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Multi-Criteria Decision-Making Framework for Evaluating Green Fuels Alternatives: A Hybrid MEREC-TODIM Approach

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Abstract

The increasing concern about climate change and the need to reduce greenhouse gas emissions have led to a growing interest in converting traditional fuels into valuable products such as green fuel. By promoting the use of green fuels, we can reduce our carbon footprint and help mitigate the effects of climate change. The reliance on conventional fossil fuels has led to severe environmental degradation, climate change, and air pollution, which in turn affect human health and quality of life. Researchers from several nations are seeking alternative sources to encourage sustainable mobility, minimize GHG emissions, and improve quality of life. This study proposes a Multi-Criteria Decision Making (MCDM) framework to assess and rank green fuel alternatives for mitigating greenhouse gas emissions. The MCDM approach incorporates four key criteria: Technical Reliability, Affordability, Availability & Durability, Environmental Compatibility, and Social Acceptance. The MEthod based on the Removal Effects of Criteria (MEREC) method is employed to determine the weights of these criteria, while an acronym in Portuguese for Interactive and Multi-criteria Decision Making (TODIM) method is used to rank the alternatives, utilizing Triangular Neutrosophic Numbers to handle the inherent uncertainty and ambiguity in the decision-making process. This integrated approach provides a comprehensive evaluation of green fuel options, enabling decision-makers to identify the most suitable alternatives for reducing greenhouse gas emissions. The paper also conducts a comparative analysis with other MCDM methods, such as TOPSIS and VIKOR, and performs a sensitivity analysis to evaluate the robustness of the decision.

Keywords: Green Fuel, Greenhouses Gas, MCDM, MEREC, TODIM, Triangular Neutrosophic Numbers.

1 | Introduction

The increasing concern about climate change and the need to reduce greenhouse gas emissions have led to a growing interest in the conversion of traditional fuel into valuable products such as green fuel. Green fuel, also known as alternative fuel or clean fuel, is a carbon-neutral alternative to fossil fuels, and it is a type of fuel that produces significantly fewer greenhouse gas emissions and other pollutants compared to traditional fossil fuels [1]. They are produced from hydrogen and electricity from renewable sources, making them a crucial step towards decarbonizing heavy industries, shipping, and power generation in the future [2]. These fuel alternatives offer a range of benefits, including reduced greenhouse gas emissions, improved air quality, and increased energy security. Biofuels (e.g., ethanol, biodiesel) made from organic matter such as plants, algae, or agricultural waste, can be used in existing vehicles [3]. Hydrogen fuel cells produce only water and

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heat as exhaust and they can be used in fuel cell electric vehicles (FCEVs) [4]. Synthetic fuels (e.g., ammonia) are produced from renewable energy sources, such as solar or wind power [5]. Electric energy storage (e.g., batteries) can be charged from renewable energy sources like solar or wind power [6]. These fuels are designed to reduce our reliance on fossil fuels and mitigate climate change by decreasing greenhouse gas emissions.

Greenhouse gases are gases in Earth's atmosphere that trap heat leaving the atmosphere. The main greenhouse gases are Carbon dioxide (CO2), Methane (CH4), Nitrous oxide (N2O), And Fluorinated gases [7]. These gases warm the planet, making life on Earth possible. However, human activities, such as burning fossil fuels and deforestation, have increased the concentration of these gases in the atmosphere, leading to additional warming and various impacts on the climate [8]. The connection between green fuels and greenhouse gases is that green fuels aim to reduce the emissions of these gases, which are primarily responsible for climate change. By switching to green fuels, we can decrease the amount of CO2 and other greenhouse gases released into the atmosphere, helping to slow down global warming and its associated impacts [9]. For example, electric vehicles powered by renewable energy sources like solar or wind power produce zero tailpipe emissions, reducing greenhouse gas emissions and air pollution [10]. Similarly, biofuels can offer a lower-carbon alternative to traditional fossil fuels, depending on the feedstock and production process used [11].

By promoting the use of green fuels, we can reduce our carbon footprint and help mitigate the effects of climate change. The transportation industry is a significant contributor to greenhouse gas emissions, and transitioning to green fuels and technologies is crucial for reducing its environmental impact [12]. However, the sector is heavily dependent on fossil fuels, which contributes to climate change. The transportation sector is responsible for around 23% of global CO2 emissions, with the majority coming from road transportation (cars, trucks, buses) and it is one of the largest consumers of energy worldwide, accounting for nearly 30% of all energy consumption [13]. This industry is heavily reliant on fossil fuels, such as gasoline, diesel, and jet fuel, which are the primary sources of greenhouse gas emissions [14]. The transportation industry is undergoing a significant transformation, driven by the need to reduce greenhouse gas emissions and mitigate climate change [15]. The reliance on conventional fossil fuels has led to severe environmental degradation, climate change, and air pollution, which in turn affect human health and quality of life [14]. To address these issues, it is essential to develop alternative energy sources for transportation. As a result, researchers from several nations have vowed to seek alternative sources that would encourage sustainable mobility to minimize GHG emissions and improve quality of life. Electric Vehicles (EVs) are gaining popularity as a cleaner alternative to traditional internal combustion engines. They produce zero tailpipe emissions, reducing air pollution and GHG emissions [16]. Hydrogen fuel cell vehicles use hydrogen as a fuel source, producing only water and heat as exhaust [17]. Autonomous vehicles have the potential to optimize routes, reduce fuel consumption, and improve safety, leading to a more sustainable transportation system [18]. These alternative solutions can help minimize GHG emissions, improve air quality, and enhance quality of life.

This study proposes a Multi-Criteria Decision Making (MCDM) framework to assess and rank green fuel alternatives for mitigating greenhouse gas emissions. The MCDM approach incorporates four key criteria: Technical Reliability, Affordability, Availability & Durability, Environmental Compatibility, and Social Acceptance. To determine the weights of these criteria, the MEREC (MEthod based on the Removal Effects of Criteria) method is employed [19]. The TODIM (an acronym in Portuguese for Interactive and Multi-criteria Decision Making) method is used to rank the alternative [20], utilizing Triangular Neutrosophic Numbers to handle the inherent uncertainty and ambiguity in the decision-making process [21]. This integrated approach provides a comprehensive evaluation of green fuel options, enabling decision-makers to identify the most suitable alternatives for reducing greenhouse gas emissions.

The primary objective of this study is to develop a comprehensive Multi-Criteria Decision Making (MCDM) framework to assess and rank green fuel alternatives for mitigating greenhouse gas emissions. The proposed framework aims to provide a systematic approach for evaluating the suitability of different green fuel options, considering multiple criteria and uncertainty. The contributions of this study are:

- A comprehensive MCDM framework that integrates MEREC for weighting criteria and TODIM for ranking alternatives.
- The study utilizes Triangular Neutrosophic Numbers to handle the inherent uncertainty and ambiguity in the decision-making process, providing a more robust and realistic evaluation of green fuel options.
- The proposed framework provides a comprehensive evaluation of green fuel options, considering four key criteria: Technical Reliability, Affordability, Availability & Durability, Environmental Compatibility, and Social Acceptance.
- Insights and recommendations for policymakers and industry stakeholders to promote the adoption of green fuels for reducing greenhouse gas emissions.

The paper is organized as follows: Section 2 literature review: Overview of existing green fuel alternatives and review of multi-criteria decision making (MCDM) methods. Section 3: Methodology: Preliminaries of triangular neutrosophic numbers, explanation of the MEREC method for determining criterion weights, and the TODIM method for ranking alternative green fuels. Section 4: Case study, description of the case study scenario. Section 5: Application: calculation of criteria weights using MEREC and ranking of alternatives using TODIM. Section 6: Results and discussion: presentation of the results of the case study, sensitivity analysis, comparison of the results with existing studies or other MCDM methods. Section 7: Conclusion: summary of the main findings of the study.

2 |Literature Review

In this section, the related work and research on green fuels are reviewed, such as greenhouse gas emissions, and the application of Multi-Criteria Decision Making (MCDM) methods in evaluating green fuel alternatives.

2.1 |Overview of Green Fuels

Green fuels are carbon-neutral or even carbon-free alternatives to fossil fuels, produced from hydrogen and electricity from renewable sources [1]. The increasing concern about climate change and the need to reduce greenhouse gas emissions have led to a growing interest in the conversion of traditional fuel into valuable products such as green fuel [11]. There are various methods to produce renewable green fuel. Swapnil L. Fegade presents a novel approach to convert municipal polymer waste into green hydrocarbons and fuels using a batch catalytic slurry process [22]. Also, Residue gas, a byproduct of various industrial processes, can be converted into green fuels through Gas-to-Liquid (GTL) technology. Thai Ngan Do et al assess the potential and benefits of producing green fuels from residue gas via GTL [23]. The use of green hydrogen as a fuel can reduce emissions of particulate matter, nitrogen oxides, and sulfur dioxide, which are major contributors to air pollution. Additionally, green hydrogen can reduce greenhouse gas emissions, which are a significant contributor to climate change [24]. Antonio Djalma Nunes Ferraz Júnior et. al proposes the production of liquefied biomethane (LBM) from sugarcane vinasse and municipal solid waste (MSW) as a sustainable fuel for a green-gas heavy-duty road freight transport corridor in Sao Paulo state, Brazil [25]. Ruxing Gao et.al present a comparative analysis of the transformation of CO2 into liquid fuels and SNG using green hydrogen [26]. The direct and continuous conversion of flue gas CO2 into green fuels using dual-function materials in a circulating fluidized bed system is a promising technology for CO2 mitigation and green fuel production [27].

MCDM methods are widely used in evaluating and ranking fuel alternatives based on multiple criteria. Numerous studies have applied MCDM methods to rank fuel alternatives. Naijie Chai and Wenliang Zhou propose a novel hybrid five-phase fuzzy MCDM approach to evaluate the sustainability of alternative aviation fuels (AAFs) using integrated interval-valued triangle fuzzy numbers (IVTFNs), IVTFN-AHP, IVTFN-TOPSIS [28]. PROMETHEE II and VIKOR methodologies can be used to evaluate the performance of different alternatives based on multiple criteria such as energy efficiency, emissions, cost, and sustainability to help decision-makers identify the optimal performance-emission trade-off vantage in a hydrogen-biohol dual fuel endeavor [29]. Kuber Singh Mehra et, al propose an integrated multi-attribute decision framework for the sustainability assessment of renewable diesel fuel production pathways. The framework utilizes various MCDM schemes, including MOORA, VIKOR, and COPRAS, to identify the most suitable renewable diesel production technology [30]. Zohreh Rahimirad and Ali Asghar Sadabadi apply SWOT analysis and MCDM methods to develop a policymaking framework for green hydrogen technology development and usage in Iran. The study aims to identify the strengths, weaknesses, opportunities, and threats (SWOT) of green hydrogen technology in Iran and to prioritize policies for its development and usage [31]. Fabio Borghetti et, al propose the evaluation of alternative fuels for a bus fleet in Italy using a multi-criteria decision-making (MCDM) approach like AHP and ELECTRE methods [32].

2.2 | Overview of MCDM Methods

This study employs the MEREC (MEthod based on the Removal Effects of Criteria) method to determine the weights of the evaluation criteria and an acronym in Portuguese for Interactive and Multi-criteria Decision Making (TODIM) method to rank the green fuel alternatives. The integration of these methods, along with the use of Triangular Neutrosophic Numbers to handle uncertainty, provides a robust framework for comprehensive evaluation.

The MEREC MCDM method is a comprehensive method that considers multiple criteria and their interdependencies to provide a more accurate and reliable evaluation [19]. Naveen Kumar and Juthika Mahanta combine the MEREC method for objective criteria, the SWARA method for calculating subjective weights, and the VIKOR method in the Pythagorean fuzzy context to determine the preference order of alternatives [33]. Karahan Kara et, al. use the MEREC-AROMAN method for determining sustainable competitiveness levels [34]. Kuttusi Zorlu et, al. use the GAM and MEREC-based PROMETHEE-GAIA method for Quantitative assessment of heritage [35]. Shankha Shubhra Goswami uses the MEREC integrated PIV MCDM tool which is a hybrid approach that combines the strengths of MEREC and PIV to evaluate and select the most suitable green renewable energy source in India [36]. Ashok Kumar Yadav et, al use the I-MEREC-T method as an improved MEREC-TOPSIS scheme for optimal network selection in 5G heterogeneous networks for IoT [37]. Naveen Kumar et, al use the MEREC-SWARA-VIKOR framework for solar panel selection [38].

TODIM is an MCDM method that was developed by Gomes and Lima in 1992. TODIM is a Portuguese acronym that translates to "Interactive Multi Criteria Decision-Making Process" [20]. The TODIM method is an MCDM support methodology that can be effectively used in an automobile parts manufacturing company based on multiple criteria with the ENTROPY method [39]. The Fuzzy TODIM method combines the TODIM method with fuzzy set theory to evaluate alternatives based on fuzzy criteria weights and fuzzy performance ratings [40]. The TODIM method has been extended to handle probabilistic hesitant fuzzy information, which is known as the probabilistic hesitant fuzzy TODIM method [41]. The TODIM method has been extended to handle novel type-2 fuzzy numbers, which is known as the extended CPT-TODIM method [42]. A novel TODIM-based multi-attribute decision-making method under information described by Z-numbers, this method combines the TODIM method with Z-numbers to handle multi-attribute decision-making problems with uncertain and ambiguous information [43]. Yushuo Cao et, al use the complex q-rung orthopair fuzzy generalized TODIM method with weighted power geometric operator as a novel approach to assess the appropriate technique for food waste treatment [44]. Kavimani Vijayananth et, al uses an integrated CRITIC-TODIM approach to evaluate the performance of composite materials [44]. Another extended TODIM method for hyperbolic fuzzy environments is a novel approach to MCDM problems in uncertain and imprecise environments [45]. Xin Wen et, al. use the CIVL-BWM-TODIM decision-making methodology to evaluate autonomous vehicle applications in smart airports [46]. This paper utilizes the MEREC and TODIM methods under Triangular neutrosophic numbers. Triangular neutrosophic numbers are a type of neutrosophic number that represents uncertainty, imprecision, and inconsistency in a more comprehensive way [21]. They are an extension of traditional fuzzy numbers and are used to model complex decision-making problems [47].

3 | Methodology

This section is divided into three parts first part proposes preliminaries of Triangular Neutrosophic Numbers, the second part describes how MEREC is used to determine criterion weights in the context of green fuel evaluation and the last part explains How TODIM is used to rank alternative green fuels in the context of green fuel evaluation.

3.1 | Preliminaries of Triangular Neutrosophic Sets [21, 48]

A TNN is a neutrosophic number that is represented by three values: truth-membership (T), indeterminacy-membership (I), and falsity-membership (F). These values are used to describe the degree of truth, indeterminacy, and falsity of a statement or event.

A single-valued triangular neutrosophic set is known as a

$\breve{A} = (A_1, A_2, A_3); \alpha_{\breve{A}}, \theta_{\breve{A}}, \beta_{\breve{A}}, where\ A_1, A_2, A_3$ Are the lower, middle, and upper parts of the neutrosophic number.

3.1.1 | Definition and Properties of Triangular Neutrosophic Numbers

Single-valued triangular neutrosophic a = $((a_1, a_2, a_3) : \alpha_a, \theta_a, \beta_a)$ is a neutrosophic set on the real line set R. a set is classified into membership function as truth-membership function (T_a), indeterminacy membership function (I_a) and falsity membership function (F_a) and the equation formed these memberships as follows:

- T(x) represents the degree of truth that the element x belongs to the neutrosophic set.

$$T_a(x) = \begin{cases} \alpha_a \left(\frac{x-a_1}{a_2-a_1}\right) & (a_1 \le x \le a_2) \\ \alpha_a & (x = \alpha_2) \\ \alpha_a \left(\frac{a_3-x}{a_3-a_2}\right) & (a_2 \le x \le a_3) \\ 0 & otherwise \end{cases}$$

- I(x) represents the degree of uncertainty or ambiguity that the element x belongs to the neutrosophic set.

$$I_a(x) = \begin{cases} \theta_a \left(\frac{a_2 - x}{a_2 - a_1}\right) & (a_1 \le x \le a_2) \\ \theta_a & (x = \alpha_2) \\ \theta_a \left(\frac{x - a_3}{a_3 - a_2}\right) & (a_2 \le x \le a_3) \\ 1 & otherwise \end{cases}$$

- F(x) represents the degree of falsity that the element x belongs to the neutrosophic set.

$$F_a(x) = \begin{cases} \beta_a \left(\frac{a_2 - x}{a_2 - a_1}\right) & (a_1 \le x \le a_2) \\ \beta_a & (x = \alpha_2) \\ \beta_a \left(\frac{(x - a_3)}{a_3 - a_2}\right) & (a_1 \le x \le a_3) \\ 1 & otherwise \end{cases}$$

Where $\alpha_a, \theta_a, \beta_a \in [0,1]$ and $a_1, a_2, a_3 \in$ R , $a_1 \le a_2 \le a_3)$

3.1.2 | TNNs can be Operated on using Various Arithmetic Operations, such as Addition, Subtraction, Inverse, Multiplication, Division, and Score Functions

These operations are defined as follows:

Let X = $((a_1, a_2, a_3) : \alpha_a, \theta_a, \beta_a)$ and Y = $((b_1, b_2, b_3) : \alpha_b, \theta_b, \beta_b)$ be two single-valued triangular neutrosophic numbers and $\gamma \neq 0$ be any real numbers. Then,

- The addition of two triangular neutrosophic numbers X + Y =

$$\langle(a_1 + b_1, a_2 + b_2, a_3 + b_3); \alpha_a \wedge \alpha_b, \theta_a \wedge \theta_b, \beta_a \wedge \beta_b\rangle$$

- Subtraction of two triangular neutrosophic numbers X - Y =

$$\langle(a_1 - b_3, a_2 - b_2, a_3 - b_1); \alpha_a \wedge \alpha_b, \theta_a \vee \theta_b, \beta_a \vee \beta_b\rangle$$

- The inverse of the triangular neutrosophic number

$$a^{-1} = ((\frac{1}{a_3}, \frac{1}{a_2}, \frac{1}{a_1}) : \alpha_a, \theta_a, \beta_a), \text{ where } (a \neq 0)$$

- Multiplication of two triangular neutrosophic numbers X* Y =

$$XY = \begin{Bmatrix} ((a_1 b_1, a_2 b_2, a_3 b_3); \alpha_a \wedge \alpha_b, \theta_a \vee \theta_b, \beta_a \vee \beta_b) if\ (a_3 > 0,\ b_3 > 0) \\ ((a_1 b_3, a_2 b_2, a_3 b_1); \alpha_a \wedge \alpha_b, \theta_a \vee \theta_b, \beta_a \vee \beta_b) if\ (a_3 > 0,\ b_3 > 0) \\ ((a_3 b_3, a_2 b_2, a_1 b_1); \alpha_a \wedge \alpha_b, \theta_a \vee \theta_b, \beta_a \vee \beta_b) if\ (a_3 > 0,\ b_3 > 0) \end{Bmatrix}$$

- Division of two triangular neutrosophic numbers X/ Y =

$$\frac{X}{Y} = \begin{Bmatrix} \left(\left(\frac{a_1}{b_3}, \frac{a_2}{b_2}, \frac{a_3}{b_1}\right); \alpha_a \wedge \alpha_b, \theta_a \vee \theta_b, \beta_a \vee \beta_b\right) if\ (a_3 > 0,\ b_3 > 0) \\ \left(\left(\frac{a_3}{b_3}, \frac{a_2}{b_2}, \frac{a_1}{b_1}\right); \alpha_a \wedge \alpha_b, \theta_a \vee \theta_b, \beta_a \vee \beta_b\right) if\ (a_3 > 0,\ b_3 > 0) \\ \left(\left(\frac{a_3}{b_3}, \frac{a_2}{b_2}, \frac{a_1}{b_1}\right); \alpha_a \wedge \alpha_b, \theta_a \vee \theta_b, \beta_a \vee \beta_b\right) if\ (a_3 > 0,\ b_3 > 0) \end{Bmatrix}$$

- Score Function to convert to crisp numbers

$$S(r_{ij}) = \frac{(L_{ij} + m_{ij} + u_{ij})}{9} * (2 + T - I - F) \quad (1)$$

3.1.3 | A linguistic Variable is a Variable that is Expressed in Linguistic Terms which are then Displayed by Triangular Neutrosophic Numbers

This study uses a linguistic scale from Table 1 to drive the relative weights of criteria. The triangular neutrosophic scale [21, 48].

Table 1. TFN scale.

Linguistic Scale	Triangular neutrosophic Number
1	((1,1,1);0.50,0.50,0.50)
3	((2,3,4);0.30,0.75,0.70)
5	((4,5,6);0.80,0.15,0.20)
7	((6,7,8);00.90,0.10,0.10)
9	((9,9,0);1.00,00.0,0.00)

3.2 | MEREC Method for Determining Criterion Weights

The MEREC method is an MCDM method used to determine the weights of criteria in a decision-making problem. The method is based on the idea of removing the effects of each criterion one by one and evaluating the changes in the ranking of alternatives.

Step 1. Define the decision-making problem: Identify the alternatives and criteria involved in the decision-making problem.

Step 2. Identify the Decision Makers: Identify a group of decision-makers who are experts in the field and have a good understanding of the decision-making problem.

Step 3. Determine the performance matrix: Create a performance matrix that shows the performance of each alternative with respect to each criterion based on the decision maker's opinions. Decision makers express their opinions using linguistic variables in triangular neturosphic numbers as shown in Table 1.

Step 4. Then aggregate these matrices to get a decision matrix using

$$\mathcal{D}_{ij} = \frac{\sum_{j=1}^{n} S(\mathcal{Y})}{N} \tag{2}$$

Where N refers to the number of decision-makers

Step 5. Convert this triangular neutrosophic matrix into crisp numbers using Eq. (1) To get the decision matrix as form

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{im} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{im} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nj} & \cdots & x_{nm} \end{bmatrix} \tag{3}$$

Step 6. Normalize the decision matrix using this equation where B shows the set of beneficial criteria, and H represents the set of non-beneficial criteria.

$$\mathrm{n}_{\mathrm{ij}}^{\mathrm{x}} = \begin{cases} \frac{\min_{k} x_{kj}}{x_{ij}}, & if\ j \in B \\ \frac{x_{ij}}{\max_{k} x_{kj}}, & if\ j \in H \end{cases} \tag{4}$$

Step 7. Calculate the overall performance of the alternatives (Si).

$$\mathrm{S_i} = \ln\left(1 + \left(\frac{1}{m} \sum_j |\ln(\mathrm{n}_{\mathrm{ij}}^{\mathrm{x}})|\right)\right) \tag{5}$$

Step 8. Remove the effects of each criterion one by one by setting its weight to zero and recalculating the overall scores of the alternatives.

$$\grave{S_{ij}} = \ln\left(1 + \left(\frac{1}{m} \sum_{k,k\neq j} |\ln(\mathrm{n}_{\mathrm{ik}}^{\mathrm{x}})|\right)\right) \tag{6}$$

Step 9. Compute the summation of absolute deviations

$$E_j = \sum_i |\ \grave{S_{ij}} - S_i| \tag{7}$$

Step 10. Finally, determine the final weights of the criteria.

$$W_j = \frac{E_j}{\sum_k E_k} \tag{8}$$

3.3 | TODIM Method for Ranking Alternative Green Fuels

The TODIM method is an MCDM method that is used to rank alternative green fuels based on their performance with respect to multiple criteria.

Step 1. Using decision matrix evaluation by decision-makers in Eq. (3) and weight calculated using MEREC method in Eq. (8).

Step 2. normalize the decision matrix as follows where B shows the set of beneficial criteria, and H represents the set of non-beneficial criteria

$$\mathcal{P}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad \text{for B} \tag{9}$$

$$\mathcal{P}_{ij} = \frac{{}^{1}/_{x_{ij}}}{\sum_{i=1}^{m} {}^{1}/_{x_{ij}}} \quad \text{for H} \tag{10}$$

Step 3. Determine the relative weight using weights obtained from MEREC using Eq. (11).

$$\breve{\mathcal{W}}_j = \frac{w_j}{\breve{\mathcal{W}}} \tag{11}$$

Where $\breve{\boldsymbol{\mathcal{W}}}$ the maximum amount of the weights.

Step 4. Calculate the dominance degree of the alternative as following equations:

$$\delta(\mathcal{A}_i, \mathcal{A}_j) = \sum_{j=1}^{m} \Phi\left(\mathcal{A}_i, \mathcal{A}_j\right)$$

$$\Phi\left(\mathcal{A}_i, \mathcal{A}_j\right) = \begin{cases} \sqrt{\dfrac{\mathcal{W}_j\,(\mathcal{P}_i - \mathcal{P}_j)}{\sum_{j=1}^{n} \breve{\mathcal{W}}_j}} & if\ (\mathcal{P}_i - \mathcal{P}_j) > 0 \\ 0 & if\ (\mathcal{P}_i - \mathcal{P}_j) = 0 \\ \dfrac{-1}{\theta}\sqrt{\dfrac{\sum_{j=1}^{n} \breve{\mathcal{W}}_j\,(\mathcal{P}_i - \mathcal{P}_j)}{\mathcal{W}_j}} & if\ (\mathcal{P}_i - \mathcal{P}_j) < 0 \end{cases} \tag{12}$$

Where $\boldsymbol{\theta}$ the attenuation factor of the losses value ranges from 1 to 10.

Step 5. Calculate the overall dominance degree of each alternative using Eq. (13):

$$\zeta_i = \frac{\sum_{j=1}^{n} \delta(\mathcal{A}_i, \mathcal{A}_j) - \min \sum_{j=1}^{n} \delta(\mathcal{A}_i, \mathcal{A}_j)}{\max \sum_{j=1}^{n} \delta(\mathcal{A}_i, \mathcal{A}_j) - \min \sum_{j=1}^{n} \delta(\mathcal{A}_i, \mathcal{A}_j)} \tag{13}$$

Step 6. Finally, rank all alternatives based on the value of the overall dominance degree.

4 | Case Study

The transportation sector is a significant contributor to global greenhouse gas (GHG) emissions, accounting for around 23% of global CO2 emissions, primarily from road transportation such as cars, trucks, and buses. The reliance on fossil fuels in this sector not only exacerbates climate change but also leads to severe environmental degradation and air pollution, which adversely affect human health and quality of life. To address these issues, it is essential to identify and promote alternative fuel options that can reduce GHG emissions and mitigate the impact of climate change. However, selecting the most suitable green fuel alternative is a complex decision-making problem, involving multiple criteria that need to be considered simultaneously. These criteria include technical performance, economic feasibility, environmental impact, and social acceptance. The problem of selecting the best green fuel alternative is a complex one. It's not as simple as just switching to biofuels, as they have their own set of drawbacks. Instead, alternative fuels like sustainable aviation fuel, emerging fuels, and vehicle conversions could be a better option. These alternatives can reduce life cycle carbon dioxide emissions compared to conventional fuels. This study proposes a Multi-Criteria Decision Making (MCDM) framework to evaluate and rank green fuel alternatives, providing a systematic approach to identify the most suitable options for reducing GHG emissions in the transportation sector. The MCDM framework incorporates the MEREC method for determining the weights of the criteria and the TODIM method for ranking the alternatives, taking into account the inherent uncertainty and ambiguity in the decision-making process. Ultimately, the best green fuel alternative will depend on various factors, including [49]:

- Technical Reliability (C1): Technical Reliability refers to the performance and dependability of green fuel in real-world applications. This criterion assesses factors such as fuel efficiency, compatibility with existing infrastructure, durability, and the maturity of the technology.
- Affordability (C2): Affordability considers the economic aspects of adopting a green fuel alternative. This criterion includes the initial investment costs, operating and maintenance costs, and the overall cost-effectiveness of the fuel.
- Availability & Durability (C3): It considers elements such as the existence of ecologically acceptable resources.
- Environmental Compatibility (C4): Environmental Compatibility assesses the environmental impact of green fuel throughout its lifecycle, from production to end-use. This criterion includes factors such as greenhouse gas emissions, air pollutants, resource consumption, and the overall ecological footprint.
- Social Acceptance (C5): Social Acceptance evaluates the societal and cultural acceptance of a green fuel alternative. This criterion considers public perception, willingness to adopt, regulatory support, and potential social impacts.

5 | Application

In this section, the integrated hybrid MEREC-TODIM method using triangular neutrosophic numbers is applied through three phases to evaluate and rank the best green fuel alternatives.

Phase 1: Data Collection

Step 1. After identifying criteria relevant to evaluating green fuel alternatives. Data is gathered on each criterion for all green fuel alternatives using decision maker's opinions in the form of linguistic variables to get Table 2 by three decision-makers and four alternatives.

Table 2. Decision maker opinion.

DMs		C1	C2	C3	C4	C5
DM1	A1	9	3	7	5	3
	A2	5	7	3	5	7
	A3	1	5	9	7	5
	A4	3	7	1	1	1
DM2	A1	5	7	3	9	1
	A2	1	3	7	5	5
	A3	9	9	7	1	7
	A4	3	5	1	3	9
DM3	A1	1	3	5	3	5
	A2	3	7	9	7	9
	A3	5	5	7	5	7
	A4	7	3	3	1	3

Step 2. Triangular neutrosophic numbers to account for uncertainties and imprecisions using the decision maker's opinions as expressed in Table 1 convert linguistic variables into triangular neutrosophic numbers.

Step 3. Then using score function Eq. (1) to convert triangular neutrosophic numbers into crisp numbers then aggregate this decision maker's matrix using Eq. (2) to get aggregated decision matrix as Table 3.

Table 3. Aggregated decision matrix.

	C1	C2	C3	C4	C5
A1	3.528	2.667	3.744	3.644	1.811
A2	1.811	4.483	4.383	4.822	5.461
A3	3.528	4.722	6.2	3.628	5.561
A4	2.667	3.744	0.617	0.617	2.45

Phase 2: Calculating weight using the MEREC method

Applying the MEREC method to get weight for the five criteria, typically involves the following steps:

Step 4. Normalize the aggregated matrix found in Table 3 where the set of beneficial criteria (C1, C3, C4), and the set of non-beneficial criteria (C2, C5) using Eq. (4) to get a normalized decision matrix as shown in Table 4.

Step 5. Use Eq. (5) to calculate the overall performance of the alternatives as shown in the first column in Table 5 then Eq. (6) to remove the effects of each criterion one by one as presented in Table 5.

Step 6. Compute the summation of absolute deviations using Eq. (7) and calculate the final weight for each criteria using Eq. (8) as shown in Table 5.

Table 4. normalized decision matrix.

	C1 +	C2 -	C3 +	C4 +	C5 -
A1	0.513386	0.564706	0.164688	0.169207	0.325674
A2	1	0.949412	0.140684	0.12788	0.982018
A3	0.513386	1	0.099462	0.169985	1
A4	0.679167	0.792941	1	1	0.440559

Table 5. Finial weight using MEREC method.

Si		C1 +	C2 -	C3 +	C4 +	C5 -
0.783021	A1	0.720143	0.729375	0.602858	0.605816	0.674831
0.597512	A2	0.597512	0.591783	0.354413	0.340933	0.595513
0.667496	A3	0.596639	0.667496	0.397268	0.466837	0.667496
0.252874	A4	0.190904	0.216175	0.252874	0.252874	0.116697
	Ej	0.195705	0.096074	0.69349	0.634444	0.246366
	Wj	0.104875	0.051485	0.37163	0.339988	0.132023

Phase 3: TODIM Method to rank green fuel alternatives

TODIM is a decision-making method that aims to determine the best alternative as follows:

Step 7. Using aggregated decision matrix in Table 3 to normalize using Eqs. (9) and (10) to get TODIM normalized decision matrix as Table 6. Using Eq. (11) and MEREC weight calculated in step 6 to get relative weight as shown in last row in Table 6.

Step 8. Using Eq. (12) to calculate the dominance degree of the alternative consider that $\boldsymbol{\theta} = 1$ the final result shown in Table 7.

Step 9. The overall dominance degree of each alternative is computed using Eq. (13) and finally the alternative based on the dominance degree value to evaluate the alternatives as presented in Table 7.

Table 6. Normalized decision matrix.

	C1 +	C2 -	C3 +	C4 +	C5 -
A1	0.305877	0.34823	0.250558	0.286713	0.417268
A2	0.157033	0.207125	0.293309	0.379371	0.138382
A3	0.305877	0.196647	0.41487	0.285402	0.135893
A4	0.231214	0.247997	0.041264	0.048514	0.308457
W~	0.282203	0.138537	1	0.914856	0.355254

Table 7. Final rank.

	$\Phi\left(\mathcal{A}_i, \mathcal{A}_j\right)$	**Ɛ**	**RANK**
A1	0.021748	1	1
A2	-7.76545	0.111151	3
A3	-5.16447	0.408032	2
A4	-8.73924	0	4

6 |Results and Discussion

6.1 |Results

The MEREC-TODIM method, augmented by triangular neutrosophic numbers, provides a structured approach to evaluating and ranking green fuel alternatives. However, stakeholders should consider specific contextual factors and conduct further analysis to align with broader sustainability goals and operational requirements. This comprehensive analysis not only identifies the best green fuel alternative but also supports informed decision-making towards reducing greenhouse gas emissions and promoting sustainable practices. The criteria weight is presented in Table 5. These weights indicate the relative importance of each criterion in the decision-making process. C3 (Availability & Durability) holds the highest weight followed by C4 (Environmental Compatibility) and then C5 (Social Acceptance) C1 (Technical Reliability) and C2 (Affordability) have the lowest weights, suggesting they are less influential in the overall evaluation. From the results, it can be seen that Alternative 1 (A1) is ranked as the best green fuel alternative, followed by Alternative 3 (A3), Alternative 2 (A2), and Alternative 4 (A4). The ranking suggests that A1 is the most suitable green fuel alternative for reducing GHG emissions, considering the technical, economic, environmental, and social aspects. By considering the relative importance of each criterion and the performance of each alternative, decision-makers can make informed choices that align with their sustainability goals and operational requirements.

6.2 |Comparative Analysis

To validate the results of the integrated hybrid MEREC-TODIM method, a comparative analysis is conducted with other MCDM methods. The results of the comparative analysis are presented in Table 8, which shows the ranking of the green fuel alternatives using TOPSIS and VIKOR methods.

Table 8. Comparative analysis.

	VIKOR		**TOPSIS**	
	Qi	RANK	Ci	RANK
A1	0.071857	3	0.332455	4
A2	0.12714	2	0.364246	3
A3	0.026528	4	0.369138	2
A4	1	1	0.369479	1

Spearman's correlation is a statistical method used to determine the correlation between two ordinal variables. It is a non-parametric test, which means it doesn't require a normal distribution of the data [50]. The Spearman's correlation is calculated using

$$\rho = 1 - \frac{6\ \sum_{m=1}^{n} d_m^2}{n\,.\,(n^2 - 1)}$$

Where n = is the number of alternatives and dm is the difference between the two ranks of alternatives.

In the context of the green fuel alternatives evaluation, Spearman's correlation can be used to analyze the relationship between the rankings of the alternatives in comparative analysis. After applying Spearman's correlation using comparative analysis the result is shown in Table 9.

Table 9. Spearman's correlation.

TODIM	TOPSIS	diff	TODIM	VIKOR	diff
1	4	9	1	3	4
3	3	0	3	2	1
2	2	0	2	4	4
4	1	9	4	1	9
	SpCorrel	-0.8		SpCorrel	-0.8

If ρ has a value close to +1 or −1, it means that it is a strong correlation. However, if the value of ρ is close to 0, it means that it is a weak correlation. So, from this table the Spearman's correlation coefficient (SpCorrel) between the TODIM and TOPSIS rankings is -0.8, indicating a strong negative correlation between the two methods. The (SpCorrel) between the TODIM and VIKOR rankings is also -0.8, indicating a strong negative correlation between the two methods. The negative correlation suggests that the rankings of the alternatives using TODIM are inversely related to the rankings using TOPSIS and VIKOR. This means that alternatives that are ranked high using TODIM tend to be ranked low using TOPSIS and VIKOR, and vice versa.

6.3 | Sensitivity Analysis

Sensitivity analysis refers to the process of evaluating how changes in the inputs or assumptions of a decision model affect the results or outcomes. It helps decision-makers understand the robustness of their decisions and identify critical factors that significantly impact the results. θ is a crucial parameter in the TODIM method, as it determines the importance of the criteria in the decision-making process. By varying the value of θ, you can analyze how the rankings of the green fuel alternatives change in response to different attenuation factors as they range from 1 to 10. Table 10 shows the final rank after changing the θ value in a random way.

Table 10. Sensitivity analysis.

	Θ =1	Θ = 1.5	Θ = 2	Θ = 2.3	Θ = 3.7	Θ = 6.4	Θ = 10
A1	1	1	1	1	1	1	1
A2	3	3	3	3	3	3	3
A3	2	2	2	2	2	2	2
A4	4	4	4	4	4	4	4

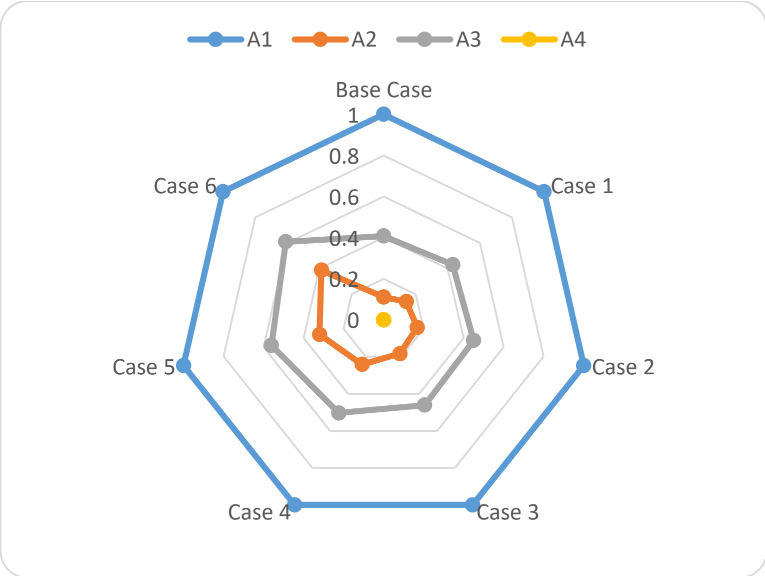

Figure 1. Sensitivity analysis

From the table, it appears that the rankings of the alternatives are relatively robust to changes in the value of θ. The rankings remain the same across all scenarios, with A1 being the top-ranked alternative, followed by A3, A2, and A4. This suggests that the decision is not highly sensitive to changes in the attenuation factor and that the rankings of the alternatives are relatively stable across different values of θ. Figure 1, would likely show a graph of the rankings of the alternatives across the different values of θ, providing a visual representation of the sensitivity analysis results. Finally, The TODIM method is not highly sensitive to changes in the attenuation factor in this particular decision-making context.

6.4 | Implications for Decision-Making

These findings provide valuable insights for stakeholders aiming to reduce GHG emissions and promote sustainable practices. The results underscore the importance of considering not only technical feasibility but also factors such as durability, environmental impact, and social acceptance when selecting green fuel alternatives.

6.5 | Limitations and Future Research

While the MEREC-TODIM method with triangular neutrosophic numbers offers a structured approach, further research could explore additional criteria or refine existing methodologies to better align with evolving sustainability goals and operational requirements.

7 | Conclusion

The study concludes with a summary of the main findings, highlighting the contributions and implications of the proposed MCDM framework for evaluating and ranking green fuel alternatives. The conclusions provide insights and recommendations for policymakers and industry stakeholders to promote the adoption of green fuels for reducing greenhouse gas emissions. This study proposes a comprehensive Multi-Criteria Decision Making (MCDM) framework to assess and rank green fuel alternatives for mitigating greenhouse gas emissions. The framework integrates the MEREC method for determining criterion weights and the TODIM method for ranking alternatives, utilizing Triangular Neutrosophic Numbers to handle uncertainty and ambiguity. The results of the case study demonstrate the effectiveness of the proposed framework in evaluating and ranking green fuel alternatives based on multiple criteria. The findings suggest that Alternative 1 is the most suitable green fuel alternative, followed by Alternative 3, Alternative 2, and Alternative 4. The comparative analysis with other MCDM methods, such as TOPSIS and VIKOR, reveals a strong negative correlation between the rankings of the alternatives using TODIM and TOPSIS, and VIKOR. The sensitivity analysis shows that the rankings of the alternatives are relatively robust to changes in the value of θ.

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Data Availability

The datasets generated during and/or analyzed during the current study are not publicly available due to the privacy-preserving nature of the data but are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest in the research.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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