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Biofuel Production Plant Location Selection Using Integrated Picture Fuzzy Weighted Aggregated Sum Product Assessment Framework

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Abstract: As an alternative for sustainable transportation and economic development, biofuels are being promoted as renewable and climate-friendly resources of energy which can help to reduce the consumption of fossil fuels, some pollutant emissions and mitigate the climate change impact from transport. With the successful development of the biofuel industry, the location selection for biofuel production plant is one of the major concerns for the governments and policymakers. Finding locations for the construction of new biofuel production plants includes several dimensions of sustainability, including economic, social and environmental; therefore, this selection process can be considered a complex multi-criteria decision-making problem with uncertainty. As an advanced version of fuzzy set, picture fuzzy set (PiFS) is one of the comprehensive tools to handle the uncertainty with the account of truth, abstinence and falsity membership degrees. Thus, this work proposes a new decision-making methodology based on the weighted aggregated sum product assessment (WASPAS) approach and similarity measure with picture fuzzy information. By using picture fuzzy numbers, the proposed methodology can effectively address the uncertain information and qualitative data that often occurs in practical applications. In this methodology, a picture fuzzy similarity measure-based weighting model is proposed to find the criteria weights under picture fuzzy environment. For this purpose, a new similarity measure is introduced to measure the degree of similarity between picture fuzzy numbers. Moreover, the rank of the options is determined based on an integrated WASPAS approach under a PiFS context. To illustrate the effectiveness of the proposed framework, a case study of biofuel production plant location selection is presented from the picture fuzzy perspective. Further, a comparison with existing methods is conducted to test the validity and applicability of the obtained results. The sensitivity analysis is performed with respect to different values of decision parameter, which proves the stability, robustness, and practicality of the proposed approach. The presented picture fuzzy WASPAS approach feasibly enables the policymakers to identify the most desirable location for a biofuel production plant by considering the social, environmental and economic aspects of sustainability.

Keywords: biofuel production plant location; multi-criteria decision-making; picture fuzzy set; similarity measure; sustainability; WASPAS

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Citation: Hezam, I.M.; Cavallaro, F.; Lakshmi, J.; Rani, P.; Goyal, S. Biofuel Production Plant Location Selection Using Integrated Picture Fuzzy Weighted Aggregated Sum Product Assessment Framework. *Sustainability* **2023**, *15*, 4215. https://doi.org/10.3390/su15054215

Academic Editor: Nana Peng

Received: 20 January 2023
Revised: 15 February 2023
Accepted: 20 February 2023
Published: 26 February 2023

1. Introduction

Energy is a critical enabler of economic transformation and social wellbeing; therefore, the need for abundant, affordable, secure, safe, and clean energy and its related services is increasing to promote the economic and social growth of the developing countries [1,2]. Increased rate of fossil fuel combustion is one of the major human sources of greenhouse gas (GHG) emissions, acid rain, pollutions and CO_2-driven climate change [3,4]. Global demand for energy, food security, environmental degradation and significant weather problems are the most critical issues that are motivating to search for low-carbon alternative fuels at both regional and national levels [5,6].

Biofuels are considered to be one of the renewable and sustainable sources of energy, with the high prospect and potential of reducing carbon emissions, as well as mitigating the climate change [7]. The production of biofuels from a sustainability perspective is an important and critical process for conserving biodiversity, ensuring global energy security, reducing environmental issues and improving economic and social aspects, especially in developing countries [8–10]. Transportation and agricultural industries are one of the main consumers of fossil fuels and a prime contributor to environmental pollution, which can be reduced by replacing biofuels. There are several complex aspects in the production of biofuels. One such aspect is the placement of biofuel production plants (BPPs), which faces challenges at all phases of the production and logistics planning [11].

The assessment of BPP locations involves numerous criteria which are strongly related to the triple bottom line (TBL) theory of sustainability [8,9]. Thus, it is essential to evaluate the criteria based on the social, environmental and economic aspects of sustainability. In the literature, few studies have been developed to assess the locations for BPP. In this context, Bai et al. [12] focused their study on the planning and assessment of biorefinery plant locations. Zhang et al. [13] suggested a two-phase multiple attribute methodology for selecting the suitable location for BPP. In that study, they used a geographic information system with a minimum transportation cost model to identify the best location. Duarte et al. [11] designed a mixed integer linear programming-based optimization tool that considers the process design and configuration of the supply chain during BPP location selection. Their study was implemented on a real case study of second-generation BPP location selection in Colombia. Kheybari et al. [9] developed a multi-criteria decision support framework based on best worst method. Further, they implemented their framework on a case study of bioethanol location selection in Iran. Najafi et al. [14] firstly identified the relevant sustainability indicators for BPP location selection. They used the Shannon entropy model to derive the criteria weights and the additive ratio assessment method to find the ranking of locations for biodiesel fuel production plants. Nordin et al. [15] presented a spatial optimization model for evaluating the locations of agricultural BPP and feedstocks in Sweden. Moreover, they provided implications for animal fodder availability, renewable energy and climate emissions.

The theory of fuzzy set (FS) [16] is characterized by the truth/membership degree of the function. After the pioneering work of Zadeh [16], various extensions of FS have been introduced to express the uncertain information of real-life problems [17–22]. In FSs, the truth degree (TD) is defined on interval [0, 1], while the falsity degree (FD) defines its complement. However, this statement does correlate with human behavior in practical examples. To evade the concerns of FSs, the notion of the intuitionistic fuzzy set (IFS) [23] has been proposed with three parameters: the TD, the FD and the indeterminacy degree (ID) satisfying the condition that the sum of TD and FD is ≤ 1. Since its appearance, many theories and applications have been discussed in the literature [24–26].

In the process of voting, the voters present multiple-selection opinions as follows: 'yes', 'no', 'abstain', and 'refusal'. This case cannot be exactly described by FSs [16], IFSs [23], Pythagorean fuzzy sets (PFSs) [27], Fermatean fuzzy sets (FFSs) [28] or hesitant fuzzy sets (HFSs) [29]. This specific type of information is frequently used in several real-life problems including survey analysis, voting system and data analysis, where voters may be separated into the aforementioned four classes. To deal with such situations, Cuong [30,31] pioneered the notion of the picture fuzzy set (PiFS) theory, which contains the degrees of truth, abstinence and falsity such that their sum cannot exceed the unit interval. The concept of PiFS expresses the uncertainty and non-determinism more efficiently than FS, IFS, PFS, FFS and HFS. Many theories and applications have been presented in the context of PiFS [32]. For instance, Jana et al. [33,34] proposed a series of Hamacher and Dombi aggregation operators to aggregate the picture fuzzy information. A new dynamic programming algorithm-based picture fuzzy clustering model has been proposed for large-scale group decision-making problems [35]. Due to the advantages of PiFSs, Simic et al. [36] extended the classical COmbinative Distance-Based ASsessment (CODAS) approach under a PiFS environment and applied it for solving vehicle shredding facility location with multiple criteria. Singh and Kumar [37] integrated the quality function deployment with picture fuzzy numbers and proposed a hybrid multi-criteria group decision-making framework. Wei et al. [38] studied the picture fuzzy bidirectional projection method for solving group decision-making problems with multiple tangible and intangible criteria. A hybrid picture fuzzy similarity measure-based ranking model has been developed for assessing projects from a sustainability perspective [39]. Fetanat and Tayebi [40] proposed a hybrid decision support system by using the PiFS concept to prioritize the petroleum refinery effluents. A strategy-based picture fuzzy conversion model has been developed by Zhao et al. [41], which considers the evidential reasoning concept with picture fuzzy information.

Despite the fact that there are several MCDM methods in the literature, the investigators generally opt for a method that works well with the type and intricacy of the problem considered. As one of the newly developed approaches, weighted aggregated sum product assessment (WASPAS) [42] optimizes the weighted aggregated functions and ranks the options according to a compromise solution. The WASPAS method has been applied for a variety of purposes, such as sustainable project portfolio selection [43], foreign direct investment assessment [44], hair mask product selection [45], etc. The classical WASPAS method has been extended from q-rung orthopair fuzzy perspective. Moreover, they utilized their method for the assessment of alternative fuel technologies under an uncertain environment [46]. Mishra et al. [47] assessed the biomass crops for biofuel production by using a new single-valued neutrosophic WASPAS methodology. Wei et al. [48] extended the WASPAS method by using the reducible weighted Maclaurin symmetric mean operator and PFS theory. Further, they presented the application of the WASPAS method in teaching quality assessment. Chakraborty and Saha [49] combined the WASPAS approach with fuzzy analytic hierarchy process (AHP) for assessing the healthcare waste technology selection problem. Utilizing the uncertainty concepts, Ebadzadeh et al. [50] proposed a fuzzy WASPAS approach for assessing the environmental risks of the petrochemical industry. In the context of PiFSs, Simic et al. [51] and Senapati and Chen [52] introduced the hybrid picture fuzzy WASPAS approaches with applications in last-mile delivery mode assessment and an air-conditioning system selection, respectively. Unfortunately, there has been no study extending the similarity measure-based WASPAS method with PiFSs to solve BPP location selection problem in the literature.

Due to the broader range of PiFSs in handling the vague information, the current work focuses on the development of a new decision support system under the PiFS context and applied for assessing the locations for BPP construction. The decision-making methods assist the "decision-making experts (DMEs)" to make an optimal decision [45]. Some MCDM methods have been developed to solve the BPP location selection problem [8–13], but these studies have some drawbacks:

(i) unable to derive the criteria weights;
(ii) unable to express the vague information.

Inspired by the concept of WASPAS, this study proposes an integrated WASPAS method with picture fuzzy information, in which the weights of the criteria are derived through the PiFSM-based model. A few studies [51,52] simply extended the classical WASPAS to PiFSs setting, but they did not consider the significance of DMEs and criteria weights during the process of decision making. To the best of the authors' knowledge, none of the previous studies have addressed the BPP location selection problem using an integrated picture fuzzy similarity measure-based WASPAS approach.

Based on the above discussions, the key contributions of this work are listed as:

- By means of literature survey and interview with experts, a comprehensive index system is presented to evaluate the key criteria for BPP locations' assessment.
- A novel formula is presented to derive the DMEs' weights.
- A novel criteria weight-determining model is developed based on PiFSM. For this purpose, we introduce a new similarity measure for PiFSs.
- A modified WASPAS method based on the combination of new weight-determination process and picture fuzzy information is introduced for solving BPP location selection from sustainability perspective.
- To prove the effectiveness of the present WASPAS approach, an empirical case study of BPP location selection is presented within the context of PiFSs.

The rest of this study is arranged as follows: Section 2 presents the basic concepts and then introduces a new SM for PiFSs. Section 3 establishes a hybrid decision support system for making decisions under picture fuzzy environment. Section 4 implements the proposed system on a case study of BPP location selection problem of Ahmedabad, India. In addition, this section further discusses the sensitivity and comparative analyses to confirm the validity of obtained results. Section 5 discusses the findings and scope for further research.

2. Literature Review

In the current section, we firstly discuss the fundamental definitions related to this study. Further, we introduce an SM, which quantifies the degree of similarity between PiFSs.

2.1. Basic Concepts

Definition 1. *A PiFS H on a finite universal set* $Y = \{o_1, o_2, \ldots, o_m\}$ *is mathematically expressed as [30,31]*

$$H = \{\langle o, (\wp_H(o_i), \eta_H(o_i), \Im_H(o_i))\rangle | o_i \in Y\}, \tag{1}$$

where $\wp_H(o_i) : Y \to [0, 1]$, $\eta_F(o_i) : Y \to [0, 1]$ *and* $\Im_H(o_i) : Y \to [0, 1]$ *denote the degrees of truth, abstinence and falsity membership of* o_i *in* H, *respectively, with the condition* $0 \le \wp_H(o_i) + \eta_H(o_i) + \Im_H(o_i) \le 1$. *For each* $o_i \in Y$, *the degree of refusal membership is computed by* $\rho_H(o_i) = 1 - (\wp_H(o_i) + \eta_H(o_i) + \Im_H(o_i))$.

Definition 2. *Let* $H = \langle \wp_H(o_i), \eta_H(o_i), \Im_H(o_i)\rangle$ *be a picture fuzzy number (PiFN). Then, the score and accuracy functions are represented by Equations (1) and (2), respectively [53].*

$$\mathbb{S}(H) = \wp_H - \eta_H - \Im_H, \text{ where } \mathbb{S}(H) \in [-1, 1], \tag{2}$$

$$A(H) = \wp_H + \eta_H + \Im_H, \text{ where } A(H) \in [0, 1]. \tag{3}$$

Example 1. *For any two PiFNs* $H_1 = \langle 0.6, 0.2, 0.2\rangle$ *and* $H_2 = \langle 0.7, 0.2, 0.1\rangle$, *the score function of* H_1 *is* $\mathbb{S}(H_1) = 0.2$ *and the score function of* H_2 *is* $\mathbb{S}(H_2) = 0.4$, *therefore, the order of the PiFNs is* $H_1 < H_2$.

Example 2. *For any two PiFNs* $H_1 = \langle 0.8, 0.2, 0.0\rangle$ *and* $H_2 = \langle 0.7, 0.0, 0.1\rangle$, *the score function of* H_1 *is* $\mathbb{S}(H_1) = 0.6$ *and the score function of* H_2 *is* $\mathbb{S}(H_2) = 0.6$, *therefore,* $H_1 = H_2$. *In this case, we are unable to discriminate the order of* H_1 *and* H_2. *Then, we compute accuracy values of* H_1 *and* H_2, *which are* $A(H_1) = 1.0$ *and* $A(H_2) = 0.9$, *respectively. Thus, the order of given PiFNs is* $H_1 > H_2$.

Definition 3 ([30,31,54]). *Let* $H_1 = \langle \wp_{H_1}(o_i), \eta_{H_1}(o_i), \Im_{H_1}(o_i)\rangle$ *and* $H_2 = \langle \wp_{H_2}(o_i), \eta_{H_2}(o_i), \Im_{H_2}(o_i)\rangle$ *be two PiFNs. Then, the operational laws on PiFNs are defined as*

(i) $H_k^c = \{\langle o, (\Im_{H_k}(o_i), \eta_{H_k}(o_i), \wp_{H_k}(o_i))\rangle | o_i \in Y\}, \ k = 1, 2;$

(ii) $H_1 \oplus H_2 = \left\{ \left\langle \begin{array}{c} o_i, \wp_{H_1}(o_i) + \wp_{H_2}(o_i) - \wp_{H_1}(o_i)\,\wp_{H_2}(o_i), \\ \eta_{H_1}(o_i)\,\eta_{H_2}(o_i), \Im_{H_1}(o_i)\,\Im_{H_2}(o_i) \end{array} \right\rangle | o_i \in Y \right\}$;

(iii) $H_1 \otimes H_2 = \left\{ \left\langle \begin{array}{c} o_i, \wp_{H_1}(o_i)\,\wp_{H_2}(o_i), \eta_{H_1}(o_i) + \eta_{H_2}(o_i) - \eta_{H_1}(o_i)\,\eta_{H_2}(o_i), \\ \Im_{H_1}(o_i) + \Im_{H_2}(o_i) - \Im_{H_1}(o_i)\,\Im_{H_2}(o_i) \end{array} \right\rangle | o_i \in Y \right\}$;

(iv) $H_1 \cap H_2 = \left\{ \left\langle \begin{array}{c} o_i, \min\{\wp_{H_1}(o_i), \wp_{H_2}(o_i)\}, \min\{\eta_{H_1}(o_i), \eta_{H_2}(o_i)\}, \\ \max\{\Im_{H_1}(o_i), \Im_{H_2}(o_i)\} \end{array} \right\rangle | o_i \in Y \right\}$;

(v) $H_1 \cup H_2 = \left\{ \left\langle \begin{array}{c} o_i, \max\{\wp_{H_1}(o_i), \wp_{H_2}(o_i)\}, \min\{\eta_{H_1}(o_i), \eta_{H_2}(o_i)\}, \\ \min\{\Im_{H_1}(o_i), \Im_{H_2}(o_i)\} \end{array} \right\rangle | o_i \in Y \right\}$.

Example 3. *Let $H_1 = \langle 0.6, 0.2, 0.2\rangle$ and $H_2 = \langle 0.7, 0.1, 0.1\rangle$ be two PiFNs. Then the operational laws given by Definition 3are computed as*

(i) $H_1^c = \langle 0.2, 0.2, 0.6\rangle$ *and* $H_2^c = \langle 0.1, 0.1, 0.7\rangle$;
(ii) $H_1 \oplus H_2 = \langle 0.6 + 0.7 - 0.6 \times 0.7, 0.2 \times 0.1, 0.2 \times 0.1\rangle = \langle 0.88, 0.02, 0.02\rangle$;
(iii) $H_1 \otimes H_2 = \langle 0.6 \times 0.7, 0.2 + 0.1 - 0.2 \times 0.1, 0.2 + 0.1 - 0.2 \times 0.1\rangle = \langle 0.42, 0.28, 0.28\rangle$;
(iv) $H_1 \cap H_2 = \langle 0.6, 0.1, 0.2\rangle$;
(v) $H_1 \cup H_2 = \langle 0.7, 0.1, 0.1\rangle$.

Definition 4 ([55]). *Let $H_1, H_2 \in PFSs(Y)$. A real-valued function $S(H_1, H_2) : PFS(Y) \times PFS(Y) \to [0, 1]$ is said to be a PiFSM if it satisfies the following postulates:*

(s1). $0 \leq S(H_1, H_2) \leq 1$;
(s2). $S(H_1, H_2) = S(H_2, H_1)$;
(s3). $S(H_1, H_2) = 1$ *if and only if* $H_1 = H_2$;
(s4). *For $H_1, H_2, H_3 \in PFSs(Y)$, if $H_1 \subseteq H_2 \subseteq H_3$, then $S(H_1, H_3) \leq S(H_1, H_2)$ and $S(H_1, H_3) \leq S(H_2, H_3)$.*

2.2. Picture Fuzzy Similarity Measure

SM, as one of the well-known information measures, is widely applied for data mining, medical diagnosis, pattern recognition, etc. As PiFS considers the wider range of fuzzy information, some authors have proposed some SMs to assess the degree of similarity between PiFSs [55]. For instance, Luo and Zhang [56] analyzed the drawbacks of the existing picture fuzzy similarity measures (PiFSMs). To overcome their drawbacks, the authors have introduced a new similarity measure (SM) for PiFSs with an application in pattern recognition problems. Singh and Ganie [57] proposed some new SMs for PiFSs with applications in several areas. Khan et al. [58] highlighted the counter-intuitive cases of several existing PiFSMs and further proposed a bi-parametric PiFSM and distance measure for a medical diagnosis application. Tian et al. [39] proposed a PiFSM and used it to develop a decision-making algorithm for solving projects evaluation from sustainability viewpoints.

The exponential function has an advantage over the polynomial, trigonometric and logarithmic functions. Unfortunately, there is no study regarding the exponential-function-based PiFSM. Inspired by this concept, we propose a SM for PiFSs and further use it to derive the numeric weights of criteria.

For $H_1, H_2 \in PiFSs(Y)$, we present a new PiFSM in accordance with [59,60]

$$S(H_1, H_2) = 1 - \frac{1 - \exp\left[-\frac{1}{2n}\sum_{i=1}^{n}\left(\begin{array}{c} |\wp_{H_1}(o_i) - \wp_{H_2}(o_i)| \\ +|\eta_{H_2}(o_i) - \eta_{H_2}(o_i)| \\ +|\Im_{H_1}(o_i) - \Im_{H_2}(o_i)| \end{array}\right)\right]}{1 - \exp(-1)}, \ \forall\, o_i \in Y. \quad (4)$$

Lemma 1. *If $f(\alpha) = 1 - \frac{1-\exp(-\alpha)}{1-\exp(-1)}$, then $\max_{\alpha \in [0,n]} f(\alpha) = f(0) = 1$ and $\min_{\alpha \in [0,n]} f(\alpha) = f(n) = 0$.*

Proof. The derivative of $f(\alpha) = 1 - \frac{1-\exp(-\alpha)}{1-\exp(-1)}$ is $-\frac{\exp(-\alpha)}{1-\exp(-1)}$, which is negative; therefore, the given function $f(\alpha)$ is decreasing in $[0, n]$. Thus, $\max_{\alpha \in [0, n]} f(\alpha) = f(0) = 1$ and $\min_{\alpha \in [0, n]} f(\alpha) = f(n) = 0$. For more details, please see ref. [59]. □

Theorem 1. *The function $S(H_1, H_2)$, given by Equation (4), is a valid similarity measure for PiFS.*

Proof. To prove this theorem, we have to verify the properties (s1)–(s4) of Definition 4.

(s1). For $H_1, H_2 \in PiFSs(Y)$, where $H_1 = (\mu_{H_1}, \eta_{H_1}, \nu_{H_1})$ and $H_2 = (\mu_{H_2}, \eta_{H_2}, \nu_{H_2})$,

$$\alpha = \frac{1}{2n}\sum_{i=1}^{n}\left(\left|\mu_{H_1}(o_i) - \mu_{H_2}(o_i)\right| + \left|\eta_{H_1}(o_i) - \eta_{H_2}(o_i)\right| + \left|\nu_{H_1}(o_i) - \nu_{H_2}(o_i)\right|\right).$$

$\alpha \in [0, n]$, therefore, $S(H_1, H_2) = f(\alpha)$. Thus, in accordance with Lemma 1, we have $0 \leq S(H_1, H_2) \leq 1$.

(s2). It is obvious from Equation (4).

(s3). From Equation (4), if $H_1 = H_2$, then $S(H_1, H_2) = 1$. Conversely, let $S(H_1, H_2) = 1$. Then, from Equation (4), we obtain

$$S(H_1, H_2) = 1 = 1 - \frac{1 - \exp\left[-\frac{1}{2n}\sum_{i=1}^{n}\begin{pmatrix} \left|\wp_{H_1}(o_i) - \wp_{H_2}(o_i)\right| \\ +\left|\eta_{H_1}(o_i) - \eta_{H_2}(o_i)\right| \\ +\left|\Im_{H_1}(o_i) - \Im_{H_2}(o_i)\right| \end{pmatrix}\right]}{1 - \exp(-1)}, \ \forall\, o_i \in Y.$$

It implies that
$\left|\wp_{H_1}(o_i) - \wp_{H_2}(o_i)\right| + \left|\eta_{H_1}(o_i) - \eta_{H_2}(o_i)\right| + \left|\Im_{H_1}(o_i) - \Im_{H_2}(o_i)\right| = 0$
$\Rightarrow \wp_{H_1}(o_i) = \wp_{H_2}(o_i)$, $\eta_{H_1}(o_i) = \eta_{H_2}(o_i)$, $\Im_{H_1}(o_i) = \Im_{H_2}(o_i)$. Hence, $H_1 = H_2$.

(s4). Given that $H_1 \subseteq H_2 \subseteq H_3$, then $\wp_{H_1}(o_i) \leq \wp_{H_2}(o_i) \leq \wp_{H_3}(o_i)$, $\eta_{H_1}(o_i) \leq \eta_{H_2}(o_i) \leq \eta_{H_3}(o_i)$ and $\Im_{H_1}(o_i) \geq \Im_{H_2}(o_i) \geq \Im_{H_3}(o_i)$, $\forall\, o_i \in Y$. Then,

$$\alpha_1 = \frac{1}{2n}\sum_{i=1}^{n}\begin{pmatrix} \left|\wp_{H_1}(o_i) - \wp_{H_2}(o_i)\right| \\ +\left|\eta_{H_1}(o_i) - \eta_{H_2}(o_i)\right| \\ +\left|\Im_{H_1}(o_i) - \Im_{H_2}(o_i)\right| \end{pmatrix} \leq \alpha_2 = \frac{1}{2n}\sum_{i=1}^{n}\begin{pmatrix} \left|\wp_{H_1}(o_i) - \wp_{H_3}(o_i)\right| \\ +\left|\eta_{H_1}(o_i) - \eta_{H_3}(o_i)\right| \\ +\left|\Im_{H_1}(o_i) - \Im_{H_3}(o_i)\right| \end{pmatrix}, \ \forall\, o_i \in Y.$$

Consequently, with Lemma 1, we have $S(H_1, H_2) = f(\alpha_1) \geq f(\alpha_2) = S(H_1, H_3)$. Similarly, we can verify that $S(H_2, H_3) \geq S(H_1, H_3)$. □

3. Integrated Picture Fuzzy WASPAS (PiF-WASPAS) Method for MCDM Problems

In this section, an integrated method is introduced to tackle the MCDM problems from a picture fuzzy perspective, which is based on the classical WASPAS approach. The proposed method is developed to handle the MCDM problems with unknown criteria and DMEs' weights. In the proposed framework, a novel formula is presented to compute criteria weights based on PiFSM. With the use of PiFSs, the DMEs provide more flexibility in expressing their preferences under uncertain situations. The steps of PiF-WASPAS method are as follows:

Step 1: Construct the linguistic decision matrix (LDM).

In the MCDM problem, consider a set of options $P = \{P_1, P_2, \ldots, P_m\}$ with respect to a set of criteria $Q = \{Q_1, Q_2, \ldots, Q_n\}$. Let $D = \{d_1, d_2, \ldots, d_l\}$ be a set of 'l' DMEs which give his/her opinions on each option $P_{\rm i}$ under the criteria Q_j in forms of PiFNs. Let $X = \left(x_{ij}^{(k)}\right)$, $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$ be the LDM provided by the DMEs, where $x_{ij}^{(k)}$ denotes the performance value of an option P_i under each criterion Q_j in terms of linguistic values (LVs) given by k^{th} expert.

Step 2: Determining the DMEs weights.

In the process of group decision-making, the significance of DMEs' weights is an important concern. For the assessment of k^{th} expert, let $E_k = (\wp_k, \eta_k, \Im_k)$ be the PiFN; then, the formula for k^{th} DME's weight is evaluated by

$$\psi_k = \frac{(\wp_k - \eta_k - \Im_k)}{\sum_{k=1}^{\ell} (\wp_k - \eta_k - \Im_k)}, \quad k = 1, 2, \ldots, l. \tag{5}$$

Clearly, $\psi_k \geq 0$ and $\sum_{k=1}^{\ell} \psi_k = 1$.

Step 3: Create an aggregated picture fuzzy decision matrix (A-PiFDM).

To aggregate the group DMEs' opinions, the picture fuzzy weighted averaging operator (PiFWAO) [28] is used on PiFDM. Let $\mathbb{Z} = (z_{ij})_{m \times n}$ be the A-PiFDM, where

$$\begin{aligned} z_{ij} &= PFWA_{\psi}\left(x_{ij}^{(1)}, x_{ij}^{(2)}, \ldots, x_{ij}^{(\ell)}\right) \\ &= \left(1 - \prod_{k=1}^{\ell} (1 - \wp_k)^{\psi_k}, \prod_{k=1}^{\ell} (\eta_k)^{\psi_k}, \prod_{k=1}^{\ell} (\Im_k + \eta_k)^{\psi_k} - \prod_{k=1}^{\ell} (\eta_k)^{\psi_k}\right). \end{aligned} \tag{6}$$

Step 4: Calculate the weights of the criteria.

Suppose $w = (w_1, w_2, \ldots, w_n)^T$ is the weight of the criterion set with $\sum_{j=1}^{n} w_j = 1$ and $w_j \in [0,\ 1]$. To find the criteria weights, we present a PiFSM-based formula, given as

$$w_j = \frac{\frac{1}{m-1} \sum_{i=1}^{m} \sum_{k=1, k \neq i}^{m} \left(1 - S\left(z_{ij}, z_{kj}\right)\right)}{\sum_{j=1}^{n} \left(\frac{1}{m-1} \sum_{i=1}^{m} \sum_{k=1, k \neq i}^{m} \left(1 - S\left(z_{ij}, z_{kj}\right)\right)\right)}, \quad j = 1, 2, \ldots, n. \tag{7}$$

Step 5: Normalize the A-PiFDM.

The normalized A-PiFDM $\mathbb{N} = (\varepsilon_{ij})_{m \times n}$ from A-PiFDM $\mathbb{Z} = (z_{ij})_{m \times n}$ is computed, where

$$\varepsilon_{ij} = \left(\widetilde{\wp}_{ij}, \widetilde{\eta}_{ij}, \widetilde{\Im}_{ij}\right) = \begin{cases} z_{ij} = (\wp_{ij}, \eta_{ij}, \Im_{ij}), & j \in Q_b, \\ z^c = (\Im_{ij}, \eta_{ij}, \wp_{ij}), & j \in Q_n, \end{cases} \tag{8}$$

Here, Q_b and Q_n denote the benefit and cost types of criteria, respectively.

Step 6: Determine the measure of weighted sum model (WSM) $s_i^{(1)}$ for each option as follows:

$$\begin{aligned} s_i^{(1)} &= \bigoplus_{j=1}^{n} w_j \, \varepsilon_{ij} \\ &= \left(1 - \prod_{j=1}^{n} (1 - \widetilde{\wp}_{ij})^{w_j}, \prod_{j=1}^{n} (\widetilde{\eta}_{ij})^{w_j}, \prod_{j=1}^{n} \left(\widetilde{\Im}_{ij} + \widetilde{\eta}_{ij}\right)^{w_j} - \prod_{j=1}^{n} (\widetilde{\eta}_{ij})^{w_j}\right), \end{aligned} \tag{9}$$

where $i = 1, 2, \ldots, m$.

Step 7: Evaluate the measure of weighted product model (WPM) $s_i^{(2)}$ for each option as follows:

$$\begin{aligned} s_i^{(2)} &= \bigotimes_{j=1}^{n} \varepsilon_{ij}^{w_j} \\ &= \left(\prod_{j=1}^{n} (\widetilde{\wp}_{ij} + \widetilde{\eta}_{ij})^{w_j} - \prod_{j=1}^{n} (\widetilde{\eta}_{ij})^{w_j}, \prod_{j=1}^{n} (\widetilde{\eta}_{ij})^{w_j}, 1 - \prod_{j=1}^{n} \left(1 - \widetilde{\Im}_{ij}\right)^{w_j}\right), \end{aligned} \tag{10}$$

where $i = 1, 2, \ldots, m$.

Step 8: Evaluate the integrated measure of the WASPAS for each option as follows:

$$s_i = \lambda s_i^{(1)} + (1 - \lambda) s_i^{(2)}, \text{ where } i = 1, 2, \ldots, m. \tag{11}$$

wherein 'λ' signifies the coefficient of decision mechanism, where $\lambda \in [0, 1]$ (when $\lambda = 0$ and $\lambda = 1$, the WASPAS is altered into the WPM and the WSM, respectively).

Step 9: According to the values of s_i, where $i = 1, 2, \ldots, m$, rank the given alternatives.

Step 10: End.

4. Case Study: Biofuel Production Plant (BPP) Location Selection

For this case study, we selected Ahmedabad, the largest city in the state of Gujarat. Ahmedabad is a lively business city and rising center of the education, information technology and manufacturing sectors. To show the performance of the present hybrid methodology, we implement it on a case study of BPP location selection problem in Ahmedabad, Gujarat. An Indian company wants to establish a new BPP in Ahmedabad but it does not have any proper procedure for establishment. In this study, we focus on the development of a new robust approach for BPP construction companies which will assist the DMEs to evaluate the most suitable location for BPP.

To select the most suitable BPP, a panel of four DMEs has been created who have more than 10 years' experience in the field of sustainability and ecological planning. After preliminary analysis, this team has considered five prospective locations, which are location 1 (P_1), location 2 (P_2), location 3 (P_3), location 4 (P_4), and location 5 (P_5). The key idea of the study is to firstly identify the indicators/criteria for locating BPP. Thirteen criteria are considered and described in Table 1.

Table 1. Considered criteria for BPP location selection.

Dimension	Criteria	Type
Social	Job creation (Q_1)	Positive
	Training employees (Q_2)	Positive
	Social effects (Q_3)	Positive
Environmental	Land use (Q_4)	Negative
	Energy consumption (Q_5)	Negative
	Relative Humidity (Q_6)	Negative
	Waste generation per capita (Q_7)	Negative
	Flood susceptibility (Q_8)	Negative
	Distance from historic tourist places (Q_9)	Positive
Economic	Land price (Q_{10})	Negative
	Pollution (Q_{11})	Negative
	Transportation cost (Q_{12})	Negative
	Operations and maintenance cost (Q_{13})	Negative

Steps 1–3: Table 2 (adopted from [37]) depicts the importance of the DMEs and criteria in the form of LVs and then converted into PiFNs. Table 3 presents the DMEs' weights with the score degree-based model using Table 2 and Equation (5). Table 4 describes the importance of DMEs as LDM to evaluate the BPP location options concerning each criterion. The LDM offered by four DMEs have been combined utilizing Equation (6) into an A-PiFDM $\mathbb{Z} = (z_{ij})_{m \times n}$, considering the significance ratings of DMEs, which are provided in Table 5.

Table 2. Linguistic ratings for weighting the DMEs, BPP locations [61].

LVs	PiFNs
Very good (VG)	(0.90, 0.05, 0.05)
Good (G)	(0.75, 0.05, 0.10)
Moderately good (MG)	(0.60, 0.05, 0.30)
Fair (F)	(0.50, 0.10, 0.40)
Moderately poor (MP)	(0.30, 0.05, 0.60)
Poor (P)	(0.20, 0.05, 0.70)
Very poor (VP)	(0.10, 0.05, 0.80)

Table 3. Weights of DMEs for evaluation of the BPP locations.

DMEs	LVs	PiFNs	Weights
d_1	Good (G)	(0.75, 0.05, 0.10)	0.256
d_2	Very good (VG)	(0.90, 0.05, 0.05)	0.288
d_3	Moderately good (MG)	(0.60, 0.05, 0.30)	0.200
d_4	Good (G)	(0.75, 0.05, 0.10)	0.256

Table 4. LDM created by DMEs for BPP location selection.

Criteria	P_1	P_2	P_3	P_4	P_5
Q_1	(G,VG,F,G)	(F,G,G,F)	(G,MG,F,MG)	(MG,MP,G,G)	(VG,MG,F,F)
Q_2	(MP,F,F,VG)	(MG,G,G,VG)	(F,F,G,G)	(MP,G,G,VG)	(MG,G,F,G)
Q_3	(MG,G,G,G)	(MP,G,VG,VG)	(F,G,F,F)	(F,G,MG,MG)	(MP,VG,VG,VG)
Q_4	(MP,P,MG,P)	(P,MP,F,MP)	(MP,MP,MG,P)	(F,MP,P,VP)	(P,MP,VP,F)
Q_5	(MG,MP,P,F)	(F,P,P,MP)	(MG,MP,F,P)	(MP,F,VP,P)	(VP,P,P,F)
Q_6	(F,MP,F,MP)	(F,VP,MP,F)	(MP,P,P,MP)	(F,P,MP,MP)	(F,F,MP,P)
Q_7	(MP,F,VP,P)	(P,MP,P,F)	(MP,MP,MP,F)	(F,F,MP,P)	(VP,VP,P,F)
Q_8	(MP,VP,VP,F)	(P,P,F,MP)	(P,F,MP,VP)	(MP,MG,P,MG)	(F,P,VP,MP)
Q_9	(G,MG,VG,F)	(F,VG,G,MG)	(MG,MG,G,MG)	(MP,G,MG,VG)	(VG,G,G,MG)
Q_{10}	(MP,VP,P,MP)	(P,MP,P,P)	(MP,MP,P,P)	(MP,P,MP,VP)	(VP,P,VP,F)
Q_{11}	(MP,P,P,P)	(MG,MP,P,MP)	(P,F,F,MP)	(F,F,MP,P)	(MG,F,P,P)
Q_{12}	(P,P,P,MP)	(VP,MP,MP,F)	(P,VP,P,MP)	(VP,MP,MG,P)	(P,F,MP,F)
Q_{13}	(MP,F,P,VP)	(P,MP,F,MP)	(F,MP,P,P)	(MG,P,F,VP)	(F,P,VP,MP)

Table 5. A-PiFDM for BPP location selection.

Criteria	P_1	P_2	P_3	P_4	P_5
Q_1	(0.773, 0.057, 0.115)	(0.643, 0.071, 0.207)	(0.629, 0.057, 0.245)	(0.621, 0.050, 0.234)	(0.689, 0.069, 0.230)
Q_2	(0.639, 0.070, 0.284)	(0.777, 0.050, 0.118)	(0.635, 0.073, 0.216)	(0.743, 0.050, 0.147)	(0.676, 0.057, 0.256)
Q_3	(0.718, 0.050, 0.136)	(0.786, 0.050, 0.131)	(0.590, 0.082, 0.272)	(0.630, 0.060, 0.241)	(0.835, 0.050, 0.111)
Q_4	(0.327, 0.050, 0.571)	(0.323, 0.057, 0.582)	(0.352, 0.050, 0.546)	(0.297, 0.060, 0.610)	(0.301, 0.060, 0.605)
Q_5	(0.428, 0.060, 0.474)	(0.315, 0.060, 0.592)	(0.413, 0.057, 0.489)	(0.309, 0.061, 0.599)	(0.269, 0.060, 0.638)
Q_6	(0.400, 0.069, 0.508)	(0.367, 0.071, 0.543)	(0.253, 0.050, 0.647)	(0.333, 0.060, 0.574)	(0.397, 0.073, 0.512)
Q_7	(0.309, 0.061, 0.599)	(0.317, 0.060, 0.589)	(0.358, 0.060, 0.548)	(0.397, 0.073, 0.512)	(0.244, 0.060, 0.664)
Q_8	(0.274, 0.060, 0.633)	(0.296, 0.057, 0.609)	(0.299, 0.061, 0.628)	(0.470, 0.050, 0.428)	(0.298, 0.060, 0.609)
Q_9	(0.715, 0.060, 0.181)	(0.741, 0.060, 0.166)	(0.636, 0.050, 0.245)	(0.717, 0.050, 0.183)	(0.777, 0.050, 0.166)
Q_{10}	(0.227, 0.050, 0.673)	(0.230, 0.050, 0.670)	(0.256, 0.050, 0.644)	(0.224, 0.050, 0.675)	(0.252, 0.060, 0.656)
Q_{11}	(0.227, 0.050, 0.673)	(0.377, 0.050, 0.521)	(0.385, 0.070, 0.523)	(0.397, 0.073, 0.512)	(0.415, 0.061, 0.488)
Q_{12}	(0.227, 0.050, 0.673)	(0.315, 0.060, 0.591)	(0.200, 0.050, 0.700)	(0.309, 0.050, 0.588)	(0.397, 0.073, 0.512)
Q_{13}	(0.304, 0.061, 0.603)	(0.334, 0.057, 0.582)	(0.317, 0.060, 0.589)	(0.372, 0.057, 0.530)	(0.298, 0.060, 0.609)

Step 4: From the proposed PiF similarity measure-based model, we find the weights of the criteria by using Equation (8), which are given as follows (see Figure 1):

$$w_j = (0.0783,\ 0.0983,\ 0.1241,\ 0.0376,\ 0.0953,\ 0.0833,\ 0.0819,\ 0.0907,\ 0.0577,\ 0.0215,\ 0.0913,\ 0.0988,\ 0.0412).$$

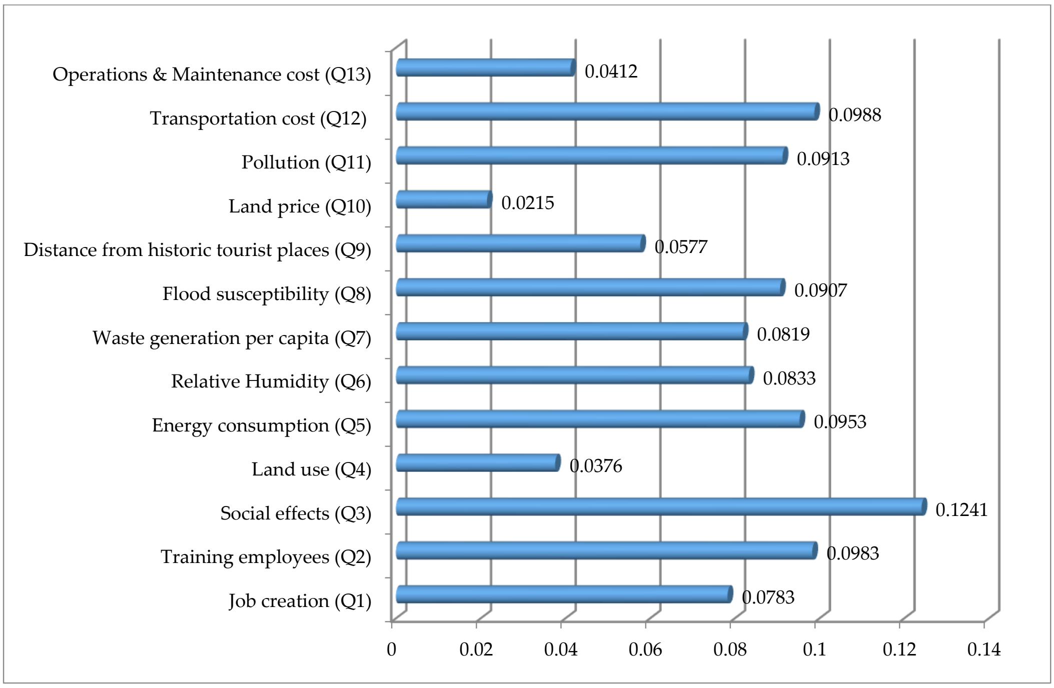

Figure 1. Significance values/weight of criteria for BPP location selection.

Here, Figure 1 presents the weights of the different indicators/criteria for locating BPP with respect to some goals. Social effects (Q_3) with a weight value of 0.1241 have turned out to be the most important criterion for locating BPP. Transportation cost (Q_{12}) with a weight value of 0.0988 is the second most important criterion for locating BPP. Training employees (Q_2) ranks third, with a significance value of 0.0983; energy consumption (Q_5) ranks fourth, with a significance value of 0.0953; and pollution (Q_{11}), with a significance value of 0.0913,ranks as the fifth most important criterion for locating BPP; others are considered crucial criteria for BPP location selection.

Step 5: Since the criteria Q_1,Q_2, Q_3 and Q_9 are of benefit types and the others are non-cost types, using Equation (8) and Table 5, the normalized A-PiFDM $\mathbb{N} = \left(\varepsilon_{ij}\right)_{m \times n}$ is presented in Table 6.

Table 6. Normalized A-PiFDM for BPP location selection.

Criteria	P_1	P_2	P_3	P_4	P_5
Q_1	(0.773, 0.057, 0.115)	(0.643, 0.071, 0.207)	(0.629, 0.057, 0.245)	(0.621, 0.050, 0.234)	(0.689, 0.069, 0.230)
Q_2	(0.639, 0.070, 0.284)	(0.777, 0.050, 0.118)	(0.635, 0.073, 0.216)	(0.743, 0.050, 0.147)	(0.676, 0.057, 0.256)
Q_3	(0.718, 0.050, 0.136)	(0.786, 0.050, 0.131)	(0.590, 0.082, 0.272)	(0.630, 0.060, 0.241)	(0.835, 0.050, 0.111)
Q_4	(0.571, 0.050, 0.327)	(0.582, 0.057, 0.323)	(0.546, 0.050, 0.352)	(0.610, 0.060, 0.297)	(0.605, 0.060, 0.301)
Q_5	(0.474, 0.060, 0.428)	(0.592, 0.060, 0.315)	(0.489, 0.057, 0.413)	(0.599, 0.061, 0.309)	(0.638, 0.060, 0.269)
Q_6	(0.508, 0.069, 0.400)	(0.543, 0.071, 0.367)	(0.647, 0.050, 0.253)	(0.574, 0.060, 0.333)	(0.512, 0.073, 0.397)
Q_7	(0.599, 0.061, 0.309)	(0.589, 0.060, 0.317)	(0.548, 0.060, 0.358)	(0.512, 0.073, 0.397)	(0.664, 0.060, 0.244)
Q_8	(0.633, 0.060, 0.274)	(0.609, 0.057, 0.296)	(0.628, 0.061, 0.299)	(0.428, 0.050, 0.470)	(0.609, 0.060, 0.298)
Q_9	(0.715, 0.060, 0.181)	(0.741, 0.060, 0.166)	(0.636, 0.050, 0.245)	(0.717, 0.050, 0.183)	(0.777, 0.050, 0.166)
Q_{10}	(0.673, 0.050, 0.227)	(0.670, 0.050, 0.230)	(0.644, 0.050, 0.256)	(0.675, 0.050, 0.224)	(0.656, 0.060, 0.252)
Q_{11}	(0.673, 0.050, 0.227)	(0.521, 0.050, 0.377)	(0.523, 0.070, 0.385)	(0.512, 0.073, 0.397)	(0.488, 0.061, 0.415)
Q_{12}	(0.673, 0.050, 0.227)	(0.591, 0.060, 0.315)	(0.700, 0.050, 0.200)	(0.588, 0.050, 0.309)	(0.512, 0.073, 0.397)
Q_{13}	(0.603, 0.061, 0.304)	(0.582, 0.057, 0.334)	(0.589, 0.060, 0.317)	(0.530, 0.057, 0.372)	(0.609, 0.060, 0.298)

Steps 6–9: Using Table 6 and Equations (9) and (10), the measures of WSM $\left(s_i^{(1)}\right)$ and WPM $\left(s_i^{(2)}\right)$ are evaluated. Subsequently, in accordance with Equation (11), the utility degree (s_i) (at $\lambda = 0.5$) is computed and shown in Table 7. From Table 7, the prioritization order of BPP locations is $P_2 \succ P_1 \succ P_5 \succ P_3 \succ P_4$; therefore, P_2 is the most desirable location for BPP location selection.

Table 7. Utility degree of each option using the PiF-WASPAS method.

Locations	$s_i^{(1)}$	$\mathbb{S}(s_i^{(1)})$	$s_i^{(2)}$	$\mathbb{S}(s_i^{(2)})$	s_i	Ranking Order
P_1	(0.646, 0.057, 0.246)	0.671	(0.632, 0.057, 0.268)	0.653	0.6624	2
P_2	(0.652, 0.058, 0.248)	0.673	(0.634, 0.058, 0.269)	0.654	0.6634	1
P_3	(0.604, 0.061, 0.286)	0.629	(0.598, 0.061, 0.295)	0.621	0.6248	4
P_4	(0.600, 0.057, 0.290)	0.626	(0.586, 0.057, 0.310)	0.610	0.6180	5
P_5	(0.658, 0.060, 0.262)	0.668	(0.632, 0.060, 0.284)	0.644	0.6556	3

5. Discussion

This section firstly discusses the effect of the parameters on the obtained outcomes and further discusses the comparative study based on the proposed and existing approaches under a PiFS context.

5.1. Sensitivity Analysis

Here, different values of $\lambda \in [0, 1]$ are considered for investigation. This assessment is performed to illustrate the performance of the present WASPAS methodology. The variation of λ values can assist us in discussing the sensitivity of the introduced methodology from WSM to WPM. From Table 8 and Figure 2, the rank of locations over different criteria for BPP location selection is presented from different parameter $\lambda \in [0, 1]$ values. Hence, it is established that the desirable location for BPP location selection is dependent on and sensitive to criteria weights. According to Figure 2, location (P_2) has obtained the first rank for each parameter λ value, location (P_4) has obtained the last rank for BPP location selection. Based on the aforementioned study, it is observed that using the diverse values of the parameters will enhance the permanence of the PiF-WASPAS methodology.

Table 8. The utility degree of option over different parameter (λ) values.

Locations	λ = 0.0	λ = 0.1	λ = 0.2	λ = 0.3	λ = 0.4	λ = 0.5	λ = 0.6	λ = 0.7	λ = 0.8	λ = 0.9	λ = 1.0
P_1	0.6534	0.6552	0.6570	0.6588	0.6606	0.6624	0.6642	0.6659	0.6677	0.6695	0.6713
P_2	0.6536	0.6555	0.6575	0.6595	0.6614	0.6634	0.6654	0.6673	0.6693	0.6712	0.6732
P_3	0.6209	0.6217	0.6224	0.6232	0.6240	0.6248	0.6255	0.6263	0.6271	0.6278	0.6286
P_4	0.6095	0.6112	0.6129	0.6146	0.6163	0.6180	0.6196	0.6213	0.6230	0.6247	0.6264
P_5	0.6436	0.6460	0.6484	0.6508	0.6532	0.6556	0.6580	0.6604	0.6628	0.6653	0.6677

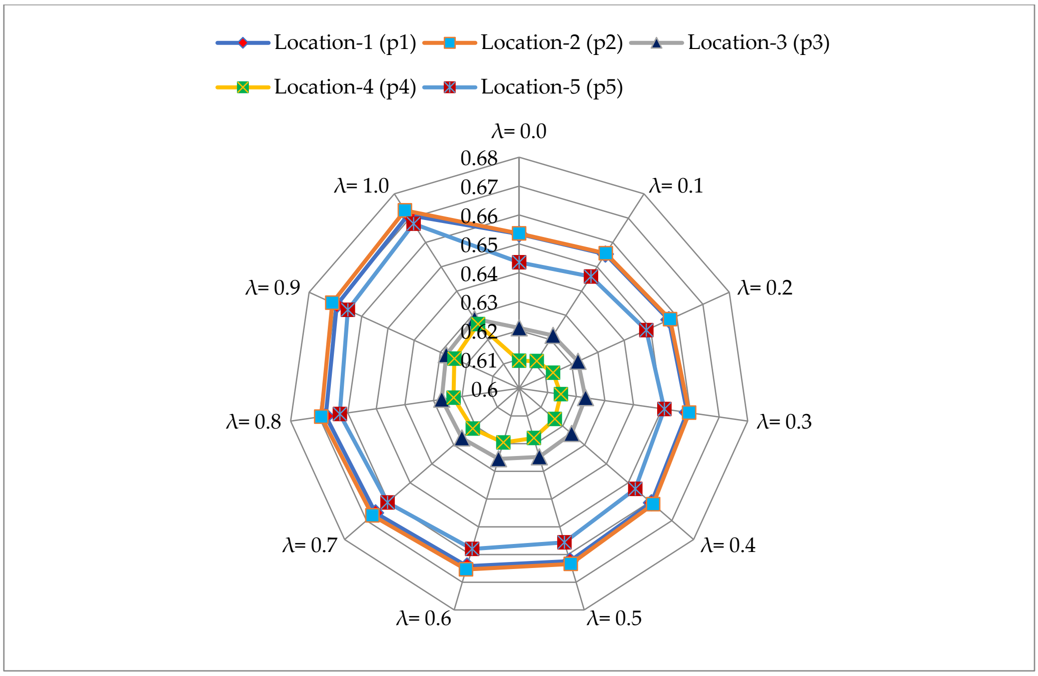

Figure 2. Sensitivity analysis test on decision parameter λ values for each option.

5.2. Comparative Study

Here, a comparative study is conducted to show the effectiveness of the obtained outcomes over the existing picture fuzzy information-based MCDM approaches. For this purpose, we compare the proposed method with some of the existing methods, including the PiF-COPRAS method [62], the PiF-VIKOR method [63] and the ranking method [64].

5.2.1. PiF-COPRAS [62]

This method involves the following steps:

Steps 1–4: Similar to proposed model.

Step 5: Sum of the ratings for benefit and cost types criteria.

Let $\beta_i^{(1)}$ and $\beta_i^{(2)}$ be the aggregated ratings of each option with benefit and cost types of criteria, respectively. Then, we utilized Equations (12) and (13) to evaluate the values of $\beta_i^{(1)}$ and $\beta_i^{(2)}$.

$$\beta_i^{(1)} = \sum_{j \in \text{benefit}} w_j \alpha_{ij}, \quad i = 1, 2, \ldots, m, \tag{12}$$

$$\beta_i^{(2)} = \sum_{j \in \cos t} w_j \alpha_{ij}, \; i = 1, 2, \ldots, m. \tag{13}$$

Step 6: The relative degree (RD) of each option is determined as

$$\gamma_i = \vartheta \, \mathbb{S}\left(\beta_i^{(1)}\right) + (1 - \vartheta) \frac{\sum_{i=1}^{m} \mathbb{S}\left(\beta_i^{(2)}\right)}{\mathbb{S}\left(\beta_i^{(2)}\right) \sum_{i=1}^{m} \frac{1}{\mathbb{S}\left(\beta_i^{(2)}\right)}}, \; i = 1, 2, \ldots, m. \tag{14}$$

Step 7: The utility degree (UD) of each option is computed as

$$\delta_i = \frac{\gamma_i}{\gamma_{\max}} \times 100\,\%, \; i = 1, 2, \ldots, m. \tag{15}$$

The PiF-COPRAS method is implemented on the same case study of BPP location selection problem. The overall results of PiF-COPRAS are shown in Table 9. From Table 5 and Equations (12)–(15), the RD and UD of each option are obtained. Based on the UD (see Table 9), option (P_2) is found to be the most suitable choice with maximum RD (0.4122) for prioritizing the BPP location.

Table 9. The results of PiF-COPRAS model for BPP location.

Options	$\beta_i^{(1)}$	$\mathbb{S}(\beta_i^{(1)})$	$\beta_i^{(2)}$	$\mathbb{S}(\beta_i^{(2)})$	γ_i	δ_i	Ranking
P_1	(0.360, 0.409, 0.256)	0.348	(0.447, 0.159, 0.356)	0.466	0.3859	93.62	4
P_2	(0.392, 0.400, 0.235)	0.378	(0.427, 0.162, 0.379)	0.443	0.4122	100.00	1
P_3	(0.292, 0.442, 0.315)	0.267	(0.440, 0.159, 0.366)	0.458	0.3496	84.81	5
P_4	(0.333, 0.415, 0.299)	0.309	(0.400, 0.164, 0.404)	0.416	0.3922	95.13	3
P_5	(0.401, 0.392, 0.261)	0.374	(0.429, 0.170, 0.374)	0.442	0.4104	99.55	2

5.2.2. PiF-VIKOR [63]

Steps 1–4: Same as previous model.

Step 5: The ideal and anti-ideal solutions are determined under a PiFS context.

Step 6: In accordance with the proposed projection measure and A-PiFDM, we compute the group utility (GU) (g_i) and the individual regret (IR) (r_i) over each option P_i, which are given by

$$g_i = \sum_{j=1}^{n} w_j \left(\frac{1 - PFNP(\phi^+, z_{ij})}{1 - PFNP(\phi^+, \phi^-)} \right), i = 1, 2, \ldots, m, \tag{16}$$

$$r_i = \max_{1 \le j \le n} w_j \left(\frac{1 - PFNP(\phi^+, z_{ij})}{1 - PFNP(\phi^+, \phi^-)} \right), i = 1, 2, \ldots, m, \tag{17}$$

where $PFNP(\phi^+, z_{ij}) = PFNP_A(z_{ij}) = \frac{P_{\phi^+}(z_{ij})}{P_{\phi^+}(z_{ij}) + \left|1 - P_{\phi^+}(z_{ij})\right|}$, such that $P_{\phi^+}(z_{ij}) = \mathrm{Proj}_{\phi^+}(z_{ij}) / |\phi^+|$. Similarly, we can compute $PFNP(\phi^+, \phi^-)$ [63].

The compromise score (CS) (e_i) for each option is computed as

$$e_i = \tau \frac{(g_i - g^+)}{(g^- - g^+)} + (1 - \tau) \frac{(r_i - r^+)}{(r^- - r^+)}, \tag{18}$$

Step 7: Prioritize the candidates.

Corresponding to the values of GU, IR and CS, determine the ranking order of the given options.

Step 8: Determination of the compromise solution.

Consider the candidate P_i as a CS in accordance with e_1 (the least among e_i values) if:

(R_1): The option P_i has an acceptable improvement, i.e., $e_2 - e_1 \geq \frac{1}{(m-1)}$, wherein m determines the number of alternatives.

(R_2): The alternative P_i is stable in the process of decision making, i.e., it is also best ranked by g_i or r_i.

If anyone of the conditions is not held, then a group of CSs is proposed, which consists of:

(a) Alternatives P_1 and P_2 if only the condition (R_2) is not held.
(b) Alternatives P_1, P_2, P_3, ..., P_k if (R_1) is not satisfied; and P_k is evaluated by the expression $e_k - e_1 < \frac{1}{(m-1)}$.

We implement the PiF-VIKOR approach on the aforementioned case study of BPP location selection problem. Therefore, the best and worst values of the BPP locations are computed as {(0.773, 0.057, 0.115), (0.777, 0.050, 0.118), (0.835, 0.050, 0.111), (0.297, 0.060, 0.610), (0.269, 0.060, 0.638), (0.253, 0.050, 0.647), (0.244, 0.060, 0.664), (0.274, 0.060, 0.633), (0.777, 0.050, 0.166), (0.224, 0.050, 0.675), (0.227, 0.050, 0.673), (0.200, 0.050, 0.700), (0.298, 0.060, 0.609)} and {(0.629, 0.057, 0.245), (0.639, 0.070, 0.284), (0.590, 0.082, 0.272), (0.352, 0.050, 0.546), (0.428, 0.060, 0.474), (0.400, 0.069, 0.508), (0.397, 0.073, 0.512), (0.470, 0.050, 0.428), (0.636, 0.050, 0.245), (0.256, 0.050, 0.644), (0.415, 0.061, 0.488), (0.397, 0.073, 0.512), (0.372, 0.057, 0.530)} (Wang et al., 2018).

Using Equations (15)–(17), the values of g_i, r_i and $e_i$based on the projection measure are derived and shown in Table 10. In accordance with these obtained values, the prioritization order of BPP location selection is determined (see Table 10). Minimum value of e_i determines the best BPP location, i.e., P_3.

Table 10. The values of g_i, r_i and e_i for the evaluation of BPP location.

Locations	g_i	r_i	e_i
P_1	1.411	0.319	0.6388
P_2	1.571	0.371	0.8546
P_3	1.091	0.141	0.0000
P_4	1.280	0.248	0.3830
P_5	1.493	0.422	0.9677
Ranking order	$P_3 \succ P_4 \succ P_1 \succ P_5 \succ P_2$	$P_3 \succ P_4 \succ P_1 \succ P_2 \succ P_5$	$P_3 \succ P_4 \succ P_1 \succ P_2 \succ P_5$

5.2.3. Ranking Method [64]

Steps 1–5: Same as previous model

Step 6: Estimate the collective value of each alternative using Equation (9).

Step 7: Find the score values of overall aggregated values.

Step 8: As per the decreasing score values, prioritize the options.

We apply the Garg's method on the aforementioned BPP location selection problem. In this regard, we obtain the collective values as c_1 = (0.646, 0.057, 0.243), c_2 = (0.652, 0.058, 0.244), c_3 = (0.604, 0.061, 0.284), c_4 = (0.600, 0.057, 0.288) and c_5 = (0.658, 0.060, 0.260).

Step 9: The score values of the aggregated values $c_i(i = 1, 2, 3, 4, 5)$ are $\mathbb{S}(c_1) = 0.6728$, $\mathbb{S}(c_2) = 0.6749$, $\mathbb{S}(c_3) = 0.6295$, $\mathbb{S}(c_4) = 0.6274$ and $\mathbb{S}(c_5) = 0.6689$.

Step 10: Since $\mathbb{S}(c_2) > \mathbb{S}(c_1) > \mathbb{S}(c_5) > \mathbb{S}(c_3) > \mathbb{S}(c_4)$, we have $P_2 \succ P_1 \succ P_5 \succ P_3 \succ P_4$. Hence, the best location for BPP is P_2.

From Table 11, it can easily be determined that option P_2 has the best significance value in all the methods except in the PiF-VIKOR [63] model. In comparison with the existing procedures, the main advantages of the introduced PiF-WASPAS methodology are as follows (see Figure 3):

- In PiF-COPRAS [62] and Garg's method [64], the overall compromise/collective scores are obtained with the use of picture fuzzy weighted averaging operators. In PiF-VIKOR [62], the compromise score is estimated based on the projection measure. The proposed PiF-WASPAS is a novel, robust, utility-based method. This approach is an integration of WPM and WSM. The precision of this approach is stronger than that of WPM and WSM. WASPAS enables the attainment of the maximum precision of assessment, utilizing the introduced methodology for optimizing the weighted AOs.
- For the PiF-COPRAS method [62], the decision expert's weight is assumed and PiF-VIKOR [63] and Garg's method [64] do not consider the decision expert's weight. In the present method, each decision expert is assigned equal weight value. In addition, the computation process of the PiF-WASPAS method is simpler, and therefore, the accuracy and reliability of the results are higher.
- In PiF-COPRAS [62], the CRITIC tool is applied to find only the objective weight of the criteria. In Garg's method [64], the weight of a criterion is randomly chosen. In the PiF-VIKOR approach [63], the entropy-based model is used to evaluate the objective weight of criteria. In the developed methodology, a procedure based on the similarity measure is applied to compute the objective weight of criteria owing to its simplicity and smaller number of calculation steps, which proves that the proposed method is more flexible, efficient, and sensible.

Table 11. Comparison of the parameters with the existing methodologies.

Parameters	Lu et al. [62]	Wang et al. [63]	Garg [64]	Proposed Model
Benchmark	COPRAS model	VIKOR model	Aggregation operator-based model	WASPAS model
MCDM model	Compromise model	Compromise model	Scoring degree model	Compromise model
Alternatives/criteria Assessments	PiFSs	PiFSs	PiFSs	PiFSs
Criteria weight	Objective weight by PiF-CRITIC	Objective weight by entropy-based method	Assumed	Objective weight by similarity measure-based method
DMEs' weights	Assumed	Not considered	Not considered	Score degree-based model
Decision-making process	Group	Single	Single	Group
Ranking order	$P_2 \succ P_5 \succ P_4 \succ P_1 \succ P_3$	$P_3 \succ P_4 \succ P_1 \succ P_2 \succ P_5$	$P_2 \succ P_1 \succ P_5 \succ P_3 \succ P_4$	$P_2 \succ P_1 \succ P_5 \succ P_3 \succ P_4$
Optimal option	P_2	P_3	P_2	P_2

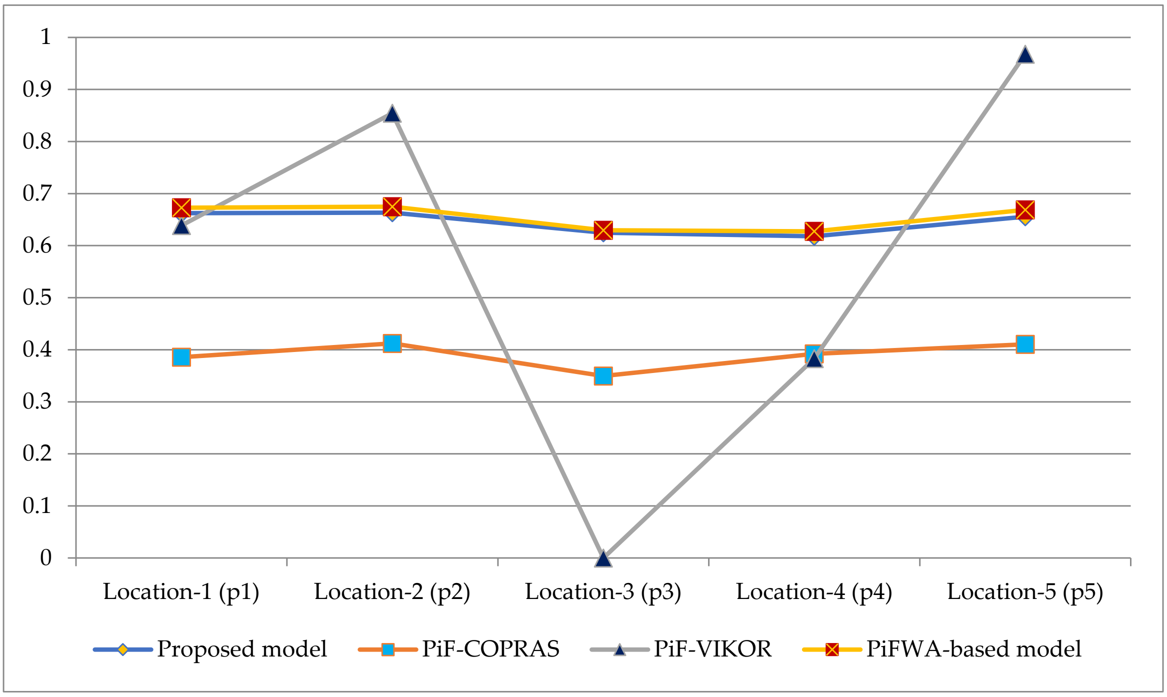

Figure 3. Comparison of degree of utility/closeness index of each manufacturing firm with various methods.

However, the method proposed in this study has some limitations:

- This method ignores the subjective and objective weights of criteria.
- In this method, we consider only benefit and cost types of criteria and ignore the target-based criteria.

6. Conclusions

In this paper, we presented a hybrid decision making framework for evaluating and prioritizing the BPP location from the uncertainty and sustainability perspectives. In this regard, first, a new similarity measure has been introduced for PiFSs. Next, we have incorporated the WASPAS approach with PiFSM and a score degree-based model within the environment of PiFSs. The criteria weights have been derived through the PiFSM-based weighting formula. Further, the proposed method has been implemented on a case study of BPP locations' assessment, which shows the applicability and effectiveness of the presented decision-making framework. The criteria evaluation index for BPP location selection is presented, which contains three aspects of sustainability, namely social, environmental and economic (Figure 4). These three dimensions consist of three, six and four criteria, respectively, and the weights of all criteria are derived using the proposed weighting model. The calculation result shows that the alternative 'location (P_2)' is the most suitable choice for a given case study based on available data. Further, sensitivity and comparative analyses have been discussed to confirm the results acquired by the proposed PiF-WASPAS model. The presented method incorporates the benefits of the picture fuzzy numbers and the WASPAS technique. In this study, the picture fuzzy numbers can express uncertain and incomplete information that inherently exists in the BPP location section decision-making problem, while WASPAS offers formulation flexibility and simple calculations. The main benefits of the presented framework are the ease of computation in the picture fuzzy background and utilizing a model for deriving more reasonable weights of indicators.

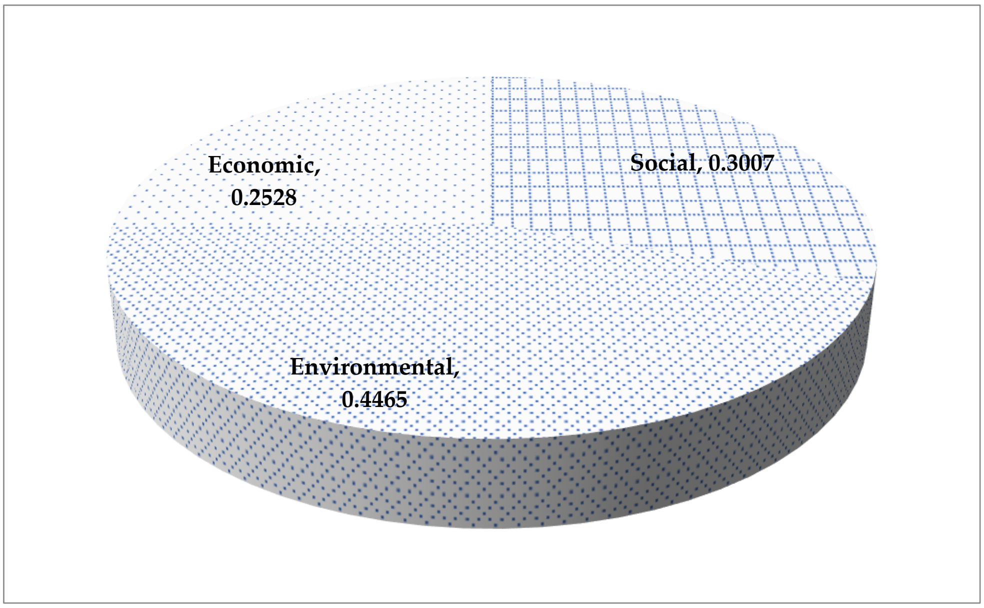

Figure 4. Depiction of the significance degrees of different aspects of sustainability.

In the future, it would be exciting to improve the limitations of the present study by proposing some new methods, such as operational competitiveness rating (OCRA), double normalization-based multiple aggregation (DNMA), gained lost dominance score (GLDS), etc. In addition, this study can be extended to q-rung orthopair rough fuzzy sets, interval-valued picture fuzzy sets, and interval-valued q-rung orthopair rough fuzzy sets by developing new aggregation operators to aggregate the DMEs' opinions, and can be applied to alternative social baking systems, transportation management, plastic waste recycling technology selection, green energy projects' assessment and vertical farming technology evaluation.

Author Contributions: Methodology, P.R.; Validation, J.L.; Formal analysis, I.M.H., F.C. and P.R.; Investigation, J.L.; Writing—original draft, I.M.H.; Supervision, F.C. and S.G.; Project administration, S.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by Researchers Supporting Project number (RSP2023R389), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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