Sustainable cultivation location optimization of the *Jatropha curcas* L. under uncertainty: A unified fuzzy data envelopment analysis approach

Reza Babazadeh a, Jafar Razmi b,⁎, Mir Saman Pishvaeae c

a Faculty of Engineering, Urmia University, Urmia, West Azerbaijan Province, Iran
b School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran
c School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran

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A B S T R A C T

Second-generation biodiesel production from non-edible high oil content feedstocks such as *Jatropha curcas* L. (JCL) has been found as a suitable alternative for the fossil diesel which is mostly consumed in transportation sector. Second-generation biodiesel eliminates the drawbacks of the first generation such as food-energy challenge and provides opportunity for rural development. Location optimization of JCL plays a vital role in the success and prosperity of JCL projects. In this study, sustainability and ecological indicators are defined to evaluate the performance and efficiency of the candidate locations for JCL cultivation under uncertainty. The values of defined indicators are highly tainted with uncertainty in real-life situation. To optimize the candidate locations for JCL cultivation under uncertainty, an efficient Unified Fuzzy Data Envelopment Analysis (UFDEA) model is developed. The proposed UFDEA model is verified and validated through investigating a real case study in Iran and the associated results are compared to those obtained by the crisp Unified Data Envelopment Analysis model under different levels of uncertainty. The obtained results show the applicability of the proposed UFDEA model in selecting suitable areas for JCL cultivation under uncertainty.

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1. Introduction

Current energy demand will be increased 50% until 2030 and liquid fuels would be the most demanded type of fuel [7]. Among the different sectors demanding energy, transportation sector has the largest share in energy demand [15]. Researchers and energy policy makers are seeking for sustainable and reliable energy sources for this sector. At the same line, biofuel has been found to be suitable alternative for fossil fuel consumed in transportation sector. The U.S. could potentially replace about 30 percent of national fossil fuel consumption by biofuels [45]. Biofuel utilization reduces dependency on crude oil and protects the economy against the fluctuations of oil price. Biodiesel and bioethanol are the most well-known biofuels commercially produced at worldwide. Biodiesel or fatty acid methyl esters produced from vegetable oils and animal fats has fuel properties of fossil diesel besides a number important advantages including simple usage in diesel engines without modification, non-flammability and nontoxicity, low Greenhouse Gas (GHG) emissions, visible smoke and noxious fumes and odors [10]. First generation biodiesel produced from edible vegetable oils and animal fats has intensified food crisis and has been criticized by FAO [16]. Indeed, while there is food crisis in many undeveloped countries, producing biodiesel from food resources is irrational. To eliminate the drawbacks of first generation biodiesel, researchers have found new non-edible feedstocks such as *Jatropha curcas* L. (JCL) for biodiesel production. Biodiesel produced from non-edible resources has been recognized as second generation biodiesel [29]. Although, as now, many other non-edible resources such as Sal, Mahua, Neem, and Pongamia have been recognized for second-generation biodiesel production, the following features of JCL have contributed JCL to be the most promising feedstock for biodiesel production [24]. These features include [25,6,24]: (1) growth in marginal lands and soil reclamation, (2) drought tolerant and low water and nutrient requirement, (3) high seed oil content and useful by-products glycerin and JCL press cake, (4) opportunity for rural development, (5) high resistance against pest and disease, and (6) no competence with food resources. Combusting biodiesel produced from JCL oil emits lower CO, carbon dioxide, sulphur dioxide and ozone-forming chemicals than fossil fuels combustion, but more NO, [12]. Moreover, since the amount of GHG emitted from biodiesel combustion is absorbed by agro-forestry of JCL, it is considered as a carbon-neutral biofuel.
These contributions of JCL plant have led to increasing cultivation areas of JCL at worldwide such that the amount of cultivated areas of JCL would reach to 13 million hectares by end of 2015 [17]. Thus, the need for an efficient location optimization tool to help energy and agriculture policy makers in taking strategic decisions for JCL cultivation is crucial. As now, JCL plant has been investigated from different point of views in the literature including risk assessment [28], social impacts [21], sustainability properties [34,43], economic viability [44], life cycle assessment [26], ecological conditions [13], and contents features [37]. To the best of our knowledge, the location optimization of JCL through sustainability indicators and under uncertain condition has not been addressed in the literature. The only study for location optimization of JCL is the work of Babazadeh et al. [8]. However, the method discussed in this paper cannot be implemented in uncertain circumstances. To fill the literature gap, this paper develops an efficient Unified Fuzzy Data Envelopment Analysis (UFDEA) model to evaluate the performance of the candidate locations for JCL cultivation under uncertainty. To do so, sustainability and ecological indicators are defined for assessing locations’ suitability for JCL cultivation. To tackle the uncertainty and ambiguity of the defined indicators, possibilistic programming approach is employed. A real case study is conducted in Iran to show the performance and efficiency of the proposed approach for ranking candidate cultivation areas of JCL plant according to sustainability measures.

This paper is organized in 6 sections. In the next section, the proposed methodology and framework for evaluating performance of cultivation locations of JCL under uncertainty are presented. In Section 3, the UFDEA model is elaborated. Section 4 describes the solution methodology for the developed UFDEA model based on possibilistic programming approach. In Section 5, description of the proposed critical and sustainability indicators are provided and thereafter the results attained from implementing the proposed UFDEA model in the concerned case study are presented and discussed. Section 6 concludes this paper and presents managerial implications according to acquired results.

2. Methodology

DEA as a mathematical programming method to assess the efficiency and performance of Decision Making Units (DMUs) was firstly introduced by Charnes et al. [11]. Banker [9] presented a general DEA model through relaxing the strict assumptions of Charnes’ model. DEA is classified into non-parametric ranking methods often used for frontier estimation [31]. To calculate the efficiency score of DMUs in DEA models, the most favorable weights for indicators (inputs and outputs) are determined through an optimization procedure [41]. According to efficiency scores, the DMUs are distinguished into efficient and inefficient DMUs. Adler et al. [1] classified ranking methods in DEA context into six major groups: super-efficiency, cross-efficiency, multivariate static, benchmark, inefficient DMUs, and multi-criteria decision making. As now, numerous researchers have addressed the applications of different DEA models in various ranking and efficiency measurement problems. Location optimization problem which is known as a strategic decision making problem, is one of the most interesting application areas of DEA models.


The important fact about various DEA models is that the results of DEA models are very sensitive to data noise and uncertainty [27]. Indeed, uncertainty in the values of indicators (inputs and outputs) has a direct impact on efficiency score of DMUs. On the other hand, in the real world situation, values of indicators are tainted with uncertainty due to problems such as inaccurate measurement. In addition, there is usually lack of knowledge about the indicators which needs the experts’ opinions to be estimated. Therefore, DEA models should be developed under uncertainty to provide reliable results [4]. We have employed the possibilistic programming approach which is known as a powerful tool to deal with epistemic uncertainty of the input parameters in mathematical programming models [36] to tackle the uncertainty of indicators’ values in the studied problem.

It should be noted that one may incorporate geostatistical approaches with geographic information system (GIS) to determine the suitable locations of JCL cultivation. However, to apply the geostatistical approaches reliable and enough historical data is needed to construct probability distributions of the uncertain parameters [20]. In the epistemic uncertainty condition like as our case in which uncertainty of parameters is modeled through subjective data provided from experts’ opinions and objective data provided from limited historical data, fuzzy programming approaches can be efficiently applied [18]. In addition, weighting of importance degree of indicators using experts’ opinions, which is a difficult managerial task in practice, is required when geostatistical approaches are incorporated with GIS method for location optimization problems. But, in the proposed UFDEA model the weights of indicators are determined mathematically within the model [39].

The methodology used in this paper is can be briefly described as follows. At first, the primary locations are filtered according to critical criteria. Then, the defined sustainability indicators are employed to assess the eligible locations for JCL cultivation. To do so, a DEA model equipped with possibilistic programming techniques is used to calculate the final scores of eligible locations. Indeed, in this paper, most of defined effective indicators for prospering JCL cultivation are not under the control of decision maker and therefore frontier analysis of DMUs is targeted instead of improving outputs for specific amount of inputs. That is, we investigate indicators being outputs for performance evaluation of DMUs. Among the different DEA models existing in the literature, we use the fuzzy DEA model proposed by Azadeh et al. [3]. This model is greatly compatible with the structure and assumptions of the studied case.

The steps of the proposed algorithm for optimizing cultivation locations of JCL can be summarized as follows:

**Step 1:** Determine the type of desirable and undesirable indicators for the sustainability indicators.

**Step 2:** Process the gathered data representing desirable and undesirable outputs. All indicators should be converted into positive values. There is no need to change the data to be compatible with maximization/minimization objective in DEA model by using Azadeh et al. [3] approach.

**Step 3:** Construct appropriate triangular or trapezoidal possibility distributions for ambiguous desirable and undesirable outputs according to available data and/or experts’ opinions.

**Step 4:** Determine the minimum acceptable feasibility degree of decision vector, i.e. $\zeta$, and convert the UFDEA model into an equivalent crisp model, and then rank the DMUs by the aid of converted model.
Step 5: Verify and validate the results of the UFDEA by the results obtained by the crisp Unified Data Envelopment Analysis (UDEA) model using spearman’s rank correlation at the confidence level of 95%.

Step 6: If the UFDEA model is verified and validated, apply the equivalent crisp auxiliary model of the UFDEA model to rank the DMUs at different \( \alpha \)-cuts and determine the best ranking of DMUs according to decision maker preferences. Otherwise the UFDEA model is not recommended for ranking the DMUs.

The general framework of the above steps is depicted in Fig. 1.

3. The Unified Fuzzy DEA (UFDEA) model for optimizing cultivation locations of JCL

In this paper a range-adjusted measure (RAM) model which is non-radial model is employed. Note that non-radial efficiency measures usually have more discriminating power than radial efficiency ones [46]. Although there are several non-radial models in the literature, we use the non-radial model proposed by Azadeh et al. [3]. Azadeh et al. [3] modified the non-radial model of Sueyoshi and Goto [39] to be applicable in fuzzy environments. In the model presented by Sueyoshi and Goto [39], inputs and outputs are distinguished into desirable (good) and undesirable (bad) ones and incorporated in a unified model. Also, this model is linear and does not have the shortcomings of non-linear and radial based models [30]. Another important feature of the method is that specifying the damage to scale (DTS) is easily performed with less computational efforts compared to other DTS specifying methods [40]. More details about the contributions and features of the unified DEA model can be found in Sueyoshi and Goto [39], Sueyoshi and Goto [40]. Notably, Sueyoshi and Goto [39] method has been developed for deterministic conditions and may result to deficiency when desirable and undesirable outputs are subject to uncertainty.

To deal with this shortcoming, Azadeh et al. [3] extended this model to be applicable under uncertain conditions by utilizing possibilistic programming method. Due to uncertain nature of desirable and undesirable outputs in the studied case we use the method proposed by Azadeh et al. [3].

The used indices, parameters and variables in formulation of the proposed UFDEA model are as follows. Parameters with a tilde (\( \sim \)) show coefficients tainted with possibilistic uncertainty.

<table>
<thead>
<tr>
<th>Indices</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( j, k )</td>
<td>Index of candidate locations for JCL cultivation (DMUs) ( j, k = 1, \ldots, n )</td>
</tr>
<tr>
<td>( r )</td>
<td>Index of desirable (good) outputs ( r = 1, \ldots, s )</td>
</tr>
<tr>
<td>( f )</td>
<td>Index of undesirable (bad) outputs ( f = 1, \ldots, h )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_g^r )</td>
<td>Range of desirable output ( r ) in objective function</td>
</tr>
<tr>
<td>( R_b^f )</td>
<td>Range of undesirable output ( f ) in objective function</td>
</tr>
<tr>
<td>( g_{j} )</td>
<td>Amount of desirable output ( r ) for DMU ( j )</td>
</tr>
<tr>
<td>( b_{f} )</td>
<td>Amount of undesirable output ( f ) for DMU ( j )</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i_g^r )</td>
<td>Structural or intensity variables of desirable outputs for DMU ( j )</td>
</tr>
<tr>
<td>( i_b^f )</td>
<td>Structural or intensity variables of undesirable outputs for DMU ( j )</td>
</tr>
<tr>
<td>( d_g^r )</td>
<td>Surplus variable for desirable output ( r )</td>
</tr>
<tr>
<td>( d_b^f )</td>
<td>Slack variable for undesirable output ( f )</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Unified efficiency score for each DMU</td>
</tr>
</tbody>
</table>

The following UFDEA model is solved for the specific \( k \)th DMU to measure its level of unified efficiency. In other words, the following

![Fig. 1. The proposed UFDEA algorithm.](image-url)
The crisp UDEA model, fuzzy parameters are replaced with crisp ones directly and must be transformed to appropriate equivalent crisp model. We assume that desirable and undesirable outputs have triangular, trapezoidal and nonlinear ones in both symmetric and asymmetric forms, and (III) the method utilizes expected value, respectively. These values are estimated through decision maker preferences and some available historical data. The membership function of a fuzzy number can be defined as follows:

\[ \mu_c(x) = \begin{cases} 0 & \text{if } x \in (-\infty, c^0] \\ f_c(x) = \frac{x - c^0}{c^c - c^0} & \text{if } x \in [c^0, c^c] \\ 1 & \text{if } x = c^c \\ g_c(x) = \frac{x - c^c}{c^b - c^c} & \text{if } x \in [c^c, c^b] \\ 0 & \text{if } x \in (c^b, +\infty) \end{cases} \]

The α-cut of fuzzy number \( c \) can be defined as \( c_\alpha = \{ x \in \Omega | \mu_c(x) \geq \alpha \} \) where \( \Omega \) is the universe set. Since \( \mu_c \) is continuous, the α-cuts are closed and bounded. Therefore, they could be presented as

\[ c_\alpha = [f_c^{-1}(\alpha), g_c^{-1}(\alpha)] \]

According to Heilpern [19] and Jimenez [22], the expected interval (EI) and expected value (EV) of fuzzy number \( c \) can be represented as follows:

\[ EI(c) = [E_1, E_2] = \left[ \int_0^1 f_c^{-1}(x)dx, \int_0^1 g_c^{-1}(x)dx \right] = \left[ \frac{1}{2}(c^c + c^m), \frac{1}{2}(c^m + c^b) \right] \]

The expected value of fuzzy number \( c \) is the half point of its expected interval. Thus, the expected value of \( c \) is calculated as follows:

\[ EV(c) = \frac{E_1 + E_2}{2} = \frac{c^m + 2c^c + c^b}{4} \]

According to Dubois and Prade [14], in order to aggregate fuzzy numbers \( a \) and \( b \), Zadeh’s minimum extension principle can be applied as follows:

\[ f_{a+b}^{-1}(x), g_{a+b}^{-1}(x) = [f_a^{-1}(x) + f_b^{-1}(x), g_a^{-1}(x) + g_b^{-1}(x)] \]
Accordingly, it can be argued that [23]:
\[ \text{El}(\alpha \hat{a} + \gamma \hat{b}) = \lambda \text{El}(\hat{a}) + \gamma \text{El}(\hat{b}), \]  
(14)

\[ \text{EV}(\alpha \hat{a} + \gamma \hat{b}) = \lambda \text{EV}(\hat{a}) + \gamma \text{EV}(\hat{b}) \]  
(15)

Furthermore, according to the ranking method of Jimenez [22] for any pair of fuzzy numbers \( \hat{a} \) and \( \hat{b} \), the degree in which \( \hat{a} \) is bigger than \( \hat{b} \) is defined as follows:
\[ \mu_{\hat{a},\hat{b}}(\hat{a}, \hat{b}) = \begin{cases} 0 & \text{if } \bar{E}_2^a - \bar{E}_2^b < 0 \\ \frac{\bar{E}_3^a - \bar{E}_3^b}{\bar{E}_3^a - \bar{E}_3^b} & \text{if } 0 \in [\bar{E}_2^a - \bar{E}_3^a, \bar{E}_2^b - \bar{E}_3^b] \\ 1 & \text{if } \bar{E}_2^a - \bar{E}_2^b > 0 \end{cases} \]  
(16)

where \( [\bar{E}_2^a, \bar{E}_2^b] \) and \( [\bar{E}_3^a, \bar{E}_3^b] \) are the expected intervals of fuzzy numbers \( \hat{a} \) and \( \hat{b} \), respectively. \( \mu_{\hat{a},\hat{b}}(\hat{a}, \hat{b}) \geq \alpha \) is said to be bigger than or equal to \( \hat{b} \), at least at degree \( \alpha \) and it is shown by \( \hat{a} \gg_\alpha \hat{b} \).

Given two fuzzy numbers \( \hat{a} \) and \( \hat{b} \), it is stated that \( \hat{a} \) is indifferent (equal) to \( \hat{b} \) in degree of \( \alpha \) if the following inequalities hold simultaneously [33]:
\[ \hat{a} \gg_{\alpha/2} \hat{b}, \quad \hat{a} \ll_{\alpha/2} \hat{b} \]  
(17)

The above equations can be rewritten as follows:
\[ \alpha \leq \mu_{\hat{a},\hat{b}}(\hat{a}, \hat{b}) \leq 1 - \frac{\alpha}{2} \]  
(18)

At the following, we present the general fuzzy mathematical programming model with ambiguous coefficients in both objective function and constraints. Then, according to above-mentioned definitions and principles, auxiliary crisp model is developed for the fuzzy model:

\[ \text{Min } z = cx \]

s.t. \[ \alpha \hat{a}x \geq \hat{b}_i, \quad i = 1, \ldots, l \]
\[ \hat{a}x = \hat{b}_i, \quad i = l + 1, \ldots, m \]
\[ x \geq 0 \]  
(19)

According to Jimenez et al. [23], a decision vector \( x \in R^n \) is feasible in degree of \( \alpha \) (\( \alpha \)-feasible) if: \( \min_{i=1,\ldots,m} (\mu_{\hat{a}_i,\hat{b}_i}) = \alpha \). In other words, when
\[ \alpha x \geq \hat{b}_i, \quad i = 1, \ldots, l \]

According to (16), it is concluded that:
\[ \frac{E_{2a}^i - E_{2b}^i}{E_{3a}^i - E_{3b}^i} \geq \alpha \quad i = 1, \ldots, l \]  
(20)

And according to principle (15), we have:
\[ \left[ (1 - \alpha)E_{2a}^i + \alpha E_{3a}^i \right] x \geq (1 - \alpha)E_{2b}^i + \alpha E_{3b}^i, \quad i = 1, \ldots, l \]  
(22)

The above procedure can be conveniently applied on fuzzy equalities. To do so, the fuzzy equalities must be converted to two fuzzy unequal form. Thus, when we have:
\[ \alpha x \approx \hat{b}_i, \quad i = l + 1, \ldots, m \]

It is deduced that:
\[ \alpha \leq \frac{E_{2a}^i - E_{2b}^i}{E_{3a}^i - E_{3b}^i} \leq 1 - \frac{\alpha}{2} \quad i = l + 1, \ldots, m \]  
(23)

And in accordance with (15), the above inequality is rewritten as follows:
\[ \left[ \left( \frac{1 - \alpha}{2} \right)E_{2a}^i + \frac{\alpha}{2}E_{3a}^i \right] x \geq \left( \frac{1 - \alpha}{2} \right)E_{2b}^i + \frac{\alpha}{2}E_{3b}^i, \quad i = l + 1, \ldots, m \]  
(25)

In order to transform the fuzzy objective function of problem (19) to its equivalent crisp model, it is proved [23] that a feasible vector like \( x^0 \) is an \( \alpha \)-acceptable optimal solution to problem (19) if and only if for all feasible decision vectors say \( x \), the following equation holds:
\[ c^Tx \geq \frac{1}{2}c^Tx^0 \]  
(27)

Note that feasible vector \( x \) satisfies the following constraints, simultaneously:
\[ \hat{a}x \geq \hat{b}_i, \quad i = 1, \ldots, l \]
\[ \hat{a}x \approx \hat{b}_i, \quad i = l + 1, \ldots, m \]
\[ x \geq 0 \]  
(28)

\( x \approx 0 \)  
(30)

Since the objective function of problem (19) is minimization, \( x^0 \) is a better choice at least in degree \( \frac{1}{2} \) as opposed to the other feasible vectors.

According to (22), inequality (27) can be rewritten as below:
\[ \frac{E_{2a}^i + E_{3a}^i}{2} \geq \frac{E_{2b}^i + E_{3b}^i}{2} \]  
(31)

Consequently, vector \( x^0 \) is an \( \alpha \)-acceptable optimal solution to problem (19), if it is optimal solution to the following crisp \( \alpha \)-parametric linear model:

\[ \text{Min } Z = EV(\hat{c})x \]

s.t. \[ \left[ (1 - \alpha)E_{2a}^i + \alpha E_{3a}^i \right] x \geq (1 - \alpha)E_{2b}^i + \alpha E_{3b}^i, \quad i = 1, \ldots, l \]
\[ \left[ \left( \frac{1 - \alpha}{2} \right)E_{2a}^i + \frac{\alpha}{2}E_{3a}^i \right] x \geq \left( \frac{1 - \alpha}{2} \right)E_{2b}^i + \frac{\alpha}{2}E_{3b}^i, \quad i = l + 1, \ldots, m \]  
(32)

The most pessimistic, most likely, and most optimistic values of the ranges can be calculated by Zadeh’s extension principle for obtaining the maximum and minimum of \( n \) fuzzy numbers. To do so, assume \( \hat{a}_1, \ldots, \hat{a}_n \) are fuzzy numbers whose maximum and minimum vales are represented as follows:
\[ \max(\hat{a}_1, \ldots, \hat{a}_n)(x) = \sup_{z=\max(x_1, \ldots, x_n)} \min(\hat{a}_1(x_1), \ldots, \hat{a}_n(x_n)), \quad \forall z \in R \]  
(33)

\[ \min(\hat{a}_1, \ldots, \hat{a}_n)(x) = \sup_{z=\min(x_1, \ldots, x_n)} \min(\hat{a}_1(x_1), \ldots, \hat{a}_n(x_n)), \quad \forall z \in R \]  
(34)

According to (33) and (34), it is deduced that:
\[ \text{Max}(\hat{g}_j) = \hat{g}_{j, \max} = \left( \hat{g}_{j, \max}^p, \max(\hat{g}_{j, \max}^m, \hat{g}_{j, \max}^o) \right) \]  
(35)

\[ \text{Min}(\hat{g}_j) = \hat{g}_{j, \min} = \left( \min(\hat{g}_{j, \min}^p, \hat{g}_{j, \min}^m), \hat{g}_{j, \min}^o \right) \]  
(36)

\[ \text{Max}(\hat{b}_j) = \hat{b}_{j, \max} = \left( \hat{b}_{j, \max}^p, \max(\hat{b}_{j, \max}^m, \hat{b}_{j, \max}^o) \right) \]  
(37)

\[ \text{Min}(\hat{b}_j) = \hat{b}_{j, \min} = \left( \min(\hat{b}_{j, \min}^p, \hat{b}_{j, \min}^m), \hat{b}_{j, \min}^o \right) \]  
(38)

where symbols \( p, m, o \) represent the most pessimistic, most likely, and most optimistic values, respectively.
Consequently, the fuzzy coefficients in the ranges of objective function of the proposed UFDEA model can be replaced by the following equations:

\[ \hat{R}_y = (R_{y1}^{up}, R_{y1}^{low}, R_{y1}^{cu}) \]

\[ = \frac{1}{1 + s + h} \left( \frac{b_{y1}^{low} - b_{y1}^{cu}}{b_{y1}^{max} - b_{y1}^{min}} - \frac{b_{y1}^{m} - b_{y1}^{cu}}{b_{y1}^{max} - b_{y1}^{min}} + 1 \right) \] (39)

\[ \hat{R}_y = (R_{y1}^{up}, R_{y1}^{low}, R_{y1}^{cu}) \]

\[ = \frac{1}{1 + s + h} \left( \frac{b_{y2}^{low} - b_{y2}^{cu}}{b_{y2}^{max} - b_{y2}^{min}} - \frac{b_{y2}^{m} - b_{y2}^{cu}}{b_{y2}^{max} - b_{y2}^{min}} + 1 \right) \] (40)

According to above-mentioned descriptions, the equivalent auxiliary crisp model for the UFDEA model can be presented as follows:

\[ \text{Max } z = \sum_{i=1}^{n} \left( \frac{R_{y1}^{up} + 2R_{y1}^{low} + R_{y1}^{cu}}{4} \right) d_i^{y} + \sum_{j=1}^{b} \left( \frac{R_{y2}^{up} + 2R_{y2}^{low} + R_{y2}^{cu}}{4} \right) b_j^{y} \] (41)

\[ \sum_{j=1}^{b} \left[ \left( 1 - \frac{x}{2} \right) \left( \frac{g_{m} + g_{n}}{2} \right) + \left( \frac{x}{2} \right) \right] b_j^{y} - d_j^{y} \] (42)

\[ \sum_{j=1}^{b} \left[ \left( 1 - \frac{x}{2} \right) \left( \frac{b_{m} + b_{n}}{2} \right) + \left( \frac{x}{2} \right) \right] b_j^{y} - d_j^{y} \] (43)

\[ \sum_{j=1}^{b} \frac{b_j^{y}}{2} = 1, \] (44)

\[ \sum_{j=1}^{b} \left[ \left( 1 - \frac{x}{2} \right) \left( \frac{b_{m} + b_{n}}{2} \right) + \left( \frac{x}{2} \right) \right] b_j^{y} + d_j^{y} \] (45)

\[ \sum_{j=1}^{b} \left[ \left( 1 - \frac{x}{2} \right) \left( \frac{b_{m} + b_{n}}{2} \right) + \left( \frac{x}{2} \right) \right] b_j^{y} + d_j^{y} \] (46)

\[ \sum_{j=1}^{b} \frac{b_j^{y}}{2} = 1, \] (47)

\[ \alpha > 0, \beta > 0, \alpha > 0, \beta > 0 \quad \forall j, r, f. \] (48)

5. Sustainability and ecological indicators description and results

In this section the proposed indicators for evaluating the JCL cultivation areas are presented and the attained results are discussed. The studied case is related to location optimization of JCL in Iran. Because of avoiding competition between JCL energy crop and food crops, arid and semi-arid areas of candidate locations are considered for JCL cultivation. Iran’s provinces especially southern provinces have great amount of arid and semi-arid areas which are not enough fertile for food crops harvesting. Iran is eliminating subsidies from domestic fossil fuels consumptions and granting biofuels and other renewable energy usages to move toward sustainable development. Thus, utilizing JCL for second-generation biodiesel production could provide opportunities such as suitable alternative for fossil diesel, dessert reduction, reduction of GHG emissions, and rural development in this country.

Two groups of indicators including critical and sustainability indicators are defined for evaluating the efficiency of candidate locations for JCL cultivation. Critical criteria including long frost period, waterlogged conditions, and low soil pH (lower than 6.0) are those factors that JCL cannot yield under such conditions. Therefore, the primary locations firstly filtered through these factors. The eligible locations that satisfy the critical criteria are then evaluated under sustainability and ecological indicators through applying the proposed UFDEA model. The proposed sustainability and ecological indicators include: (1) cultivation cost per hectare, (2) human development index (HDI): due to rural development consideration, provinces with low HDI have higher priority for JCL cultivation, (3) Annual rainfall, (4) annual average of mean daily temperature: the higher weather temperature, the better condition would be for JCL cultivation, (5) amount of water resources, (6) area of arid and semi-arid lands, (7) cultivated area of different gardens (this factor is representative of gardening development in any province; therefore, execution of JCL project in provinces with higher cultivated area of different gardens will be most likely succeeded), (8) population. The proposed sustainability and ecological indicators are uncertain parameters and differ for different provinces.

Evaluating the primary locations under critical criteria illustrates that the provinces Tabriz, Uromieh, Ardabil, Kurdistan, Gilan, Mazandaran, and Golestan should be eliminated from potential cultivation areas. Other 23 provinces satisfy the critical criteria and so their efficiency scores are measured by the proposed UFDEA model under defined sustainability and ecological indicators.

After primary filtration of the candidate locations, the results of the proposed UFDEA model are verified and validated by crisp UDEA model and optimized for different level of minimum acceptable feasibility degree of decision vector (α-cut) according to decision maker preferences. Among the defined sustainability and ecological indicators, seven criteria factors including annual rainfall, annual average of mean daily temperature, amount of water resources, area of semi-arid lands, area of arid land, cultivation area of different gardens, and population indicators should be maximized and therefore, are considered as desirable outputs. Other two criteria including cultivation cost per hectare and human development index should be minimized and hence, they are assumed as undesirable outputs. The CPLEX solver of GAMS optimization software is employed to solve the crisp equivalent model of the proposed UFDEA model.

Fig. 2 shows the filtered locations (illustrated by orange color) and the four best locations (illustrated by green color) for JCL cultivation according to the results of crisp UDEA model. The acquired results are compatible with JCL belt (30° N-35° S) illustrating the most suitable areas for JCL cultivation through all over the world. According to this belt, southern half of Iran has the most suitable conditions for JCL cultivation.

5.1. Verification and validation

Verification and validation of the UFDEA model is essential before applying it in real-world practices. To do so, the
non-parametric Spearman’s rank correlation method \[38\] is adopted. The method analyzes the positive correlation between the two sets of ranks obtained by the UFDEA and UDEA models using the measure 
\[ q = \frac{1}{n^2 - 1} \sum d_i^2 \] 
Where, \( d_i \) is difference between the ranks of each method and \( n \) stands for the total number of DMUs. In this way, null hypothesis \( H_0: r_s = 0 \) is tested against alternative hypothesis \( H_1: r_s > 0 \) as follows:

**H0:** There is no correlation between the ranks obtained by the proposed UFDEA model and the crisp UDEA model.

**H1:** There is a positive correlation between the ranks obtained by the proposed UFDEA model and the crisp UDEA model.

Table 1 illustrates the Spearman’s rank correlation coefficient and corresponding \( P \)-values for different values of \( \alpha \)-cuts. According to Table 1, the \( P \)-values of the test for different values of \( \alpha \)-cuts are near to zero and hence \( H_0 \) is rejected at confidence level equal to 0.0000001 for all the experiments. In other words, there is a high and strong correlation between the ranks obtained by the UFDEA and crisp UDEA models.

Another evidence which indicates the validity of the UFDEA model is the increasing trend of Spearman’s rank correlation coefficient according to increase in the values of \( \alpha \)-cuts (see Fig. 3). In other words, when the values of \( \alpha \)-cuts is increased, the ambiguity in data is reduced and approach to crisp one. Therefore, higher Spearman’s rank correlation coefficient between the ranks obtained by the UFDEA and crisp UDEA is expected by increasing the values of \( \alpha \)-cuts. Note that when \( \alpha \) is equal to 1 the UFDEA model is equivalent to the crisp UDEA model.

5.2. The results of the proposed UFDEA model

Since the results of the proposed UFDEA model is verified and validated by the crisp UDEA model, now the UFDEA model can
be applied to cultivation location optimization of JCL for any desired confidence level of $\alpha$. Table 2 indicates the UNEs and ranks obtained by crisp UDEA model and the equivalent auxiliary crisp model of the proposed UFDEA model for different values of $\alpha$-cut levels. It is worthy to note that other values of the proposed UFDEA model at different levels of acceptable uncertainty can be conveniently determined according to decision maker preferences. The results of the crisp UDEA model and UFDEA model for $\alpha = 1$ are the same.

### Table 2
The results of the proposed UFDEA model for different $\alpha$-cuts.

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6.1. Policy implications

Some useful managerial implications can be extracted from this paper as follows:

- The presented critical, sustainability and ecological indicators in this paper, provide useful and comprehensive indicators for evaluating JCL cultivation areas.
- Uncertainty and fuzziness are integral parts of indicators in real-world practices due to problems such as inaccurate measurement. Therefore, using crisp DEA models for ranking DMUs will lead to efficient and unreliable results.
- Expert’s opinions about future realizations of indicators and available historical data can be used for determining the suitable level of acceptable uncertainty ($\alpha$-cut).
- The proposed UFDEA model can be effectively used for ranking cultivation locations of JCL under uncertainty of indicators.

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