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A Multi-Criteria Decision Making Approach to Feedstock Selection

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Abstract

Selection of the appropriate feedstock for biodiesel production, taking into consideration several potentially conflicting quantitative and qualitative criteria, is a complex multiple-criteria decision making (MCDM) problem that requires an extensive evaluation process of a group of decision makers (DMs). In this paper, as the MCDM method, fuzzy Analytic Hierarchy Process (F-AHP) and fuzzy Technique for Order Preference by Similarity to Ideal Solution (F-TOPSIS) methods are integrated to evaluate plant based feedstock alternatives for biodiesel production in Turkey. The F-AHP method is used to determine the importance weights of criteria, and the F-TOPSIS method is implemented to evaluate and rank feedstock alternatives with respect to a set of qualitative and quantitative benefit criteria. More specifically, in this paper, plant based feedstocks in Turkey: Sunflower, peanut, cottonseed, canola, safflower, soybean, and poppy seed are evaluated and ranked by decision makers (DMs) with respect to several benefit criteria: Price adequacy, suitability of the plant to the climate and environment, benefits of the plant after processing (the sediment), suitability of the feedstock for technological processing, and yield efficiency, implementing the integrated fuzzy AHP-TOPSIS method.

Keywords: Multi-criteria decision making; fuzzy methods; biodiesel production; feedstock selection.

1. Introduction

Worldwide energy trend is changing from conventional, fossil-based fuel to alternative renewable, environmental friendly energy such as biodiesel. Biodiesel is mono alkyl esters of long chain fatty acids that can be produced from vegetable oils with transesterification with short chain alcohols.

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It is non-toxic, renewable, biodegradable, sulfur-free, environmental friendly and it has low fossil energy ratio (FER) and low exhaust emissions [19]. Various kinds of vegetable oils can be used as biodiesel feedstock. An extensive review with production technologies and characteristics of biodiesel produced with soybean, rapeseed, mustard, canola, sunflower, rice bran, jatropha, palm and karanja oils were given by Issariyakul and Dalai [19].

The feedstocks used for biodiesel production differs in different countries. In European countries, rapeseed oil; in USA soybean oil; in tropical countries, palm oil; and in coastal areas coconut oil are the most common vegetable oils used as lipid feedstock for biodiesel production [19]. Due to increasing energy demand in Turkey, significant research has been done about domestic, effective renewable energy resources and biodiesel is one of the most efficient ones based on the climate and the availability of wide agricultural areas in Turkey. The biodiesel production in Turkey was 17,729 ton in 2012 and 21,876 ton in 2013 [15]. Eryilmaz and his colleagues [15] studied the biodiesel production potential of Turkey from oil seeds and mentioned that approximately 3.31 million tons of oil seed crops are available in Turkey with a potential production of 1.12 million tons every year.

In this paper, plant based biodiesel feedstock alternatives in Turkey: Sunflower, peanut, cottonseed, canola, safflower, soybean, and poppy seed are evaluated and ranked based on a set of qualitative and quantitative criteria with an integrated F- AHP and F-TOPSIS method, namely, fuzzy AHP-TOPSIS method.

The Analytic Hierarchy Process (AHP) [32] is a hierarchical-structured MCDM method for evaluation of alternatives with respect to quantitative and qualitative criteria using pairwise comparisons. Its fuzzy extension, F-AHP has been developed to capture the uncertainty and vagueness in the evaluation process. F-AHP has been applied to various MCDM evaluation and ranking problems throughout the literature. Some of these problems are evaluation of: suppliers [21], managerial competence activities for the assessors of IC packaging industry [16], machine tool alternatives [4, 14], service quality of healthcare systems [8], city logistics initiatives [2], academic staff [31] and disassembly line task assignments [1].

TOPSIS method, that is developed by Hwang and Yoon [18], and improved by Yoon [42] and Hwang and his colleagues [17], is a MCDM method that is based on the idea that the best alternative should be closer to the positive ideal solution and further away from the negative ideal solution when compared to other alternatives. In F-TOPSIS, its fuzzy extension, linguistic preferences provided by DMs are converted to fuzzy numbers which are then used in calculations. F-TOPSIS has been used in various applications such as facility location selection [11, 43], bridge risk evaluation [40], evaluation of travel websites [20], selection of the energy technologies [7, 23], weapon selection [13], aircraft selection [36, 39] and evaluation of candidate materials for designing automotive components that are more remanufacturable [41].

F-AHP, integrated with F-TOPSIS has been applied to MCDM problems such as performance evaluation of companies [35], evaluation of hospital websites [9], ranking 3PLs [24], evaluation of trading partners for an automotive parts manufacturing company [28], evaluation of Regional Development Agencies (RDAs) projects [34], ranking university research assistant candidates [38], assessment of risks associated with implementation of green supply chain [27], and assessment of safety conditions at construction worksites [5]. In these MCDM problems, first criteria weights are determined with F-AHP and then ranking of the alternatives are obtained with F-TOPSIS utilizing the weights determined with F-AHP.

Previously in the literature, various MCDM methods have been used to evaluate biodiesel feedstock. Costa and his colleagues [12] used Data Envelopment Analysis (DEA) to evaluate the raw materials for biodiesel production in Brazil with respect to investment cost, operation and maintenance, green-house emissions, potential job creation and potential production, and determined that residues of frying oil and palm oil are the best sources. Ren and his colleagues [29] studied soybean, rapeseed, sunflower, jatropha and palm for biodiesel production in China using DEA and mentioned that soybean, sunflower, and palm are DEA efficient, however rapeseed and jatropha-based production need to be improved. Balezentiene, Streimikiene and Balezentis [6] employed fuzzy MULTIMOORA method to asses and prioritize energy crops. Zonin and his colleagues [44] evaluated soybean, canola, sunflower and castor with respect to economic, technological and social factors and presented a multi-criteria matrix for biodiesel production in Brazil. Based on their analysis, the main source of raw materials is determined to be soybean.

At present, there does not appear to be a research paper in the literature that focuses on the selection of biodiesel feedstock using F-AHP integrated with F-TOPSIS. In this paper, linguistic terms and fuzzy numbers are used to capture the uncertainty and vagueness on judgments of the DMs and F-AHP and F-TOPSIS are integrated to have both methods' advantages. In general, F-TOPSIS method is particularly useful when there are a large number of alternatives to rank since it does not impose any limits on the number of alternatives [26] and it provides stable results in many real life applications, however it does not include specific guidelines for assigning weights to criteria so a systematic MCDM method such as F-AHP is needed to determine the weights. On the other hand, pairwise comparisons in F-AHP can be burdensome for the DM(s) if there are many alternatives and criteria. With the proposed fuzzy AHP-TOPSIS integration, alternatives are ranked without too many repetitive pairwise comparisons and without complicated calculations. At this integration, first criteria weights are determined with F-AHP since with F-AHP, reliable weights can be determined through pairwise comparisons of quantitative and qualitative criteria and then F-TOPSIS is used to rank the alternatives, utilizing the weights determined with F-AHP. In this paper, biodiesel feedstock alternatives in Turkey are evaluated with respect to potentially competing benefit criteria: Price adequacy, suitability of the plant to the climate and environment, benefits of the plant after processing, suitability of the feedstock for technological processing, and yield efficiency. In the following sections, the details of the fuzzy AHP-TOPSIS method is presented along with a case study in Turkey.

2. Integrated Fuzzy AHP-TOPSIS Approach

In this research, triangular fuzzy numbers (TFNs) are used for fuzzy AHP-TOPSIS calculations. A fuzzy number is a special fuzzy set $\tilde{A}=\{(x,\mu_{\tilde{A}}(x)),x\in R\}$, where $R:-\infty<x<+\infty$ and membership function $\mu_{\tilde{A}}(x)$ is a continuous mapping from R to [0, 1]. A TFN $\tilde{n}=(l,m,u)\quad l\le m\le u$, has the triangular membership function (1):

$$\mu_{\tilde{n}}(x)=\begin{cases} 0, & x<l \\ \dfrac{x-l}{m-l}, & l\le x\le m \\ \dfrac{u-x}{u-m}, & m\le x\le u \\ 0, & x>u \end{cases}$$

(1)

The α -cut of fuzzy number $\tilde{n}$, α defining the interval of confidence, is defined as $\tilde{n}^{\alpha}=\{x_i : \mu_{\tilde{n}}(x_i)\ge \alpha, x_i\in X\}$, where $\alpha\in[0,1]$. Then, the TFN can be written as:

$$\forall\alpha\in[0,1],\quad \tilde{n}^{\alpha}=[n_l^{\alpha},n_u^{\alpha}]=[(m-l)\alpha+l,-(u-m)\alpha+u] \qquad (2)$$

$\tilde{n}$ is called a positive fuzzy number when $n_l^{\alpha}>0$ for $\alpha\in[0,1]$. $\tilde{n}$ is called a normalized positive TFN when $n_l^{\alpha}>0, n_u^{\alpha}\le 1$ for $\alpha\in[0,1]$. Given any two positive fuzzy numbers $\tilde{n}$ and $\tilde{p}$ and a positive real number t, the α -cut of two fuzzy numbers are $\tilde{p}^{\alpha}=[p_l^{\alpha},p_u^{\alpha}]$ and $\tilde{n}^{\alpha}=[n_l^{\alpha},n_u^{\alpha}]$ $\alpha\in[0,1]$, respectively. Some necessary operations (3)-(9) of $\tilde{p}$ and $\tilde{n}$ are given below [22]:

$$(\tilde{p}(+)\tilde{n})^{\alpha}=[p_l^{\alpha}+n_l^{\alpha},p_u^{\alpha}+n_u^{\alpha}], \qquad (3)$$

$$(\tilde{p}(-)\tilde{n})^{\alpha}=[p_l^{\alpha}-n_u^{\alpha},p_u^{\alpha}-n_l^{\alpha}], \qquad (4)$$

$$(\tilde{p}(.)\tilde{n})^{\alpha}=[p_l^{\alpha}.n_l^{\alpha},p_u^{\alpha}.n_u^{\alpha}], \qquad (5)$$

$$(\tilde{m}(/)\tilde{n})^{\alpha}=[m_l^{\alpha}/n_u^{\alpha},m_u^{\alpha}/n_l^{\alpha}],$$

(6)

$$(\tilde{p}(.)t)^{\alpha}=[m_l^{\alpha}.t,m_u^{\alpha}.t], \qquad (7)$$

$$(\tilde{p}(/)t)^{\alpha}=[p_l^{\alpha}/t,p_u^{\alpha}/t], \qquad (8)$$

$$(\tilde{m}^{\alpha})^{-1}=[1/m_u^{\alpha},1/m_l^{\alpha}], \qquad (9)$$

Let $\tilde{p}=(p_1, p_2, p_3)$ and $\tilde{n}=(n_1, n_2, n_3)$ be two TFNs, then the distance between these numbers can be calculated with the vertex method as:

$$d(\tilde{p},\tilde{n})=\sqrt{\frac{1}{3}\left[(p_1-n_1)^2+(p_2-n_2)^2+(p_3-n_3)^2\right]} \qquad (10)$$

In this paper, the importance weights of criteria and ratings of each alternative with respect to each criterion are first considered as linguistic terms which are then expressed as positive TFNS. As part of the integrated approach, first the weights of the criteria are calculated with F-AHP, and then the ranking of each alternative is determined with F-TOPSIS utilizing the weights obtained with F-AHP. Detailed explanations related to the integrated approach are given in the sections below.

2.1. Importance Weights of Evaluation Criteria with F-AHP

In order to capture the vagueness in DMs' judgements, due to its simplicity, TFNs ($\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$) are used to represent subjective pairwise comparisons of evaluation criteria in F-AHP. The scale used is given in Table 1. [3].

Table 1: Linguistic terms and triangular fuzzy numbers for the evaluation of criteria

Fuzzy number	Definition	Triangular fuzzy number
$\tilde{1}$	Equally important/preferred (EP)	(1, 1, 2)
$\tilde{3}$	Moderately more important/preferred (MP)	(2, 3, 4)
$\tilde{5}$	Strongly more important/preferred (SP)	(4, 5, 6)
$\tilde{7}$	Very strongly more important/preferred (VSP)	(6, 7, 8)
$\tilde{9}$	Extremely more important/preferred (ESP)	(8, 9, 10)

Steps of F-AHP are given as:

Step 1: Form a decision group of *R* people. Identify the criteria; and select the suitable linguistic terms for the comparison. Calculate the aggregated $\tilde{a}_{ij} = \frac{1}{R}\left(\tilde{a}_{ij}^{1}(+)\tilde{a}_{ij}^{2}(+)...(+)\tilde{a}_{ij}^{R}\right)$ where $\tilde{a}_{ij}^{R}$ is the evaluation of the R^{th} DM. By using TFNs ($\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$), via pair wise comparison, the fuzzy pairwise comparison matrix of evaluation criteria $\tilde{A}\left(a_{ij}\right)$ is constructed as given below.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & .. & .. & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & .. & .. & \tilde{a}_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \tilde{a}_{n1} & \tilde{a}_{n2} & .. & .. & 1 \end{bmatrix} \tag{11}$$

where, $\tilde{a}_{ij} = 1$, if *i* is equal *j*, and $\tilde{a}_{ij} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ or $\tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}$, if *i* is not equal to *j*.

Step 2: $\alpha - cut$ ($0 < \alpha \leq 1$) shows the DMs' confidence over preferences and index of optimism μ shows the degree of satisfaction. The large values of μ indicate the high degrees of optimism. The index of optimism is a

$$\tilde{a}_{ij}^{\alpha} = \mu a_{iju}^{\alpha} + (1-\mu) a_{ijl}^{\alpha}, \ \forall \mu \in [0,1] \tag{12}$$

linear convex combination shown as [25]:

Fixing α value, the $\tilde{A}$ matrix below can be obtained.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12}^{\alpha} & .. & .. & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & 1 & .. & .. & \tilde{a}_{2n}^{\alpha} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & .. & .. & 1 \end{bmatrix} \tag{13}$$

Step 3: By setting the μ value, the matrix A is obtained. A is normalized and the entries on each row is averaged to obtain the priority weight vector (normalized principal eigen vector) $w_{criteria} = (w_1 \ldots w_j \ldots w_n)$. The maximum eigen value (principal eigen value, $\lambda_{\max}$) is calculated as in Eq. (14).

$$A w_{criteria}^{T} = \lambda_{\max} w_{criteria}^{T} \tag{14}$$

Step 4: Afterwards, the consistency ratio (CR) of the pairwise comparison matrix is calculated. The measure of inconsistency is called the consistency index (CI) and it is calculated as:

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{15}$$

The CR is computed as:

$$CR = \frac{CI}{RI} \tag{16}$$

Random Consistency Index (RI) is the average index of a randomly generated matrix. If the CR is less than 0.10, the comparisons are acceptable. [32]

2.2. Ranking of Alternatives with F-TOPSIS

In the previous section, criteria weights $w_{criteria} = (w_1 \ldots w_j \ldots w_n)$ were obtained with F-AHP. After the determination of weights with F-AHP, in order to rank alternatives, F-TOPSIS is used. Steps of F-TOPSIS are given below. *Step 1:* A fuzzy multi-criteria problem with *m* alternatives that are evaluated in terms of *n* criteria can be expressed in a fuzzy matrix format as:

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ . & . & \cdots & . \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}$$

and where $\tilde{x}_{ij} \forall i, j$ are linguistic terms that are described by positive TFNs $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$. Here, to rate alternatives, the linguistic terms and corresponding TFNs that are listed in Table 2 are used. [10, 33]

Table 2: Linguistic terms and triangular fuzzy numbers for the ratings of alternatives

Definition	Triangular fuzzy number
Very poor (VP)	(0,0,1)
Poor (P)	(0,1,3)
Medium poor (MP)	(1,3,5)
Fair (F)	(3,5,7)
Medium good (MG)	(5,7,9)
Good (G)	(7,9,10)
Very good (VG)	(9,10,10)

With the decision group of *R* people, the aggregated $\tilde{x}_{ij} = \frac{1}{R}\left[\tilde{x}_{ij}^{1}(+)\tilde{x}_{ij}^{2}(+)...(+)\tilde{x}_{ij}^{R}\right]$ are calculated. Here, $\tilde{x}_{ij}^{R}$ is the evaluation of the R^{th} DM. The fuzzy decision matrix $\tilde{D}$ is constructed.

Step 2: $\tilde{D}$ is normalized and $\tilde{S}$ is obtained. Sets of benefit and cost criteria are *B* and *C*, respectively.

$\tilde{S} = \left[\tilde{s}_{ij}\right]_{mxn}$, and $\tilde{s}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B$; $\tilde{s}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C$; $c_j^* = \max_i c_{ij} \quad j \in B$, and $a_j^- = \min_i a_{ij} \quad j \in C$.

The weighted normalized fuzzy decision matrix $\tilde{V} = \left[\tilde{v}_{ij}\right]_{mxn}$ is constructed where $\tilde{v}_{ij} = \tilde{s}_{ij}(.)w_{criteria}$ are normalized positive TFNs in the interval [0, 1].

Step 3: The fuzzy positive-ideal solution $\left(A^*\right)$ and fuzzy negative-ideal solution $\left(A^-\right)$ are defined as $A^* = \left(\tilde{v}_1^*, \tilde{v}_2^*, ..., \tilde{v}_n^*\right)$, and $A^- = \left(\tilde{v}_1^-, \tilde{v}_2^-, ..., \tilde{v}_n^-\right)$, where $\tilde{v}_j^* = (1,1,1)$ and $\tilde{v}_j^- = (0,0,0)\ \forall j$. The distances of each alternative from A^* and A^- are calculated with the vertex method as $d_i^* = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^*\right) \forall i$, $d_i^- = \sum_{j=1}^{n} d\left(\tilde{v}_{ij}, \tilde{v}_j^-\right) \forall i$. The closeness coefficient of each alternative is determined as $CC_i = \frac{d_i^-}{d_i^- + d_i^*} \forall i$. The alternatives are ranked from best to worst based on CC_i. An alternative A_i is better if CC_i approaches to 1.

3. A Case Study in Turkey

Above, an integrated approach, fuzzy AHP-TOPSIS has been proposed to evaluate biodiesel feedstock alternatives. In this section, a case study in Turkey is presented to prove the method's applicability and validity, and to make this approach more understandable for the DM(s). A committee of three DMs (*R*=3), D1, D2, and D3 has been formed from an industrial practitioner (D1) and two field experts (D2 and D3). Alternative plant based feedstocks in Turkey which are determined by DMs are as follows: sunflower (A1), peanut (A2), cottonseed (A3), canola (A4), safflower (A5), soybean (A6), and poppy seed (A7). These alternatives are evaluated based on six benefit criteria that are determined by DMs: Price adequacy (C1), suitability of the plant to the climate (C2), suitability of the plant to the environment (C3), benefits of the plant after processing (C4), suitability of the plant for technological processing (C5), and yield efficiency (C6). The comparison matrix of criteria by 3 decision makers (D1, D2, D3) and corresponding fuzzy numbers are given in Tables 3 and 4.

Table 3: The comparison matrix of criteria by decision makers (D1, D2, D3)

Criteria	C1	C2	C3	C4	C5	C6
C1	1	(SP, SP, MP)	(ESP, VSP, ESP)	(MP,MP,MP)	(EP,MP,EP)	(EP,EP,EP)
C2		1	(EP,EP,MP)			
C3			1			
C4		(EP,MP,EP)	(MP,MP,MP)	1		
C5		(MP,MP,EP)	(SP,SP,SP)	(EP,EP,MP)	1	
C6		(MP,SP,MP)	(VSP,VSP, VSP)	(MP,MP,EP)	(EP,EP,EP)	1

Table 4: Fuzzy comparison matrix of the criteria for 3 decision makers ($\tilde{a}_{ij}^{1}, \tilde{a}_{ij}^{2}, \tilde{a}_{ij}^{3}$)

Criteria	C1	C2	C3	C4	C5	C6
C1	1	$(\tilde{5},\tilde{5},\tilde{3})$	$(\tilde{9},\tilde{7},\tilde{9})$	$(\tilde{3},\tilde{3},\tilde{3})$	$(\tilde{1},\tilde{3},\tilde{1})$	$(\tilde{1},\tilde{1},\tilde{1})$
C2	$(\tilde{5}^{-1},\tilde{5}^{-1},\tilde{3}^{-1})$	1	$(\tilde{1},\tilde{1},\tilde{3})$	$(\tilde{1}^{-1},\tilde{3}^{-1},\tilde{1}^{-1})$	$(\tilde{3}^{-1},\tilde{3}^{-1},\tilde{1}^{-1})$	$(\tilde{3}^{-1},\tilde{5}^{-1},\tilde{3}^{-1})$
C3	$(\tilde{9}^{-1},\tilde{7}^{-1},\tilde{9}^{-1})$	$(\tilde{1}^{-1},\tilde{1}^{-1},\tilde{3}^{-1})$	1	$(\tilde{3}^{-1},\tilde{3}^{-1},\tilde{3}^{-1})$	$(\tilde{5}^{-1},\tilde{5}^{-1},\tilde{5}^{-1})$	$(\tilde{7}^{-1},\tilde{7}^{-1},\tilde{7}^{-1})$
C4	$(\tilde{3}^{-1},\tilde{3}^{-1},\tilde{3}^{-1})$	$(\tilde{1},\tilde{3},\tilde{1})$	$(\tilde{3},\tilde{3},\tilde{3})$	1	$(\tilde{1}^{-1},\tilde{1}^{-1},\tilde{3}^{-1})$	$(\tilde{3}^{-1},\tilde{3}^{-1},\tilde{1}^{-1})$
C5	$(\tilde{1}^{-1},\tilde{3}^{-1},\tilde{1}^{-1})$	$(\tilde{3},\tilde{3},\tilde{1})$	$(\tilde{5},\tilde{5},\tilde{5})$	$(\tilde{1},\tilde{1},\tilde{3})$	1	$(\tilde{1}^{-1},\tilde{1}^{-1},\tilde{1}^{-1})$
C6	$(\tilde{1}^{-1},\tilde{1}^{-1},\tilde{1}^{-1})$	$(\tilde{3},\tilde{5},\tilde{3})$	$(\tilde{7},\tilde{7},\tilde{7})$	$(\tilde{3},\tilde{3},\tilde{1})$	$(\tilde{1},\tilde{1},\tilde{1})$	1

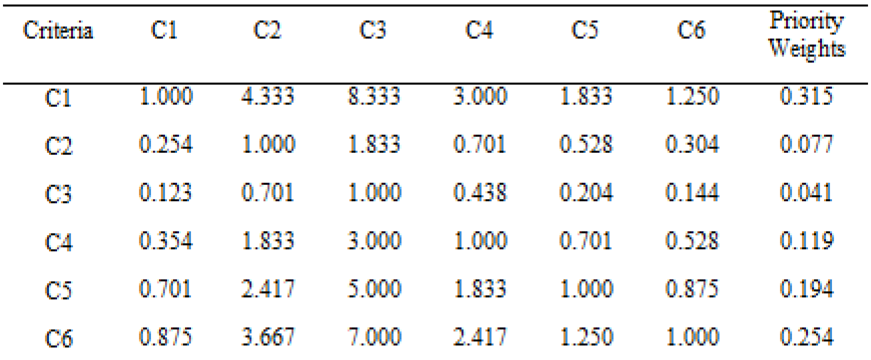
The aggregated $\tilde{a}_{ij} = \frac{1}{3}\left(\tilde{a}_{ij}^1 (+) \tilde{a}_{ij}^2 (+) \tilde{a}_{ij}^3\right)$ are calculated and substituting $\alpha = 0.5$ determined by the DMs at Eq. (2), the $\alpha - cuts$ fuzzy comparison matrix of the criteria is obtained as shown in Table 5.

Table 5: $\alpha - cuts$ fuzzy comparison matrix for the criteria for $\alpha = 0.5$

Criteria	C1	C2	C3	C4	C5	C6
C1	[1.000,1.000]	[3.833,4.833]	[7.833,8.833]	[2.500,3.500]	[1.500,2.167]	[1.000,1.500]
C2	[0.219,0.289]	[1.000,1.000]	[1.500,2.167]	[0.597,0.806]	[0.444,0.611]	[0.256,0.353]
C3	[0.115,0.130]	[0.597,0.806]	[1.000,1.000]	[0.417,0.458]	[0.183,0.225]	[0.134,0.155]
C4	[0.292,0.417]	[1.500,2.167]	[2.500,3.500]	[1.000,1.000]	[0.597,0.806]	[0.444,0.611]
C5	[0.597,0.806]	[2.000,2.833]	[4.500,5.500]	[1.500,2.167]	[1.000,1.000]	[0.750,1.000]
C6	[0.750,1.000]	[3.167,4.167]	[6.500,7.500]	[2.000,2.833]	[1.000,1.500]	[1.000,1.000]

Substituting $\mu = 0.5$ determined by the DMs at Eq. (12), the comparison matrix in Table 6 is obtained. Using this comparison matrix, the priority weights of criteria ($w_{criteria}$) are calculated, and after the calculation of the eigenvector, $\lambda_{\max}$ is calculated with Eq. (14). In Table 6, these values are given along with CI and CR values. The consistency ratio is calculated by using Eq. (15) and Eq. (16) as follows;

Table 6: The eigenvector for comparison matrix of the criteria



Criteria	C1	C2	C3	C4	C5	C6	Priority Weights
C1	1.000	4.333	8.333	3.000	1.833	1.250	0.315
C2	0.254	1.000	1.833	0.701	0.528	0.304	0.077
C3	0.123	0.701	1.000	0.438	0.204	0.144	0.041
C4	0.354	1.833	3.000	1.000	0.701	0.528	0.119
C5	0.701	2.417	5.000	1.833	1.000	0.875	0.194
C6	0.875	3.667	7.000	2.417	1.250	1.000	0.254

After determining $w_{criteria} = (0.315, 0.077, 0.041, 0.119, 0.194, 0.254)$, the overall scores of the alternatives for ranking are calculated by using F-TOPSIS. The DMs rate each alternative based on each criterion as seen in Table 7.

Converting the lingusitic terms to the corresponding TFNs, the fuzzy decision matrix ($\tilde{D}$) is obtained as shown in Table 8. Normalizing the fuzzy decision matrix $\tilde{D}$, the normalized fuzzy decision matrix $\tilde{S}$ in Table 9 is obtained. Here *B* and *C* are the sets of the benefit and cost criteria, respectively.

$\tilde{S}=\left[\tilde{s}_{ij}\right]_{mxn}$, and $\tilde{s}_{ij}=\left(\frac{a_{ij}}{c_j^*},\frac{b_{ij}}{c_j^*},\frac{c_{ij}}{c_j^*}\right),\ j\in B$; $\tilde{s}_{ij}=\left(\frac{a_j^-}{c_{ij}},\frac{a_j^-}{b_{ij}},\frac{a_j^-}{a_{ij}}\right),\ j\in C$; $c_j^*=\max_i c_{ij}\ \ j\in B$, and $a_j^-=\min_i a_{ij}\ \ j\in C$.

Table 7: The ratings of alternatives by decision makers (D1, D2, D3) with respect to criteria

Criteria	Alternatives	Decision-makers			Criteria	Alternatives	Decision-makers		
		D1	D2	D3			D1	D2	D3
C1	A1	VG	VG	VG	C4	A1	G	VG	VG
	A2	VG	MP	MG		A2	G	VG	VG
	A3	VG	MP	MG		A3	VG	VG	VG
	A4	MG	MP	F		A4	G	VG	F
	A5	VG	MP	G		A5	VG	VG	VG
	A6	MG	MP	F		A6	VG	VG	VG
	A7	MG	MP	MP		A7	G	VG	F
C2	A1	G	VG	VG	C5	A1	G	VG	MG
	A2	VG	MG	F		A2	G	G	MG
	A3	VG	G	VG		A3	G	VG	VG
	A4	VG	G	F		A4	VP	VP	VG
	A5	VG	VG	F		A5	G	P	MP
	A6	VG	VG	G		A6	G	VG	MG
	A7	P	MP	MP		A7	G	VG	MG
C3	A1	G	VG	VG	C6	A1	F	MP	F
	A2	G	MG	MG		A2	F	MG	MG
	A3	G	G	MG		A3	F	F	MG
	A4	G	G	MG		A4	VG	VG	VG
	A5	G	VG	MG		A5	MP	F	MP
	A6	G	VG	MG		A6	MP	MP	F
	A7	P	MP	MG		A7	VG	G	G

The weighted normalized fuzzy decision matrix is constructed as $\tilde{V}=\left[\tilde{v}_{ij}\right]_{mxn}$, where $\tilde{v}_{ij}=\tilde{s}_{ij}(.)w_{criteria}$ are normalized positive triangular fuzzy numbers in the interval [0, 1].

Here there are six benefit criteria. The fuzzy normalized decision matrix ($\tilde{S}$) and the fuzzy weighted normalized decision matrix ($\tilde{V}$) are seen in Tables 9 and 10, respectively.

Table 8: The fuzzy decision matrix $\tilde{D}$

	C1	C2	C3	C4	C5	C6
A1	(9.0,10.0,10.0)	(8.3,9.7,10.0)	(8.3,9.7,10.0)	(8.3,9.7,10.0)	(7.0,8.7,9.7)	(2.3,4.3,6.3)
A2	(5.0,6.7,8.0)	(5.7,7.3,8.7)	(5.7,7.7,9.3)	(8.3,9.7,10.0)	(6.3,8.3,9.7)	(4.3,6.3,8.3)
A3	(5.0,6.7,8.0)	(8.3,9.7,10.0)	(6.3,8.3,9.7)	(9.0,10.0,10.0)	(8.3,9.7,10.0)	(3.7,5.7,7.7)
A4	(3.0,5.0,7.0)	(6.3,8.0,9.0)	(6.3,8.3,9.7)	(6.3,8.0,9.0)	(3.0,3.3,4.0)	(9.0,10.0,10.0)
A5	(5.7,7.3,8.3)	(7.0,8.3,9.0)	(7.0,8.7,9.7)	(9.0,10.0,10.0)	(2.7,4.3,6.0)	(1.7,3.7,5.7)
A6	(3.0,5.0,7.0)	(8.3,9.7,10.0)	(7.0,8.7,9.7)	(9.0,10.0,10.0)	(7.0,8.7,9.7)	(1.7,3.7,5.7)
A7	(2.3,4.3,6.3)	(0.7,2.3,4.3)	(2.0,3.7,5.7)	(6.3,8.0,9.0)	(4.7,6.0,7.3)	(7.7,9.3,10.0)

Table 9: The fuzzy normalized decision matrix $\tilde{S}$

	C1	C2	C3	C4	C5	C6
A1	(0.90,1.00,1.00)	(0.83,0.97,1.00)	(0.83,0.97,1.00)	(0.83,0.97,1.00)	(0.70,0.87,0.97)	(0.23,0.43,0.63)
A2	(0.50,0.67,0.80)	(0.57,0.73,0.87)	(0.57,0.77,0.93)	(0.83,0.97,1.00)	(0.63,0.83,0.97)	(0.43,0.63,0.83)
A3	(0.50,0.67,0.80)	(0.83,0.97,1.00)	(0.63,0.83,0.97)	(0.90,1.00,1.00)	(0.83,0.97,1.00)	(0.37,0.57,0.77)
A4	(0.30,0.50,0.70)	(0.63,0.80,0.90)	(0.63,0.83,0.97)	(0.63,0.80,0.90)	(0.30,0.33,0.40)	(0.90,1.00,1.00)
A5	(0.57,0.73,0.83)	(0.70,0.83,0.90)	(0.70,0.87,0.97)	(0.90,1.00,1.00)	(0.27,0.43,0.60)	(0.17,0.37,0.57)
A6	(0.30,0.50,0.70)	(0.83,0.97,1.00)	(0.70,0.87,0.97)	(0.90,1.00,1.00)	(0.70,0.87,0.97)	(0.17,0.37,0.57)
A7	(0.23,0.43,0.63)	(0.07,0.23,0.43)	(0.20,0.37,0.57)	(0.63,0.80,0.90)	(0.47,0.60,0.73)	(0.77,0.93,1.00)

Assuming;

$A^* = \left((1,1,1),(1,1,1),(1,1,1),(1,1,1),(1,1,1),(1,1,1)\right)$, $A^- = \left((0,0,0),(0,0,0),(0,0,0),(0,0,0),(0,0,0),(0,0,0)\right)$ distance from fuzzy positive-ideal solution (d_i^*), distance from fuzzy negative-ideal solution (d_i^-), and closeness coefficients (CC_i) are calculated as shown in Table 11. Based on the CC_i values, alternatives are ranked from best to worst as listed in Table 11.

Table 10: The fuzzy weighted normalized decision matrix $\tilde{V}$

	C1	C2	C3	C4	C5	C6
A1	[0.28,0.32,0.32]	[0.06,0.07,0.08]	[0.03,0.04,0.04]	[0.10,0.12,0.12]	[0.14,0.17,0.19]	[0.06,0.11,0.16]
A2	[0.16,0.21,0.25]	[0.04,0.06,0.07]	[0.02,0.03,0.04]	[0.10,0.12,0.12]	[0.12,0.16,0.19]	[0.11,0.16,0.21]
A3	[0.16,0.21,0.25]	[0.06,0.07,0.08]	[0.03,0.03,0.04]	[0.11,0.12,0.12]	[0.16,0.19,0.19]	[0.09,0.14,0.19]
A4	[0.09,0.16,0.22]	[0.05,0.06,0.07]	[0.03,0.03,0.04]	[0.08,0.10,0.11]	[0.06,0.06,0.08]	[0.23,0.25,0.25]
A5	[0.18,0.23,0.26]	[0.05,0.06,0.07]	[0.03,0.04,0.04]	[0.11,0.12,0.12]	[0.05,0.08,0.12]	[0.04,0.09,0.14]
A6	[0.09,0.16,0.22]	[0.06,0.07,0.08]	[0.03,0.04,0.04]	[0.11,0.12,0.12]	[0.14,0.17,0.19]	[0.04,0.09,0.14]
A7	[0.07,0.14,0.20]	[0.01,0.02,0.03]	[0.01,0.02,0.02]	[0.08,0.10,0.11]	[0.09,0.12,0.14]	[0.19,0.24,0.25]

Table 11: Distance measurements, closeness coefficients and ranking from best alternative to worst alternative

Alternatives	d_i^*	d_i^-	CC_i	Ranking
A1	5.202	0.810	0.135	1
A2	5.280	0.735	0.122	3
A3	5.250	0.762	0.127	2
A4	5.346	0.667	0.111	4
A5	5.389	0.630	0.105	6
A6	5.367	0.655	0.109	5
A7	5.394	0.626	0.104	7

4. Conclusions

As seen from the fuzzy AHP-TOPSIS results, based on the criteria considered, biodiesel feedstock alternatives in Turkey are ranked from best to worst as: Sunflower (A1), cottonseed (A3), peanut (A2), canola (A4), soybean (A6), safflower (A5), and poppy seed (A7). In fact, based on 2016 data, sunflower takes the first place in oil seeds that are grown in Turkey in terms of cultivation area with 7201081 decare **(**6167800 decare is used for oil) and in terms of production with 1670716 ton (1500000 ton is used for oil). The second best alternative in Turkey is cotton seeds with a production of 1260000 ton based on the 2016 data of Turkish Statistical Institute [37]. Energy saving and efficiency are the most important components of Turkish national energy strategies in order to provide demand safety, reduce the external dependence risks, and to protect the environment [30]. As an environmental-friendly, non-toxic, biodegradable, renewable energy source, it is predicted that biodiesel will continue to be a significant part of Turkey's energy efficiency plan.

5. Recommendations

Implementing fuzzy numbers in AHP and TOPSIS captures the uncertainty and vagueness on DM's judgments and with fuzzy AHP-TOPSIS, DMs have the advantages of both F-AHP and F-TOPSIS in the evaluation and selection process of biodiesel feedstock. With this integration, biodiesel feedstock alternatives are ranked in a reasonable time and with little effort without requiring complicated calculations. However, there are some limitations of the study: The criteria considered in this study are only the most significant, main criteria and they are assumed to be independent. Therefore, correlations, interdependence, outer-dependence and feedback relationships between criteria are not taken into consideration. For future research, sub-criteria can be included and correlations between criteria can be studied with correlated F-AHP. Also, interdependence, outer-dependence and feedback relationships between criteria can be investigated with fuzzy Analytic Network Process (F-ANP) and F-ANP and F-TOPSIS can then be integrated to evaluate and rank alternatives.

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