon cooling, they solidify. These plastics can be molded into diverse shapes through successive heating and cooling cycles. They find utility in a wide range of everyday applications, including household appliances and automotive components. Moreover, they serve as essential materials for containers, packaging, and various applications such as film, paper, and bottle production.
- *Thermosetting plastics* These plastics exhibit limited molecular movement. They undergo a chemical reaction during formation. However, if exposed to heat and maintained, they undergo further chemical reactions. High molecular weights contribute to their formation of a three-dimensional matrix system. Once set, they cannot be softened by reheating. Examples of thermosetting plastics include containers for food, circuit boards for electronics, shafts for golf clubs and tennis grips, and boats made of fiber-reinforced plastic.Plastic recycling stands as a crucial endeavor, offering a solution to our mounting plastic waste predicament. Embracing principles of the circular economy and zero-waste practices forms an integral aspect of plastic

recycling initiatives. The overarching goal is to curtail waste generation and foster sustainability. Our current waste disposal system carries significant ecological and economic ramifications. Regrettably, there exists a deficiency in awareness regarding the severity of the plastic waste issue within our nation. Addressing the challenges posed by plastic waste proves to be a formidable task, compounded by resistance from the plastics industry against meaningful reform. Nonetheless, recycling remains paramount in our efforts to mitigate the impact of plastic waste. Two primary challenges contribute to plastics ending up in landfills rather than being recycled. Firstly, attempting to recycle contaminated plastics containing substances like adhesives, chemicals, or food residue can disrupt the recycling process and introduce contaminants. Secondly, mixing non-recyclable plastics with recyclable ones further exacerbates the issue. While some products, such as PETE-based water bottles, are easily recyclable, others, especially those made from plastic composites, pose significant difficulties. Many products combine plastics with non-plastic materials like wood or metal, but the plastic component often bypasses recycling centers.

The steps of plastic recycling process

- *Collecting* To initiate recycling, the initial step involves collecting consumer goods from households, businesses, and companies. Government entities and private firms commonly undertake this task, offering convenient options for businesses to participate. Another approach is to transport plastic waste to centralized collection points such as recycling bins or facilities. These collection points vary in scale, ranging from simple roadside bins to complex municipal solid waste (MSW) landfill sites with designated areas for sorting recyclable and non-recyclable materials. The recycling process of plastics is shown in Fig. 1.
- *Sorting* In the plastic recycling process, sorting constitutes the second crucial step. Since plastics come in various types, they must be separated accordingly. Sorting can be based on different characteristics such as color, thickness, and intended use. Recycling centers utilize machines to carry out this sorting process. It is imperative as it enhances the efficiency of the plants and helps prevent contamination in the final recycled products.
- *Washing* A critical stage in plastic recycling involves washing to eliminate contaminants that could disrupt the process and ensure the recycled plastic's purity. This washing process effectively removes labels, adhesives, as well as dirt and food residues. It is essential to strive for minimal contamination before collection to streamline this washing process.
- *Shredding* The plastic is shredded into smaller pieces and then processed further. These smaller plastic pieces can be utilized for various purposes, such as creating tarmac compound or sold as a valuable material. Breaking down the plastic material into smaller pieces aids in detecting any remaining contaminants. Certain pollutants, like metals, cannot be removed through washing. However, these remaining contaminants can be separated by using a magnet.
- *Identification and separation of plastics* During this phase, the quality of plastics undergoes testing, and they are sorted based on their density. Verification is conducted by observing the buoyancy of plastic particles in a water container, which helps assess their density. Additionally, the width of plastic components is determined by passing the shredded plastic through an air channel.

Fig. 1. Plastic recycling process.

- *Compounding* In the last stage of the recycling process, compounding involves converting shredded plastic particles into usable material for manufacturers. The shredded plastic is melted together to form pellets. It's not always practical to include all types of plastics in a single recycling plant due to variations in classifications and properties. Consequently, different types of plastics are sometimes sent to specialized recycling facilities for further processing.

Different type of plastics

Plastics come in various types, categorized into seven distinct groups, which are crucial to consider when aiming to reduce pollution through plastic recycling efforts. You might have noticed symbols on plastic products resembling recycling logos, but they often denote the type of plastic rather than indicating recyclability. The different types of plastics and their characteristics is given in Fig. 2.

Plastic recycling techniques

Plastic recycling involves the process of reprocessing plastic waste to create functional and efficient products. Its primary goal is to reduce plastic pollution in oceans and on land while conserving natural resources. Additionally, plastic recycling contributes to addressing plastic pollution issues. It's worth noting that recycling plastics requires less energy compared to producing them from scratch. Plastic, being the most cost-effective, durable, and lightweight material, finds extensive use across various applications, making its production and

No	Identification Code for Plastic	Acronym	Type of Plastic Polymer and Their Uses
1	1	PET	**Polyethylene terephthalate**-Soft drink, water and salad dressing bottles; peanut butter and jam jars; ice cream cone lids; small non-industrial electronics.
2	2	HDPE	**High-density polyethylene**-Water pipes, gas and fire pipelines, electrical and communications conduits, five gallon buckets, milk, juice and water bottles, grocery bags, some toiletry bottles.
3	3	PVC	**Polyvinyl chloride**-Stretch wrap for non-food items, sometimes blister packaging. Non-packaging uses include electrical cable insulation, rigid piping and vinyl records.
4	4	LDPE	**Low-density polyethylene**-Frozen food bags; squeezable bottles, e.g. honey, mustard; cling films; flexible container lids.
5	5	PP	**Polypropylene**-Reusable microwaveable ware or take-away containers; kitchenware; yogurt or margarine containers; disposable cups and plates; soft drink bottle caps.
6	6	PS	**Polystyrene** - Egg cartons; disposable cups, plates, trays and cutlery; foam food containers; packing peanuts and package cushioning;
7	7	Others	**Other (often polycarbonate or ABS)**-Beverage bottles, baby milk bottles. Non-packaging uses for polycarbonate: compact discs, "unbreakable" glazing, electronic apparatus housing, lenses (including sunglasses), instrument panels.

Fig. 2. Classification for different types of plastics.

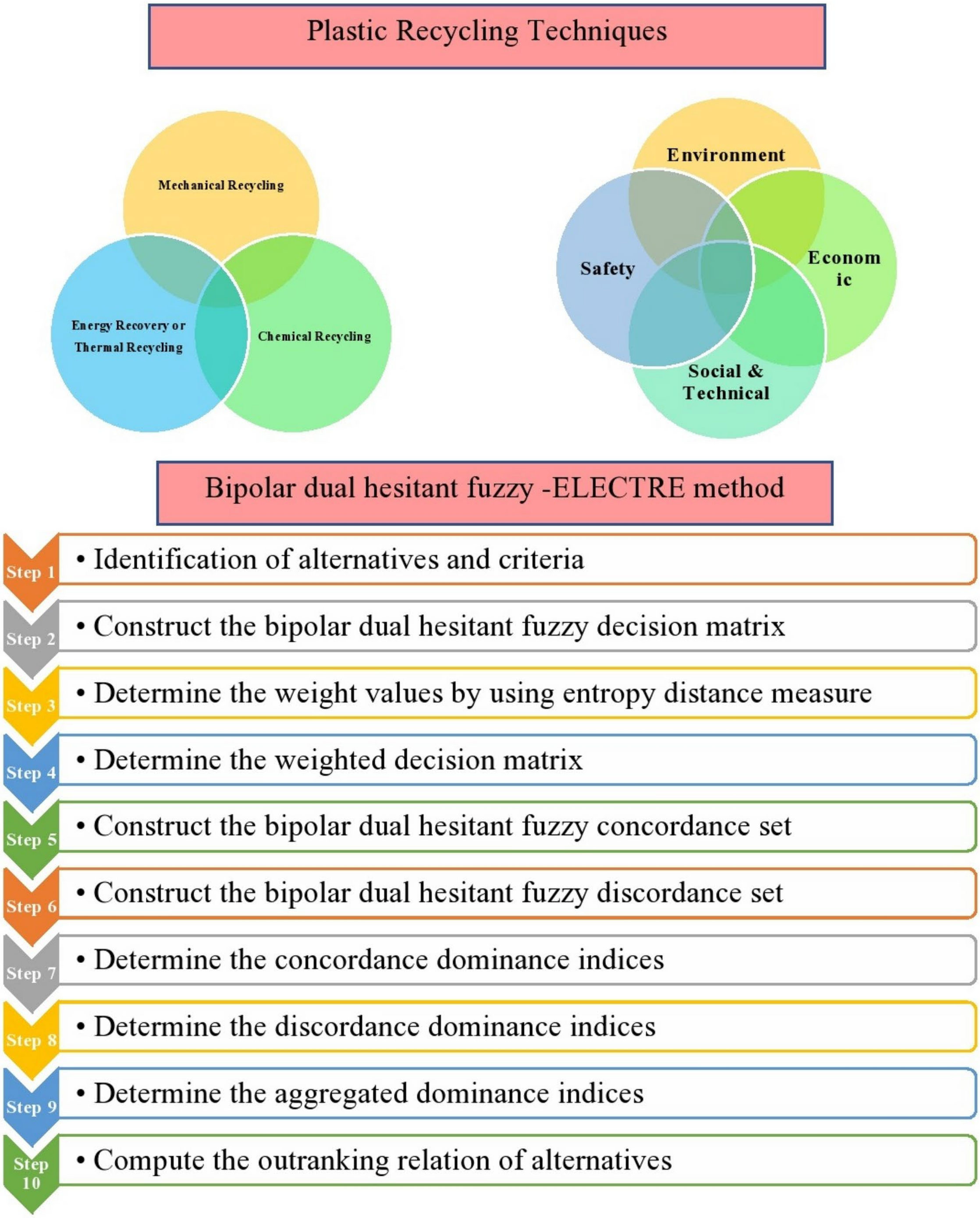

Fig. 3. Research methodology.

recycling processes crucial. Globally, approximately 420 million tons of plastics are manufactured annually, highlighting the significance of both production and recycling efforts. In this context, three plastic recycling techniques and four related criteria are examined below.

Research methodology

The research methodology is described in Fig. 3.

Problem formulation of bipolar dual hesitant fuzzy entropy distance measure

In this subsection, a variant of hesitant fuzzy set called bipolar dual hesitant fuzzy set is introduced. Additionally, a novel entropy distance measure for bipolar dual hesitant fuzzy sets is proposed here.

Definition 5.1 An Entropy distance measure on BDHF, $\psi = \left\langle h_{B^*(u)}, h'_{B^*(u)} \right\rangle$ is a real valued function $h_{B^*(u)} : BDHF(u) \to [0,1]$.The entropy distance measure is $h'_{B^*(u)} : BDHF(u) \to [0,1]$. But its element $\mu^P_{B^*(u)} \to [0,1]$ and $\mu^N_{B^*(u)} \to [-1,0]$ of the set $h_{B^*(u)}$ element having both positive and negative membership degree and its element $\nu^P_{B^*(u)} \to [0,1]$ and $\nu^N_{B^*(u)} \to [-1,0]$ of the set $h'_{B^*(u)}$ element having both positive and negative non-membership degree. This is named as bipolar dual hesitant fuzzy set if its gratifies the below require axioms.

1. $\psi(\lambda) = 0$ iff λ is a crisp set
2. $\psi(\lambda) = 1$ iff $\mu^N_\lambda(u) = \nu^N_\lambda(u)$, $\mu^P_\lambda(u) = \nu^P_\lambda(u)$ for all $u \in U$.
3. $\psi(\lambda) = \psi(\lambda^c)$
4. $\psi(\lambda) \le \psi(\varphi)$ if $\mu^N_\lambda(u) \le \mu^N_\varphi(u) \le \nu^N_\varphi(u) \le \nu^N_\lambda(u), \mu^P_\lambda(u) \le \mu^P_\varphi(u) \le \nu^P_\varphi(u) \le \nu^P_\lambda(u)$ every $u \in U$.Now, we introduced an entropy distance measure for BDHFs. For every $\lambda \in BDHF(u)$, The entropy distance measure denoted as

$$\psi(\lambda) = \frac{1}{l}\sum_{i=1}^{l} 1 - \frac{\left[\mu^{\sigma(i)} - \nu^{\sigma(i)}\right]^\omega + \left[\mu^{\sigma(i)} + \nu^{\sigma(i)}\right]^\omega}{2} = 0 \tag{17}$$

Problem formulation of bipolar dual hesitant fuzzy ELECTRE proposed method

In this subsection, we present the BDHF-ELECTRE (bipolar dual hesitant fuzzy ELECTRE) technique, which employs a method for detecting weights based on bipolar dual hesitant fuzzy entropy distance measures to address MCDM (multiple criteria decision making) problems. In this research article, we assume $A = \{A_1, A_2, ..., A_m\}$ as the alternative and $C = \{C_1, C_2, ..., C_n\}$ as the criteria then the set of all alternatives is *m* and the is set of all criteria is *n*. Assume that $A_i (i = 1, 2, ..., m)$ is alternative performance and assume that $C_j (j = 1, 2, ..., n)$ is criteria performance, calculate via bipolar hesitant dual fuzzy element.

$$B^*_{DHFS} = \{\langle u, h_{B^*}(u), h'_{B^*}(u)\rangle \, u \in U\} \tag{18}$$

$$= \left\{\left\langle u, \left(\mu^P_{B^*}(u), \nu^N_{B^*}(u)\right)\right\rangle h_{B^*}(u), h'_{B^*}(u) \in U\right\} \tag{19}$$

In this research article, we consider more than one decision makers deliver their opinion in similar assessment, then the assessment comes merely on one occasion in the B^*_{DHFS}. Then, $(k = 1, 2, ..., n)$ where *n* is the number of decision makers.

Step 1 Construct the bipolar dual hesitant fuzzy decision matrix. The decision matrix of bipolar dual hesitant fuzzy set is given in Table 3.

Determine the bipolar dual hesitant fuzzy decision matrix

$$\tilde{B}^* = B^*_{DHFS} = \left[h_{B^*_{ij}}\right]_{m\times n} = \left\{\left\langle u, \left(\mu^P_{B^*}(u), \nu^N_{B^*}(u)\right)\right\rangle h_{B^*}(u), h'_{B^*}(u) \in U\right\} \tag{20}$$

In that matrix, $h_{B^*(u)} \in [0,1]$ every membership degree satisfies this condition and $h'_{B^*(u)} \in [0,1]$ every non-membership degree satisfies this condition. This condition $\mu_{ij} \in [0,1]$ which satisfies every positive membership degree and this condition $\nu_{ij} \in [-1,0]$ which satisfies every negative membership degree,its applied for positive and negative degree of non-membership. *Step 2* Construct the importance of criteria weight value by using entropy distance measure

$$\psi(\lambda) = \frac{1}{l}\sum_{i=1}^{l} 1 - \frac{\left[\mu^{\sigma(i)} - \nu^{\sigma(i)}\right]^\omega + \left[\mu^{\sigma(i)} + \nu^{\sigma(i)}\right]^\omega}{2} = 0 \tag{21}$$

The entire assessment of importance of weighted criteria is 1. The importance of criteria doesn't exist more than 1.

	C_1	C_2	$\cdots$	C_n
A_1	$\left(\mu^P_{B^*_{11}}(u), \nu^N_{B^*_{11}}(u)\right)$	$\left(\mu^P_{B^*_{12}}(u), \nu^N_{B^*_{12}}(u)\right)$	$\cdots$	$\left(\mu^P_{B^*_{1n}}(u), \nu^N_{B^*_{1n}}(u)\right)$
A_2	$\left(\mu^P_{B^*_{21}}(u), \nu^N_{B^*_{21}}(u)\right)$	$\left(\mu^P_{B^*_{22}}(u), \nu^N_{B^*_{22}}(u)\right)$	$\cdots$	$\left(\mu^P_{B^*_{2n}}(u), \nu^N_{B^*_{2n}}(u)\right)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
A_m	$\left(\mu^P_{B^*_{m1}}(u), \nu^N_{B^*_{m1}}(u)\right)$	$\left(\mu^P_{B^*_{m2}}(u), \nu^N_{B^*_{m2}}(u)\right)$	$\cdots$	$\left(\mu^P_{B^*_{mn}}(u), \nu^N_{B^*_{mn}}(u)\right)$

Table 3. Bipolar dual hesitant fuzzy decision matrix.

Step 3 Construct, weighted decision matrix. Its computing the multiple value of decision matrix and weight vector value.

$$H_{ij} = \left[h_{B^*_{ij}}\right]_{m\times n} = \begin{bmatrix} h_{11} & h_{12} & \dots & h_{1n} \\ h_{21} & h_{22} & \dots & h_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ h_{m1} & h_{m2} & \dots & h_{mn} \end{bmatrix}$$

Step 4 Determine the concordance of BDHFs is $C_{\alpha\beta}$ and the discordance of BDHFs is $D_{\alpha\beta}$. The concordance set and discordance set based on their priority through respect to both positive and negative degree of BDHFs. The concordance and discordance set define as $C_{\alpha\beta}$, $D_{\alpha\beta}$.

$$C_{\alpha\beta} = \{1 \le j \le n | q_{\alpha j} \ge q_{\beta j}, \alpha \ne \beta, \alpha, \beta = 1, 2, ..., m\} \tag{22}$$

$$D_{\alpha\beta} = \{1 \le j \le n | q_{\alpha j} \ge q_{\beta j}, \alpha \ne \beta, \alpha, \beta = 1, 2, ..., m\} \tag{23}$$

Step 5 Determine the concordance indices fo bipolar dual hesitant fuzzy set

$$C_{\alpha\beta} = \sum_{j\in C_{\alpha\beta}} w_j \tag{24}$$

The concordance matrix constructed as follows

$$C_{\alpha\beta} = \begin{bmatrix} C_{11} & C_{12} & \dots & C_{1n} \\ C_{21} & C_{22} & \dots & C_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{m1} & C_{m2} & \dots & C_{mn} \end{bmatrix}$$

Step 6 Determine the discordance indices for bipolar dual hesitant fuzzy set

$$D_{\alpha\beta} = \frac{max_{j\in D_{\alpha\beta}}\sqrt{\frac{1}{2}\left[(m_{\alpha j} - m_{\beta j})^2 + (n_{\alpha j} - n_{\beta j})^2\right]}}{max_j\sqrt{\frac{1}{2}\left[(m_{\alpha j} - m_{\beta j})^2 + (n_{alphaj} - n_{\beta j})^2\right]}} \tag{25}$$

The discordance matrix constructed as follows

$$D_{\alpha\beta} = \begin{bmatrix} D_{11} & D_{12} & \dots & D_{1n} \\ D_{21} & D_{22} & \dots & D_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ D_{m1} & D_{m2} & \dots & D_{mn} \end{bmatrix}$$

Step 7 Determine the hesitant values to rank the alternatives. The bipolar dual hesitant fuzzy concordance denote as $\bar{C}$. The bipolar dual hesitant fuzzy discordance denote as $\bar{D}$. The concordance and discordance indices averages is define below,

$$\bar{C} = \frac{1}{m(m-1)} \sum_{\alpha=1\alpha\ne\beta}^{m} \sum_{\beta=1\beta\ne\alpha}^{m} C_{\alpha\beta} \tag{26}$$

$$\bar{D} = \frac{1}{m(m-1)} \sum_{\alpha=1\alpha\ne\beta}^{m} \sum_{\beta=1\beta\ne\alpha}^{m} D_{\alpha\beta} \tag{27}$$

Step 8 Determine the concordance dominance matrix of bipolar dual hesitant fuzzy set(BDHFs)

$$T_{\alpha\beta} = \begin{bmatrix} - & t_{12} & \dots & t_{1n} \\ t_{21} & - & \dots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ t_{m1} & t_{m2} & \dots & - \end{bmatrix}$$

then defined t_{ij} are

$$t_{ij} = \begin{cases} 1 & \text{if } C_{ij} \ge \bar{C} \\ 0 & \text{if } C_{ij} < \bar{C} \end{cases} \tag{28}$$

Step 9 Determine the discordance dominance matrix of bipolar dual hesitant fuzzy set(BDHFs)

$$L_{\alpha\beta} = \begin{bmatrix} - & l_{12} & \dots & l_{1n} \\ l_{21} & - & \dots & l_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{m1} & l_{m2} & \dots & - \end{bmatrix}$$

then defined l_{ij} are

$$l_{ij} = \begin{cases} 1 & \text{if } D_{ij} \leq \bar{d} \\ 0 & \text{if } D_{ij} > \bar{d} \end{cases} \tag{29}$$

Step 10 Determine the bipolar dual hesitant fuzzy aggregated dominance matrix is

$$Z_{\alpha\beta} = \begin{bmatrix} - & z_{12} & \dots & z_{1n} \\ z_{21} & - & \dots & z_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ z_{m1} & z_{m2} & \dots & - \end{bmatrix}$$

The calculation of Z_{ij} is $Z_{ij} = t_{ij}l_{ij}$

Step 11 Ranking the alternative based on Z_{ij} values. The each pair of alternatives D_i and D_j, D_i into D_j exists iff $Z_{ij} = 1$. Accordingly, there are three conceivable cases:

1. There exist an exclusive direction from D_i and D_j.
2. There exist two possible direction between D_i and D_j.
3. There is no direction between D_i and D_j.Then, In case 1, we determine that D_i is preferred to D_j, In case 2, D_i and D_j are indifferent, In case 3, D_i and D_j are incomparable.

Numerical analysis: recycling techniques for plastic to proposed method

In this section, a mathematical illustration will be given the explanation of our proposed BDHF-ELECTRE technique. Here we evaluate listed criteria and alternative for selecting the recycling techniques. The problem is selecting process of plastic recycling techniques this is a kind of MCDM problem. The description for the problem are given in subsection 6.1 and the procedure and details of the solution are given in subsection 6.2.

Problem description

A plastic recycling techniques selection process is one of the most needed think. A plastic is the one of the necessary thinks nowadays. We have many types of plastic for various kind of usage, moreover we want to recycling it properly. Many techniques are used for plastic recycling techniques. But here, we choose three plastic recycling techniques. These three recycling techniques, we consider as alternatives, who should be evaluated by the one decision makers, against four criteria. A brief description of the selected alternative and criteria are presented below:

The alternatives are,

- *Chemical recycling* Plastic products are often made from a type of oil, natural gas, petroleum and some petrochemicals. Ethylene and propylene are formed by the process of heating petroleum. These are made with chemical construction modules for many plastics. These combine with other chemicals to produce a polymer. Chemical recycling is the procedure of converting plastic polymers back into separate monomers. The chemical structure blocks that improvise plastic are recovered in the process of chemical recycling. By re-polymerizing the plastics indefinitely it gives the brand new adhesive-like properties when returning to the basic construction modules. The hardest of the recycling methods is chemical recycling. This process is applicable to multi-coating or seriously polluted plastics. An important benefit of the chemical recycling progression is that it tolerates contamination and provides polymers similar to the original state and eliminates down cycling.
- *Mechanical recycling* The dispensation of plastic waste into subordinate raw materials or materials short of knowingly fluctuating the chemical structure of the material is called Mechanical recycling of plastic. The whole type of thermoplastics can be mechanically recycled. Most plastics are organized before recycling conferring to their adhesive type. Plastic recyclers classify polymers using adhesive identification code (RIC). Polyethylene terephthalate commonly referred to as PET. Their adhesive code is referred to as 1. Automated automation processes have been used since manual sorting and removal of plastic materials to identify the resin of the plastic. Some plastic products are separated by color before being recycled. After the plastics are properly sorted they are shredded for mechanical recycling. The plastic pieces thus shredded are subjected to the process of removing contaminants such as paper labels. These materials are often melted and excreted in particle form. They are used to produce other products undergoing a standard refining process called regeneration.
- *Energy recovery or thermal recycling* This recycling system represents the process of recovering the energy content of plastic. These include ways to reduce the amount of organic matter involved, including recovering energy through combustion. This process is a good solution for generating considerable energy from polymers. However it is ecologically unacceptable due to the health risk posed by airborne toxins. Thermal recycling is one of the acceptable recycling techniques mentioned above, based on the principles of sustainable devel-

	C_1	C_2	C_3	C_4
A_1	$\{\{0.1, 0.2, 0.3\}, \{-0.1, -0.1, -0.2\}\}$	$\{\{0.2, 0.3, 0.4\}, \{-0, 2, -0.3\}\}$	$\{\{0.4, 0.4, 0.5\}, \{-0.1, -0.3, -0.4\}\}$	$\{\{0.1\}, \{-0.3, -0.4\}\}$
A_2	$\{\{0.5, 0.6, 0.6\}, \{-0.2, -0.3\}\}$	$\{\{0.2, 0.3\}, \{-0.1, -0.2\}\}$	$\{\{0.1, 0.2, 0.3\}, \{-0.1\}\}$	$\{\{0.2, 0.4, 0.5\}, \{-0.1, -0.2\}\}$
A_3	$\{\{0.3, 0.3, 0.4\}, \{-0.4\}\}$	$\{\{0.3, 0.4\}, \{-0.1\}\}$	$\{\{0.2, 0.3\}, \{-0.2, -0.3\}\}$	$\{\{0.1, 0.2\}, \{-0.2, -0.3\}\}$

Table 4. Dual hesitant bipolar fuzzy decision matrix.

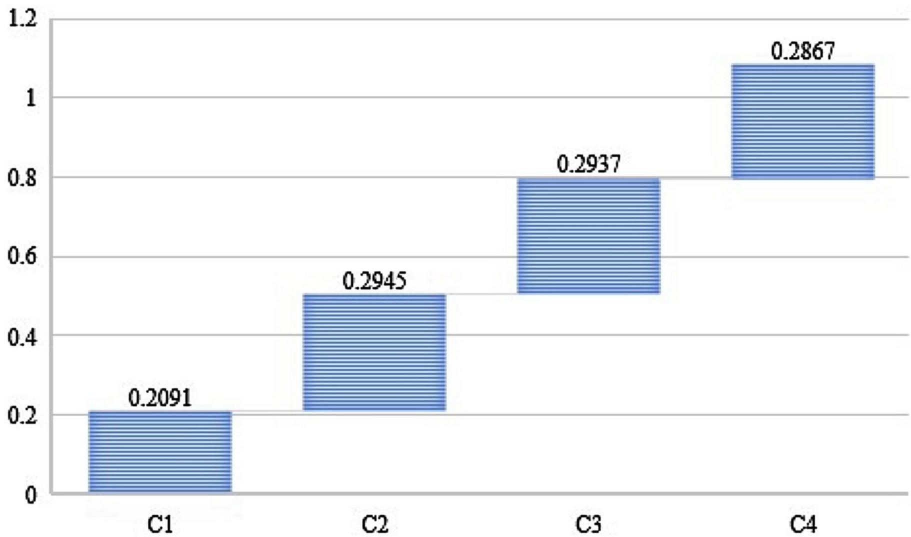

Fig. 4. The weight values of criteria.

opment. Energy recovery or Thermal recycling is the progression of altering waste energy into energy. The improvement in incineration and aeration is analogous to a elementary level. By the burning waste material the ash waste and flue gas become hot. The heat from burning waste is also used to generate heat electricity. The criteria are,

- *Environment* Air pollution is found to be low in plastic recycling. Despite that numerous landfill offices carry toxic pollution or bad air into the air when burning plastic waste. Reduces pollution levels in surrounding and water sources by recycling plastic waste. It also reduces emissions of ozone-depleting harmful substances. Plastics are used to make adhesive raw materials. These chemicals are harmful chemicals. These chemicals can contaminate groundwater if they fall into the soil or in a landfill.
- *Economic* There are also some costs for disposing of plastic waste. The costs of operating them in recycling centers include sorting costs according to the type of plastic, transportation costs of plastic waste, labor cost, electricity bill, food allowance, insurance and chemical costs. The recycling centers where the plastic waste is composed their estimated using the amount of plastic obtained through the cost of recycling process.
- *Social and technical* The technical feature refers to the rudimentary and functioning practices of plastic waste management. That includes recycling tools, materials, project structure and source of materials used in plastic waste management.
- *Safety* A lot of pollutants are exposed in the recycling areas. The pollution affects the persons who worked in that particular recycling process field. They also face serious risks in their work. Plastic recycling workers also process hazardous materials that had best not be in recycling plants, such as needles, chemicals, animal cadavers and cracked glass. Industrial hazards such as engineering controls, enhanced safety systems, work functions and extensive training can sometimes be eliminated.

Ranking of alternatives via BDHF-entropy-ELECTRE technique

Step 1 Determine the decision matrix. The decision maker estimates the alternatives by reference to every criterion by means of bipolar dual hesitant fuzzy number. The result of evaluation are shown in Table 4. The membership and non-membership degree include both positive and negative values in decision matrix.

Step 2 Construct the importance of each criteria weight value. The decision makers are determine the relative importance is based on entropy distance measure. The weight of criteria value is evaluate via consuming Eq. (21). The importance of criteria weight value is 1. The criteria weight value does not exist more than 1. The weight values are given below and the weight values are shown in Fig. 4.

$$W_1 = 0.2091, \qquad W_2 = 0.2945, \qquad W_3 = 0.2937, \qquad W_4 = 0.2867. \tag{30}$$

Step 3 Determine the weighted decision matrix. This value is evaluate by a value as to decision matrix and criteria weight value. The weighted decision matrix as shown below,

$$H_{ij} = \begin{bmatrix} 0.1254 & 0.1619 & 0.2232 & 0.0286 \\ 0.1986 & 0.1914 & 0.1909 & 0.2293 \\ 0.0836 & 0.2650 & 0.1468 & 0.1003 \end{bmatrix}$$

Step 4 Next we determine the concordance and discordance set.The bipolar dual hesitant fuzzy concordance and discordance are calculate via consuming Eqs. (22) and (23). The concordance bipolar dual hesitant fuzzy set as shown below,

$$C_{\alpha\beta} = \begin{bmatrix} - & \{3\} & \{1,3\} \\ \{1,2,4\} & - & \{1,3,4\} \\ \{2,4\} & \{2\} & - \end{bmatrix}$$

The discordance bipolar dual hesitant fuzzy set as shown below,

$$D_{\alpha\beta} = \begin{bmatrix} - & \{1,2,4\} & \{2,4\} \\ \{3\} & - & \{2\} \\ \{1,3\} & \{1,3,4\} & - \end{bmatrix}$$

Step 5 Determine the bipolar dual hesitant fuzzy concordance interval matrix. The interval matrix value of concordance bipolar dual hesitant fuzzy is calculate via consuming Eq. (24). The value matrix as shown below,

$$C_{\alpha\beta} = \begin{bmatrix} 0 & 0.2937 & 0.5028 \\ 0.7903 & 0 & 0.7895 \\ 0.5812 & 0.2945 & 0 \end{bmatrix}$$

Step 6 Determine the bipolar dual hesitant fuzzy discordance interval matrix. The interval matrix value of discordance bipolar dual hesitant fuzzy is calculate via consuming Eq. (25). The value of the matrix is given below, with the concordance and discordance interval matrix values are shown in Figs. 5 and 6 respectively.

$$D_{\alpha\beta} = \begin{bmatrix} 0 & 1 & 1 \\ 0.1609 & 0 & 0.5706 \\ 0.7408 & 1 & 0 \end{bmatrix}$$

Steps 7– 9 Determine the bipolar dual hesitant fuzzy concordance index matrix. The matrix value of concordance bipolar dual hesitant fuzzy is calculated via consuming Eq. (26).The value of matrix as shown below,

$$\bar{C} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

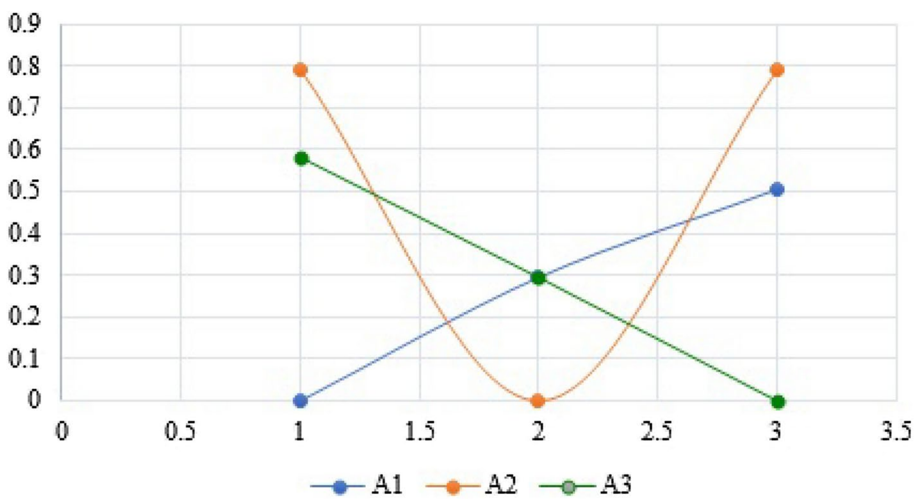

Fig. 5. Concordance interval matrix.

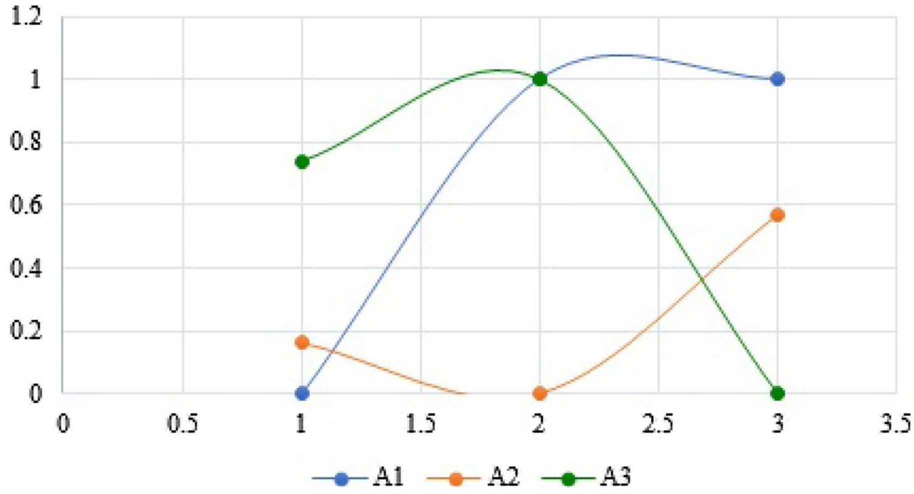

Fig. 6. Discordance interval matrix.

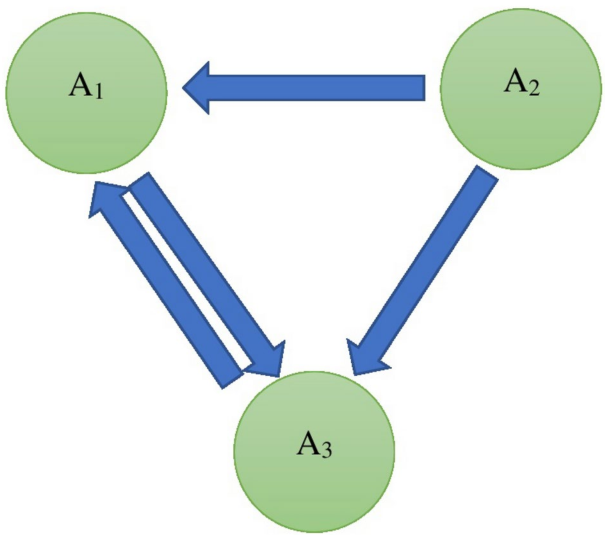

Fig. 7. Concordance index matrix.

Determine the bipolar dual hesitant fuzzy discordance index matrix. The matrix value of discordance bipolar dual hesitant fuzzy is calculated via consuming Eq. (27).The value of matrix as shown below,

$$\bar{D} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix}$$

The concordance and discordance index matrix value are depends upon the Eqs. (28) and (29). The $\bar{C}$ and $\bar{D}$ value is 0.5 and 0.7.

Steps 10 and 11 Determine the bipolar dual hesitant fuzzy aggregated dominance matrix. The bipolar dual hesitant fuzzy aggregated dominance matrix value as shown below,

$$Z_{\alpha\beta} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

The optimal ranking order is $A_2 > A_3 > A_1$. In our proposed method A_2 is the best alternative. The concordance index matrix, discordance index matrix and the result of aggregated dominance matrix values are shown in Figs. 7, 8, and 9 respectively.

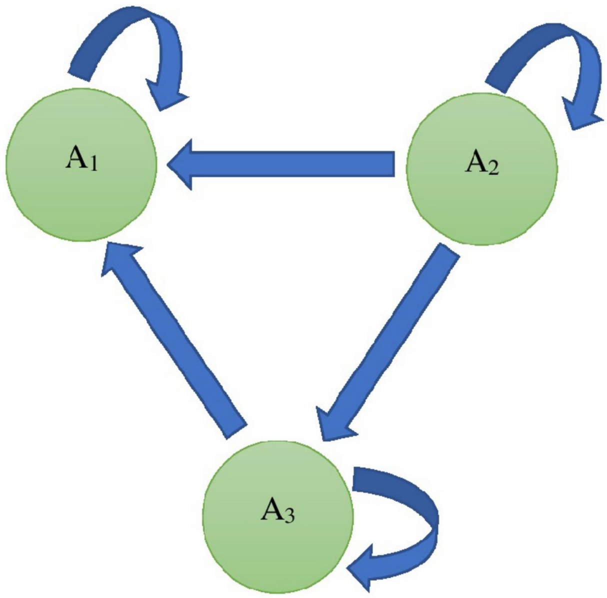

Fig. 8. Discordance index matrix.

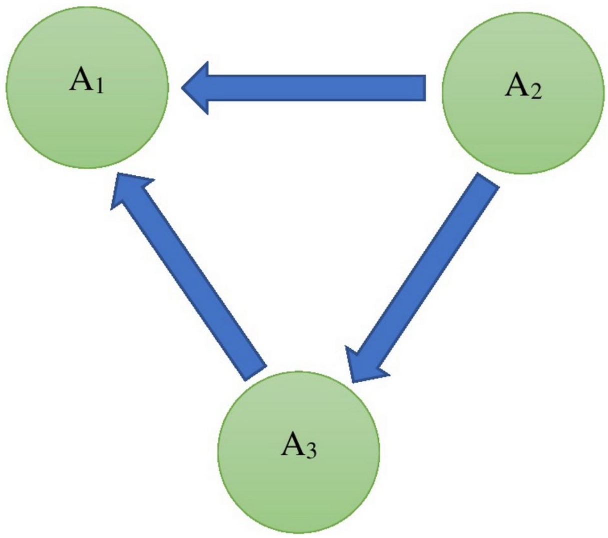

Fig. 9. Result of aggregated dominance matrix.

Result and discussion

In this section, we will highlight the outcomes of the proposed method along with the discussions. The proposed technique incorporates a novel approach for determining weights by utilizing bipolar dual hesitant fuzzy entropy distance measures. By employing this technique, we aim to effectively address the problem under consideration. The BDHF-ELECTRE technique leverages the unique characteristics of bipolar dual hesitant fuzzy sets to handle uncertainties and imprecisions in decision-making processes. Specifically, it considers both positive and negative attitudes toward decision criteria, offering a more comprehensive perspective in evaluating alternatives. The proposed method for weight detection based on entropy distance measures enhances the accuracy and reliability of the decision-making process. It allows for the quantification of uncertainties associated with each criterion, thereby enabling a more informed and robust decision-making framework. ELECTRE method provide a new tactic of integrate perception of outranking techniques. This method has different type of classification, concordance set and discordance set, index set of both concordance and discordance.

In our study, we considered four main criteria essential while considering the PRMs. They are environment(C_1), Economic(C_2), social and technical(C_3) and Safety(C_4) and the recycling alternatives, are chemical recycling(A_1), mechanical recycling(A_2) and energy recovery or thermal recycling(A_3). Among the four criteria, the economic factor received the highest score of 0.2945 among the other factors since economic considerations are crucial in choosing the most efficient plastic recycling method, as they ensure sustainability, cost-effectiveness, resource allocation, and overall feasibility in managing plastic waste. This factor was followed by social & technical factor with a score of 0.2937. Social factors, such as cultural norms, waste management practices, and public attitudes, significantly impact the effectiveness of recycling programs. When there's limited community engagement and awareness, the potential impact of these programs diminishes, thereby influencing consumer preferences and market demand. On the other hand, technical factors encompass the infrastructure, technology, and processes involved in plastic collection, sorting, and recycling. Even the factor safety played an important role while making a decision for plastic recycling.

Mechanical recycling holds significant importance in the realm of plastic recycling due to its cost-effectiveness, environmental benefits, and versatility[52]. Unlike chemical and thermal recycling techniques, which often involve complex processes and high energy consumption, mechanical recycling offers a simpler and more energy-efficient approach. By sorting, shredding, and melting down plastic waste into reusable pellets or flakes, mechanical recycling preserves the inherent properties of the original plastic material, enabling it to be transformed into a wide range of new products. Mechanical recycling additionally helps reduce the amount of plastic waste sent to landfills or incinerators, thus mitigating environmental pollution and conserving natural resources. Its relative simplicity and scalability make mechanical recycling a preferred choice for addressing the growing challenge of plastic waste management on a global scale.

Numerous research articles underscore the critical significance of plastic recycling, emphasizing its potential to not only enhance our environment but also restore ecological balance for flora and fauna[53]. Recycling plastic plays a pivotal role in reducing pollution, conserving resources, and minimizing the adverse impacts of plastic waste on ecosystems. Additionally, recycling promotes sustainability by mitigating the need for virgin plastic production, which requires significant amounts of energy and resources. By diverting plastic waste from landfills and oceans, recycling helps protect wildlife habitats and marine ecosystems, safeguarding biodiversity and supporting the well-being of various plant and animal species. Furthermore, promoting recycling initiatives fosters environmental stewardship and encourages individuals and communities to adopt eco-friendly practices, contributing to a more harmonious relationship between humanity and nature.

Many stakeholders in a variety of industries stand to gain from this article on the significance of recycling plastic. Conservationists and environmental activists will learn important lessons about the vital role recycling plays in reducing plastic pollution and protecting ecosystems. This information can be used by waste management authorities and government policymakers to create and execute recycling programs and policies that will enhance waste management techniques and promote environmental sustainability. A better understanding of the financial and environmental benefits of recycling will help the plastic production and recycling industries, and it may encourage further investment in recycling infrastructure and technology. The general public also stands to learn more about the value of recycling, enabling people to take an active role in recycling and make educated decisions. Furthermore, the people will be better informed about the value of recycling and will be able to make more informed decisions and actively engage in recycling initiatives, helping to create a cleaner and healthier environment for both current and future generations.

Result validation

Comparative analysis

Many researchers have done a lot of research on plastic recycling techniques in an uncertain environment. Here is a comparison of our proposed method with methods already existing in MCDM. There are a lot of methods available in MCDM techniques, but here we are selecting the TOPSIS, the VIKOR, and the ARAS methods. Each multi-criteria decision-making method has its own uniqueness.

Comparison between BDHF-ELECTRE and BDHF-TOPSIS method In MCDM, the TOPSIS method is a based method. The TOPSIS method is commonly trained to evaluate the delinquent of a decision. The comparison between all the selected alternatives is based on this technique. The TOPSIS method deals with the concept that a chosen alternative may potentially have a positive ideal solution at the minimum distance and a negative ideal solution at the maximum distance. The alternative ranking depends on the relative closeness coefficient. The results of the BDHF-TOPSIS method are displayed in Table 5, and the results of the BDHF-TOPSIS method are shown in Fig. 10.

Comparison between BDHF-ELECTRE and BDHF-VIKOR method Multi-criteria optimisation of intricate classifications is created by the VIKOR method. It determines the concession ranking list and the concession

Alternatives	S_i^+	S_i^-	P_i	Rank
A_1	0.2364	0.1132	0.3237	2
A_2	0.0374	0.2579	0.8733	1
A_3	0.2059	0.0815	0.2836	3

Table 5. The ranking result of BDHF-TOPSIS method.

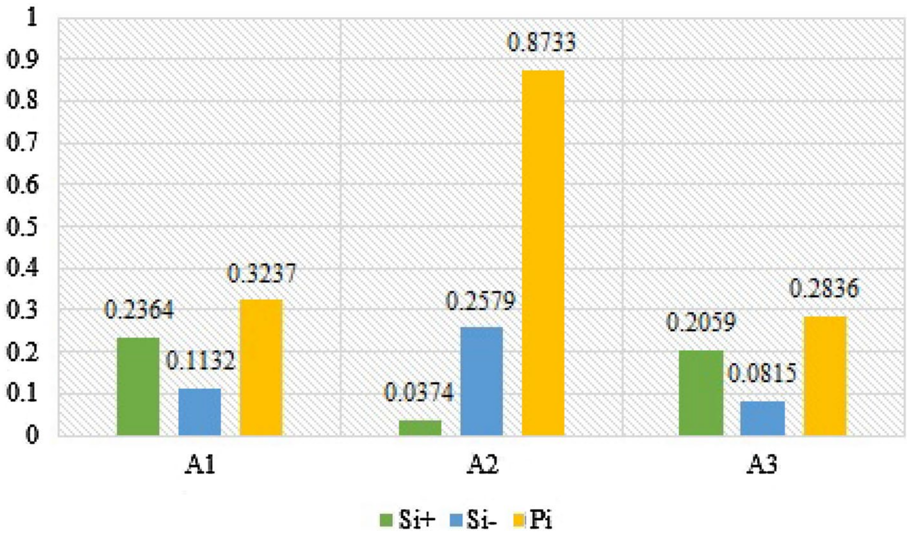

Fig. 10. The ranking result of BDHF-TOPSIS method.

Alternatives	S_j	R_j	Q_j	Rank
A_1	0.6642	0.2945	0.8633	2
A_2	0.8755	0.2867	0.9796	3
A_3	0.1023	0.1023	0	1

Table 6. The ranking result of BDHF-VIKOR method.

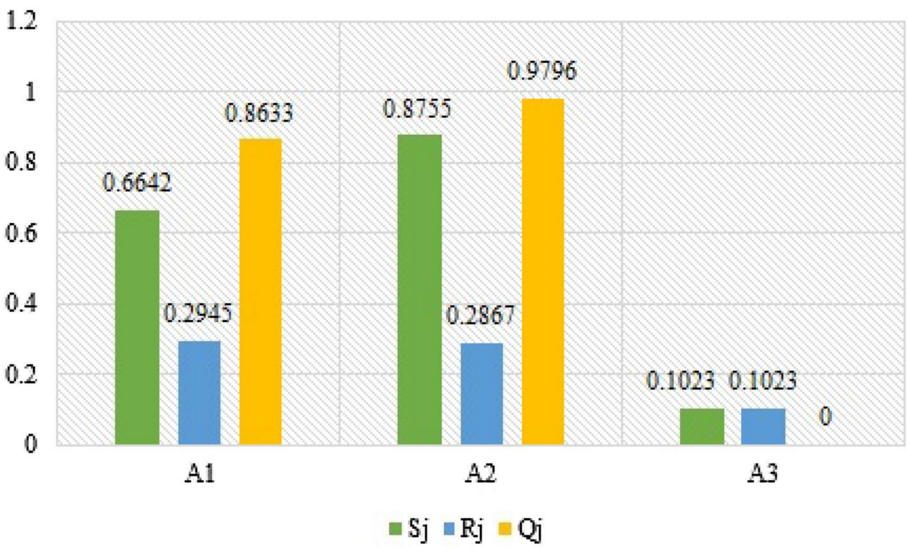

Fig. 11. The ranking result of BDHF-VIKOR method.

result determined through the initial weights. The set of selected alternatives in the selected criteria ranking process is considered by the VIKOR method. The VIKOR method depends on three main values. Based on those values, we are listing the alternatives. There is a utility measure, a regret measure, and an index value. The results of the BDHF-VIKOR method are displayed in Table 6, and the results of the BDHF-VIKOR method are shown in Fig. 11.

Comparison between BDHF-ELECTRE and BDHF-ARAS method The best alternative selection is based on the utility degree, which simplifies complex decision-making problems. The ARAS method determines the

Alternatives	S_i	K_i	Rank
A_1	0.2744	0.7608	2
A_2	0.1731	0.4799	3
A_3	0.2757	0.7644	1

Table 7. The ranking result of BDHF-ARAS method.

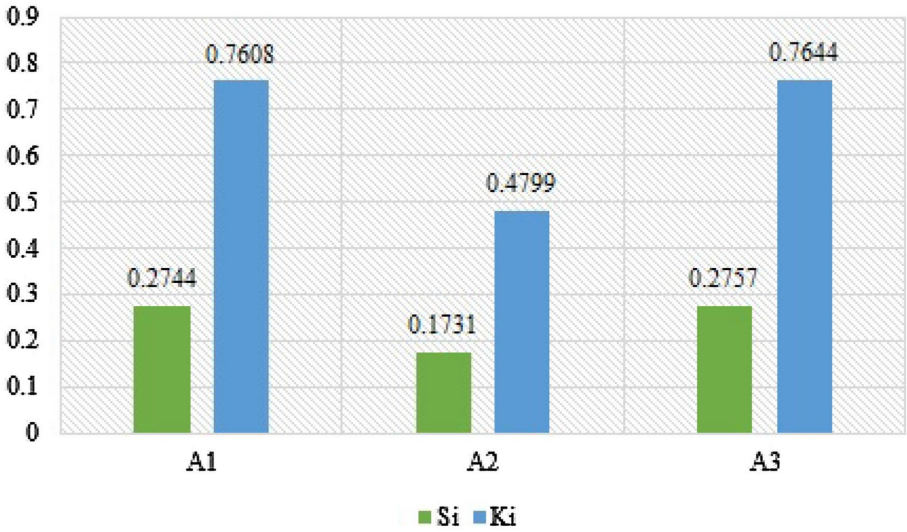

Fig. 12. The ranking result of BDHF-ARAS method.

Alternatives	$BDHF-ELECTRE$	$BDHF-TOPSIS$	$BDHF-VIKOR$	$BDHF-ARAS$
A_1	3	2	2	2
A_2	1	1	3	3
A_3	2	3	1	1

Table 8. The ranking result of BDHF-ELECTRE method and existing methods.

difference among the selected alternatives, the ideal solution to the problem, and the elimination of the influence of various measures. The results of the BDHF-ARAS method are displayed in Table 7, and the results of the BDHF-ARAS method are shown in Fig. 12.

The comparison is only between the ranking methods. The importance of the criteria weight value is the same for our selected existing method. Evaluate the importance of the criteria weight value using the entropy distance measure. The ranking comparison of the BDHF-ELECTRE method and existing methods is given in Table 8. The ranking results are shown in Fig. 13.

Sensitivity analysis
A sensitivity analysis is obtained by altering the values of the concordance and discordance dominance matrices. In the ELECTRE method, concordance and discordance matrix results are very necessary because these two values carry out the hole matrix result values. In our proposed method, the concordance dominance matrix value is $\bar{C} = 0.5$, and the discordance dominance matrix value is $\bar{D} = 0.7$. In this section, we are categorised into two divisions: case 1 and case 2. The ranking of the alternatives will affect the assortment of concordance and discordance levels. This creates an excessive impression on our proposed method result. The calculation of concordance and discordance levels is an exposed problem.

Case 1 In case 1, we are increasing the concordance and discordance dominance matrix values. If the sensitivity analysis is obtained with the increasing $\bar{C}$ and $\bar{D}$ values, it is changing our proposed method result. The alternatives also accept the preference $\bar{C}$ and $\bar{D}$ values. Here, the values of $\bar{C} = 0.7$ and $\bar{D} = 0.9$. The result of case 1 values is displayed in Table 9, and the result of case 1 values is shown in Figs. 14, 15, and 16.

Case 2 In case 2, we are decreasing the concordance and discordance dominance matrix values. If the sensitivity analysis is obtained with the decreasing $\bar{C}$ and $\bar{D}$ values, it is changing our proposed method result. The alternatives also accept the preference $\bar{C}$ and $\bar{D}$ values. Here, the values of $\bar{C} = 0.3$ and $\bar{D} = 0.5$. The result of case 2 values is displayed in Table 10, and the result of case 2 values is shown in Figs. 17, 18, and 19.

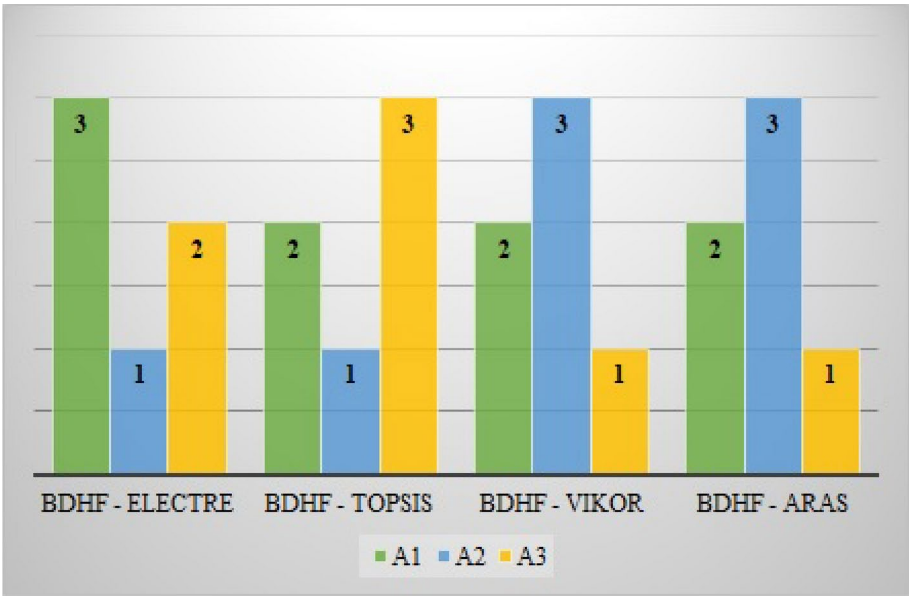

Fig. 13. The ranking result of BDHF-ELECTRE and existing methods.

	A_1	A_2	A_3
(a) Concordance index matrix			
A_1	0	0	0
A_2	1	0	1
A_3	0	0	0
(b) Discordance index matrix			
	A_1	A_2	A_3
A_1	0	1	1
A_2	0	0	0
A_3	0	1	0
(c) Result of aggregated dominance matrix			
	A_1	A_2	A_3
A_1	0	0	0
A_2	0	0	0
A_3	0	0	0

Table 9. Case 1:The result of increasing concordance and discordance dominance matrix value.

Conclusion

A new approach in MCDM is introduced, utilizing the ELECTRE method within a framework of BDHF environment. ELECTRE, known for its effectiveness in decision-making scenarios, particularly thrives in handling BDHF data, ensuring clarity in decision-making processes. The ELECTRE methodology, renowned for its effectiveness and potency, is employed to tackle decision-making problems reliant on bipolar dual hesitant fuzzy data, facilitating decision makers in unambiguous situations. The concept of outranking relations in ELECTRE, including concordance and discordance matrices, is adapted to accommodate BDHFs. In this study, we employ the BDHF-ELECTRE methodology to evaluate and select the optimal recycling technique for plastic waste, considering three alternatives: mechanical recycling, chemical recycling, and energy (thermal) recycling. These techniques are treated as alternatives, denoted as A_1 (chemical recycling), A_2 (mechanical recycling), and A_3 (chemical and energy recycling). Criteria for selection include Environment (C_1), Economic (C_2), social and technical (C_3), and safety (C_4). Weight values for the decision matrix are determined using entropy distance measures to account for haziness and indistinctness. The resulting weight values are $W_1 = 0.2091$, $W_2 = 0.2945$, $W_3 = 0.2937$, and $W_4 = 0.2867$. The ELECTRE method employs various concordance and discordance matrices,

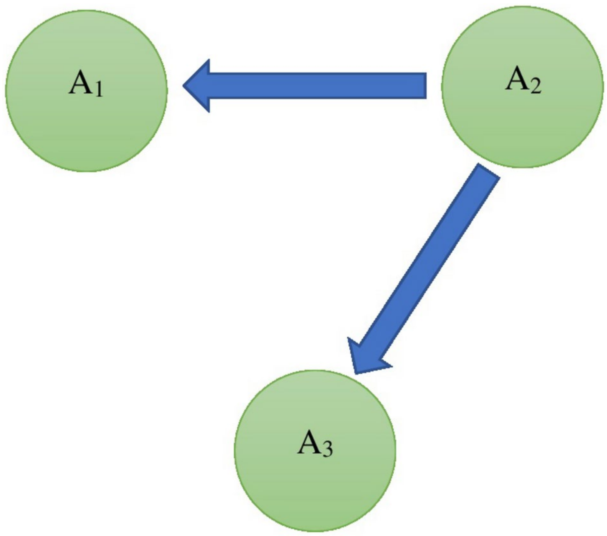

Fig. 14. Concordance index matrix.

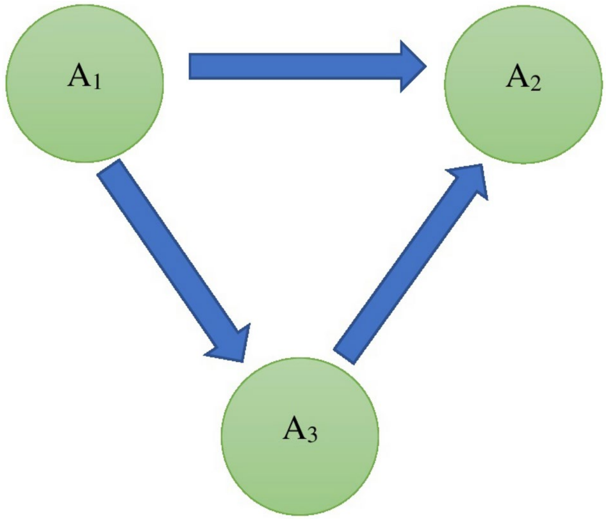

Fig. 15. Discordance index matrix.

with the aggregated dominance matrix determining the final ranking. According to our findings, mechanical recycling emerges as the most flexible and effective technique for recycling plastics, with the ranking order being $A_2 > A_3 > A_1$. Additionally, we provide a discussion on the results, comparative analysis of existing MCDM techniques such as TOPSIS, VIKOR, and ARAS in a BDHF environment, and sensitivity analysis involving variations in concordance and discordance matrices.

Entropy-based MCDM techniques are effective at handling ambiguities and uncertainties in the criterion weighting process, but they have trouble in accurately expressing the priorities and preferences of decision-makers, particularly in intricately linked and complicated preference environments. For this reason, the combination weighing techniques along with the suggested BDHF-ELECTRE approach can be adopted. Beyond the alternatives considered in this study, we hope to investigate further hybrid recycling techniques in the future. To effectively solve the worldwide plastic waste issue in the years to come, it will be imperative to embrace a wide range of cutting-edge techniques and technology. In our upcoming work, we will also include further significant qualitative and quantitative criteria.

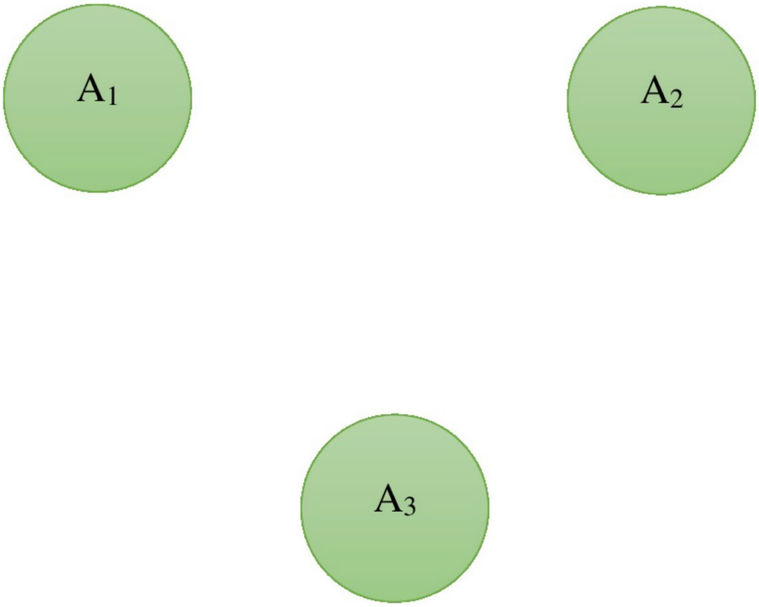

Fig. 16. Result of aggregated dominance matrix.

	A_1	A_2	A_3
(a) Concordance index matrix			
A_1	0	0	1
A_2	1	0	1
A_3	1	0	0
(b) Discordance index matrix			
A_1	0	1	1
A_2	0	0	1
A_3	1	1	0
(c) Result of aggregated dominance matrix			
A_1	0	0	1
A_2	0	0	1
A_3	1	0	0

Table 10. Case 2: The result of decreasing concordance and discordance dominance matrix value.

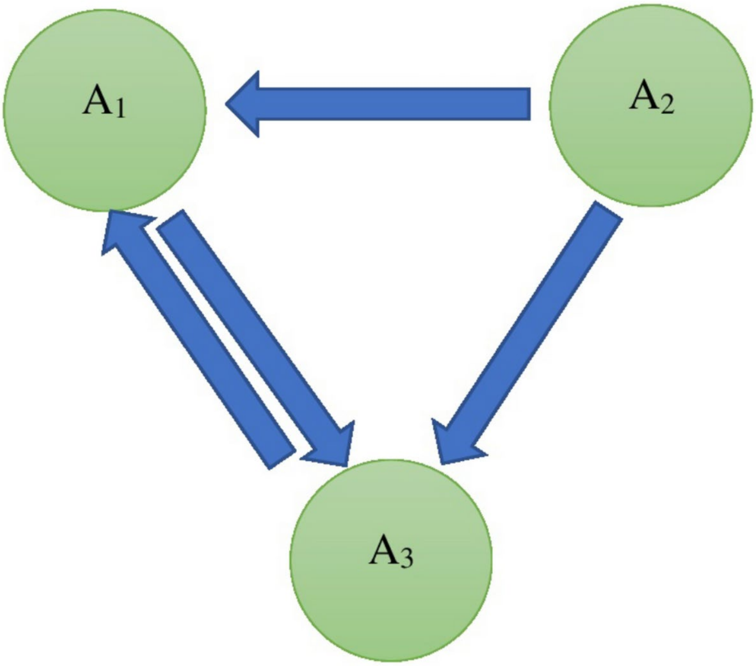

Fig. 17. Concordance index matrix.

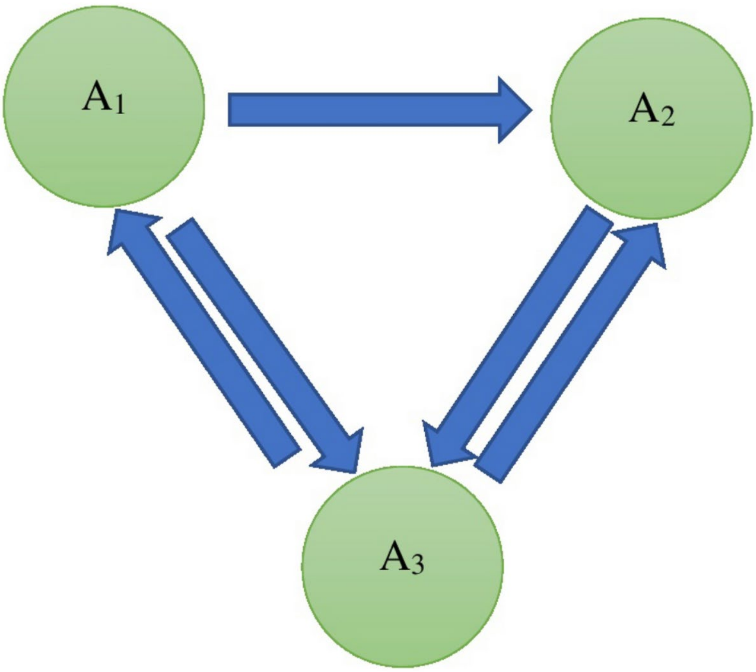

Fig. 18. Discordance index matrix.

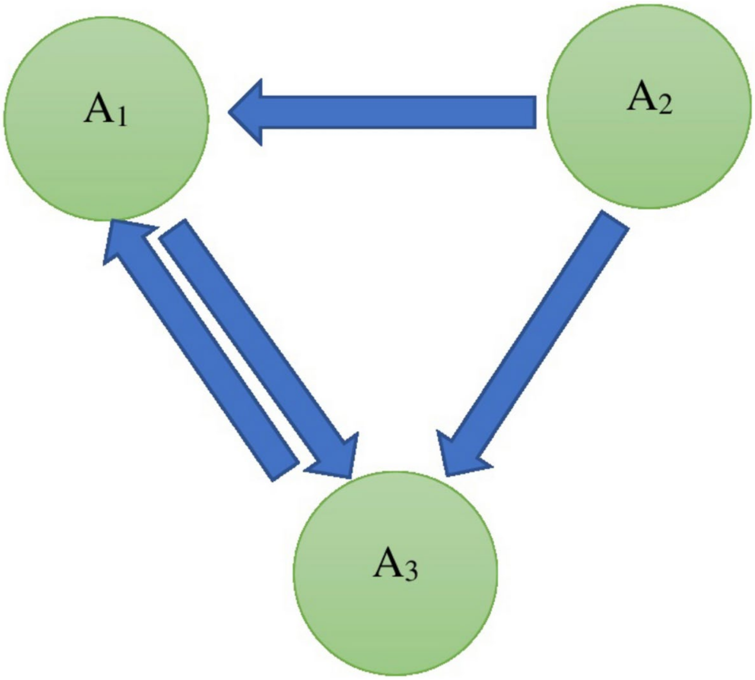

Fig. 19. Result of aggregated dominance matrix.

Data availability
The datasets used and analysed during the current study available from the corresponding author on reasonable request.

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References
1. Lukumon, S., Patinvoh, R. J., & Taherzadeh, M. J. Waste Plastic Char as Adsorbent for Removal of Pollutants from Landfill Leachates-A Critical Review. *Environ. Adv*. 100522 (2024).
2. Yucesan, M., Gul, M. & Pamucar, D. A holistic failure modes and effects analysis for university plastic injection laboratory under Bayesian network. *Appl. Soft Comput.* **147**, 110759 (2023).
3. Baidya, J. et al. Selection of third party reverses logistic providers: An approach of BCF-CRITIC-MULTIMOORA using Archimedean power aggregation operators. *Complex Intell. Syst.* **7**(5), 2503–2530. https://doi.org/10.1007/s40747-021-00413-x (2021).
4. Nagarajan, D., Gobinath, V. M. & Broumi, S. Multicriteria decision making on 3D printers for economic manufacturing using neutrosophic environment. *Neutrosophic Sets Syst.* **57**(1), 3 (2023).
5. Kokkinos, K., Lakioti, E., Moustakas, K., Tsanaktsidis, C. & Karayannis, V. Sustainable medical waste management using an intuitionistic fuzzy-based decision support system. *Sustainability* **16**(1), 298. https://doi.org/10.3390/su16010298 (2023).
6. Jeon, J. et al. An innovative probabilistic hesitant fuzzy set MCDM perspective for selecting flexible packaging bags after the prohibition on single-use plastics. *Sci. Rep.* **13**(1), 10206. https://doi.org/10.1038/s41598-023-37200-2 (2023).
7. Aghajani Mir, M. et al. Application of TOPSIS and VIKOR improved versions in a multi criteria decision analysis to develop an optimized municipal solid waste management model. *J. Environ. Manage.* **166**, 109–115. https://doi.org/10.1016/j.jenvman.2015.09.028 (2016).
8. Akram, M., Luqman, A. & Kahraman, C. Hesitant Pythagorean fuzzy ELECTRE-II method for multi-criteria decision-making problems. *Appl. Soft Comput.* **108**, 107479. https://doi.org/10.1016/j.asoc.2021.107479 (2021).
9. Altieri, V. G. et al. Treating and reusing wastewater generated by the washing operations in the non-hazardous plastic solid waste recycling process: Advanced method vs. conventional method. *J. Environ. Manage.* **284**, 112011. https://doi.org/10.1016/j.jenvman.2021.112011 (2021).
10. Cali, S. & Balaman, S. Y. A novel outranking based multi criteria group decision making methodology integrating ELECTRE and VIKOR under intuitionistic fuzzy environment. *Expert Syst. Appl.*[SPACE]https://doi.org/10.1016/j.eswa.2018.10.039 (2018).
11. Carlos, F. et al. Multicriteria decision making applied to waste recycling in Brazil. *Omega* **36**(3), 395–404. https://doi.org/10.1016/j.omega.2006.07.009 (2008).
12. Chaurasiya, R. & Jain, D. Pythagorean fuzzy entropy measure-based complex proportional assessment technique for solving multi-criteria healthcare waste treatment problem. *Granul. Comput.* **7**, 917–930. https://doi.org/10.1007/s41066-021-00304-z (2022).
13. Chen, N., Xu, Z. & Xia, M. The ELECTRE I Multi-Criteria Decision-Making Method Based on Hesitant Fuzzy Sets. *Int. J. Inf. Technol. Decis. Mak.* **14**(3), 621–657. https://doi.org/10.1142/S0219622014500187 (2022).
14. Coban, A., Ertis, I. F. & Cavdaroglu, N. A. Municipal solid waste management via multi-criteria decision making methods: A case study in Istanbul, Turkey. *J. Clean. Prod.* **180**, 159–167. https://doi.org/10.1016/j.jclepro.2018.01.130 (2018).
15. Cruz Sanchez, F. A., Boudaoud, H., Camargo, M. & Pearce, J. M. Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *J. Clean. Prod.*[SPACE]https://doi.org/10.1016/j.jclepro.2020.121602 (2020).
16. Wang, Y., Ma, X., Qin, H., Sun, H. & Wei, W. Hesitant Fermatean fuzzy Bonferroni mean operators for multi-attribute decision-making. *Complex & Intell. Syst.* **10**(1), 1425–1457. https://doi.org/10.1007/s40747-023-01203-3 (2024).

17. Krishankumar, R., Ramanujam, N., Zavadskas, E. K., Ravichandran, K. S. & Gandomi, A. H. Ranking barriers impeding sustainability adoption in clean energy supply chains: A hybrid framework with Fermatean fuzzy data. *IEEE Trans. Eng. Manage.*[SPACE]https://doi.org/10.1109/TEM.2024.3350249 (2024).
18. Nithyanandham, D. et al. Bipolar intuitionistic fuzzy graph based decision-making model to identify flood vulnerable region. *Environ. Sci. Pollut. Res.* **30**(60), 125254–125274. https://doi.org/10.1007/s11356-023-27548-3 (2023).
19. Davidson, M. G., Furlong, R. A. & McManus, M. C. Developments in the life cycle assessment of chemical recycling of plastic waste: A review. *J. Clean. Prod.* **293**, 126163. https://doi.org/10.1016/j.jclepro.2021.126163 (2021).
20. Akram, M., Shumaiza, & Arshad, M. Bipolar fuzzy TOPSIS and bipolar fuzzy ELECTRE-I methods to diagnosis. *Comput. Appl. Math.* **39**(1), 7. https://doi.org/10.1007/s40314-019-0980-8 (2020).
21. Alghamdi, M. A., Alshehri, N. O. & Akram, M. Multi-criteria decision-making methods in bipolar fuzzy environment.. *Int. J. Fuzzy Syst.* **20**, 2057–2064. https://doi.org/10.1007/s40815-018-0499-y (2018).
22. Al-Quran, A., Awang, A., Ali, M. & Abdullah, L. Hesitant bipolar-valued neutrosophic set: Formulation. *Theory Appl. IEEE Access* **7**, 176099–176114. https://doi.org/10.1109/access.2019.2946985 (2019).
23. Fatih, E. A consolidated MCDM framework for performance assessment of battery electric vehicles based on ranking strategies. *Renew. Sustain. Energy Rev.* **143**, 110916. https://doi.org/10.1016/j.rser.2021.110916 (2021).
24. Gao, H., Wei, G. & Huang, Y. Dual Hesitant Bipolar Fuzzy Hamacher Prioritized Aggregation Operators in Multiple Attribute Decision Making. *IEEE Access* **6**, 11508–11522. https://doi.org/10.1109/access.2017.2784963 (2018).
25. Komsiyah, S., Wongso, R. & Pratiwi, S. W. Applications of the fuzzy ELECTRE method for decision support systems of cement vendor selection. *Procedia Comput. Sci.* **157**, 479–488. https://doi.org/10.1016/j.procs.2019.09.003 (2019).
26. Liu, P., Shen, M. & Pedrycz, W. MAGDM framework based on double hierarchy bipolar hesitant fuzzy linguistic information and its application to optimal selection of talents. *Int. J. Fuzzy Syst.* **24**, 1757–1779. https://doi.org/10.1007/s40815-021-01231-6 (2022).
27. Mahmood, T. & Rehman, U. A novel approach towards bipolar complex fuzzy sets and their applications in generalized similarity measures. *Int. J. Intell. Syst.* **37**, 535–567. https://doi.org/10.1002/int.22639 (2021).
28. Mandal, P. & Ranadive, A. S. Hesitant bipolar-valued fuzzy sets and bipolar-valued hesitant fuzzy sets and their applications in multi-attribute group decision making. *Granular Comput.* **4**, 559–583. https://doi.org/10.1007/s41066-018-0118-1 (2018).
29. Özçelik, G. & Nalkıran, M. An extension of EDAS method equipped with trapezoidal bipolar fuzzy information: An application from healthcare system. *Int. J. Fuzzy Syst.* **23**, 2348–2366. https://doi.org/10.1007/s40815-021-01110-0 (2021).
30. Pandey, S. D., Ranadive, A. S. & Samanta, S. Bipolar-valued hesitant fuzzy graph and its application. *Soc. Netw. Anal. Min.* **12**, 14. https://doi.org/10.1007/s13278-021-00824-1 (2022).
31. Qi Han; Weimin Li; Qiling Xu; Yafei Song; Chengli Fan;Minrui Zhao. Novel measures for linguistic hesitant Pythagorean fuzzy sets and improved TOPSIS method with application to contributions of system-of-systems. *Expert Systems with Applications* **199**, 0957-4174. doi.org/10.1016/j.eswa.2022.117088, (2022).
32. Lin, R., Lu, S., Yang, A., Shen, W. & Ren, J. Multi-criteria sustainability assessment and decision-making framework for hydrogen pathways prioritization: An extended ELECTRE method under hybrid information. *Int. J. Hydrog. Energy* **46**, 13430–13445. https://doi.org/10.1016/j.ijhydene.2021.01.018 (2021).
33. Demets, R. et al. Development and application of an analytical method to quantify odour removal in plastic waste recycling processes. *Resour. Conserv. Recycl.* **161**, 104907. https://doi.org/10.1016/j.resconrec.2020.104907 (2020).
34. Ebner, N. & Iacovidou, E. The challenges of Covid-19 pandemic on improving plastic waste recycling rates. *Sustain. Product. Consum.* **28**, 726–735. https://doi.org/10.1016/j.spc.2021.07.001 (2021).
35. Fei, L., Xia, J., Feng, Y. & Liu, L. An ELECTRE-based multiple criteria decision making method for supplier selection using Dempster–Shafer theory. *IEEE Access* **7**, 84701–84716. https://doi.org/10.1109/ACCESS.2019.2924945 (2019).
36. Geetha, S., Narayanamoorthy, S., Kureethara, J. V., Baleanu, D. & Kang, D. The hesitant Pythagorean fuzzy ELECTRE III: An adaptable recycling method for plastic materials. *J. Clean. Product.*[SPACE]https://doi.org/10.1016/j.jclepro.2020.125281 (2020).
37. Gu, F., Hall, P., Miles, N. J., Ding, Q. & Wu, T. Improvement of mechanical properties of recycled plastic blends via optimizing processing parameters using the Taguchi method and principal component analysis. *Mater. Design* **62**, 189–198. https://doi.org/10.1016/j.matdes.2014.05.013 (2015).
38. Marazzi, L. et al. Consumer-based actions to reduce plastic pollution in rivers: A multi-criteria decision analysis approach. *PLOS ONE* **15**(8), e0236410. https://doi.org/10.1371/journal.pone.0236410 (2020).
39. Milutinović, B., Stefanović, G., Dekić, P. S., Mijailović, I. & Tomić, M. Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multi-criteria analysis. *Energy* **137**, 917–926. https://doi.org/10.1016/j.energy.2017.02.167 (2017).
40. Mojaver, M., Hasanzadeh, R., Azdast, T. & Park, C. B. Comparative study on air gasification of plastic waste and conventional biomass based on coupling of AHP/TOPSIS multi-criteria decision analysis. *Chemosphere* **286**, 131867. https://doi.org/10.1016/j.chemosphere.2021.131867 (2022).
41. Nik, M. M. & Shahrul, K. Optimization of mechanical properties of recycled plastic products via optimal processing parameters using the Taguchi method. *J. Mater. Process. Technol.* **211**(12), 1989–1994. https://doi.org/10.1016/j.jmatprotec.2011.06.014 (2011).
42. Rani, P. et al. A novel VIKOR approach based on entropy and divergence measures of Pythagorean fuzzy sets to evaluate renewable energy technologies in India. *J. Clean. Product.*[SPACE]https://doi.org/10.1016/j.jclepro.2019.117936 (2019).
43. Senthil, S., Srirangacharyulu, B. & Ramesh, A. A robust hybrid multi-criteria decision making methodology for contractor evaluation and selection in third-party reverse logistics. *Expert Syst. Appl.* **41**(1), 50–58. https://doi.org/10.1016/j.eswa.2013.07.010 (2014).
44. Senthil, S., Murugananthan, K. & Ramesh, A. Analysis and prioritisation of risks in a reverse logistics network using hybrid multi-criteria decision making methods. *J. Clean. Prod.* **179**, 716–730. https://doi.org/10.1016/j.jclepro.2017.12.095 (2018).
45. Shumaiza, Akram, M. & Al-Kenani, A. N. Multiple-attribute decision making ELECTRE II method under bipolar fuzzy model. *Algorithms* **12**(11), 226. https://doi.org/10.3390/a12110226 (2019).
46. Thao, N. X. Similarity measures of picture fuzzy sets based on entropy and their application in MCDM. *Pattern Anal. Appl.* **23**, 1203–1213. https://doi.org/10.1007/s10044-019-00861-9 (2020).
47. Ügdüler, S., Van Geem, K. M., Roosen, M., Delbeke, E. I. P. & De Meester, S. Challenges and opportunities of solvent-based additive extraction methods for plastic recycling. *Waste Manage.* **104**, 148–182. https://doi.org/10.1016/j.wasman.2020.01.003 (2020).
48. Vinodh, S., Prasanna, M. & Hari Prakash, N. Integrated Fuzzy AHP-TOPSIS for selecting the best plastic recycling method: A case study. *Appl. Math. Model.* **38**(19–20), 4662–4672. https://doi.org/10.1016/j.apm.2014.03.007 (2014).
49. Wang, C., Wang, H. & Liu, Y. Separation of aluminum and plastic by metallurgy method for recycling waste pharmaceutical blisters. *J. Clean. Prod.* **102**, 378–383. https://doi.org/10.1016/j.jclepro.2015.04.067 (2015).
50. UzZaman, U. K., Rivette, M., Siadat, A. & Mousavi, S. M. Integrated product-process design: Material and manufacturing process selection for additive manufacturing using multi-criteria decision making. *Robot. Comput.-Integr. Manuf.* **51**, 169–180. https://doi.org/10.1016/j.rcim.2017.12.005 (2018).
51. Zhang, Hongshen & Chen, Ming. Research on the recycling industry development model for typical exterior plastic components of end-of-life passenger vehicle based on the SWOT method. *Waste Manage.* **33**(11), 2341–2353. https://doi.org/10.1016/j.wasman.2013.07.004 (2013).
52. Klotz, M., Haupt, M. & Hellweg, S. Potentials and limits of mechanical plastic recycling. *J. Ind. Ecol.* **27**(4), 1043–1059 (2023).
53. Tiwari, R., Azad, N., Dutta, D., Yadav, B. R. & Kumar, S. A critical review and future perspective of plastic waste recycling. *Sci. Total Environ.* **881**, 163433 (2023).

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Competing interests

The authors declare that they have no competing interests.

Additional information

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