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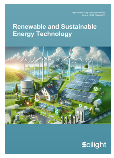

Article

Multi-Criteria Decision-Making for Selecting Renewable and Sustainable Gasoline Biofuel Additives Based on an Integrated AHP-TOPSIS Model

Montaser Mahmoud [1], Tamer M. M. Abdellatief [1,2], Ridvan Aydin [3] and Mohammad Ali Abdelkareem [1,2,*]

1 Sustainable Energy & Power Systems Research Centre, RISE, University of Sharjah, Sharjah P.O. Box 27272, United Arab Emirates
2 Chemical Engineering Department, Minia University, Elminia 61519, Egypt
3 Department of Industrial Engineering and Engineering Management, College of Engineering, University of Sharjah, Sharjah P.O. Box 27272, United Arab Emirates
* Correspondence: mabdulkareem@sharjah.ac.ae

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Abstract: The production of biofuel from locally available biomass resources is a crucial step toward achieving a sustainable energy production system. As a result, it is crucial to select a suitable biomass resource by considering its availability and combining several other factors simultaneously. Since conventional single-criteria decision-making techniques can no longer handle such complexity, multi-criteria decision-making (MCDM) is recommended. The current paper aims to apply MCDM to select renewable and sustainable gasoline biofuel additives to produce high-octane gasoline with high gasoline engine performance and low exhaust emissions based on an integrated AHP-TOPSIS model. The compared gasoline biofuel alternatives are isopropanol, ethanol, methanol, isobutanol, di-isobutylene, n-butanol, and (Di isopropyl ether) DIPE. Ten technical criteria that address various elements such as research octane number, motor octane number, density, Reid vapor pressure, boiling point temperature, auto-ignition temperature, heat of evaporation at 25 °C, Flashpoint, stoichiometric air-fuel ratio (AFR), and laminar flame speed are used in MCDM. The overall MCDM results revealed that isopropanol and ethanol achieved the highest rankings, which is consistent with the advantages and technical characteristics of the gasoline biofuel additives. The ranking of gasoline additives places isopropanol at the top with a score of 0.6576, primarily due to its anti-knock properties, which contribute to the formation of gasoline with high octane, which is environmentally in fuel blending. This was closely followed by ethanol and isobutanol, with scores of 0.6301 and 0.626, respectively.

Keywords: multi-criteria decision-making; gasoline biofuel; Analytical Hierarchy Process; gasoline additives; TOPSIS

1. Introduction

Energy crops and biodegradable wastes from industry, agriculture, and households are two possible strategies for utilizing renewable energy sources in sustainable fuel production: either completely substituting fossil fuels with biofuels or reformulating fossil fuels with biofuel additives. Although reformulation additives should match the qualities of gasoline, biofuel additives do not require modifications to the current fleet of engines in transport vehicles; hence, this option has attracted significant attention. This means that biomass-derived oxygenates added to gasoline should have the same qualities as current gasoline, namely density, viscosity, and compressibility, within an acceptable range. These biomass-derived oxygenates can also be used to reduce the aromatic component of gasoline, which normally has detrimental effects on health [1].

Chemicals made from biomass can be added to gasoline as biofuel additives to improve the fuel's characteristics and efficiency, thereby reducing greenhouse gas emissions, lessening the environmental effects of fossil fuels, and enhancing energy security through fuel source diversification, which are the main reasons for adopting biofuel additives. Alternative and sustainable fuels are becoming increasingly popular due to growing environmental concerns and the depletion of fossil fuel supplies. Because they are sustainable and have the potential to lower greenhouse gas emissions, biofuels made from biomass are viewed as a possible solution to these problems. However, choosing the right biofuel additives for gasoline is a difficult process that considers several factors, such as performance qualities, economic viability, and environmental effects. Figure 1 illustrates the overview of gasoline biofuel additives, including the resources, production processes, several types of renewable gasoline biofuel and their characteristics, and the current challenges.

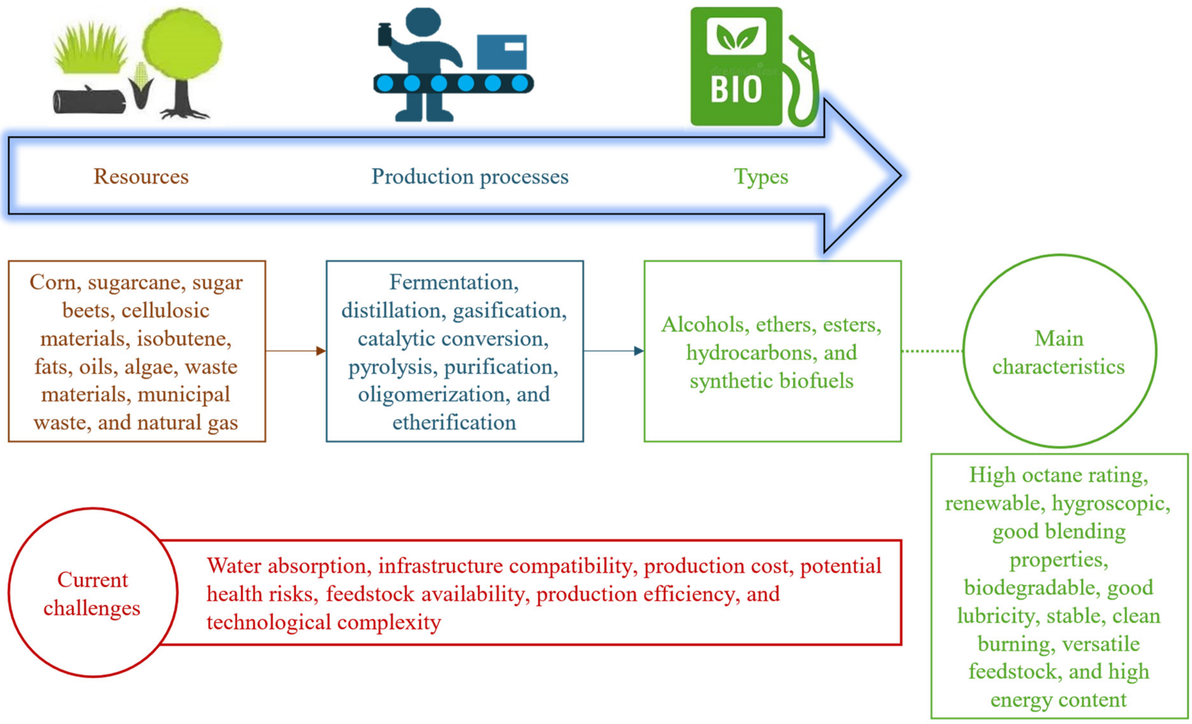

Figure 1. Overview of gasoline biofuel additives.

With an emphasis on increasing octane levels and lowering hazardous emissions, future gasoline additives can potentially revolutionize the energy and automobile industries. Developing new gasoline additives is crucial as environmental rules become more rigorous and demand for high-performance engines increases. The industry seeks to improve engine performance and lower emissions by concentrating on novel solutions, including alcohols, ethers, and environmentally friendly production techniques. These additives are essential to the shift to cleaner and more efficient transportation fuels as research advances and market demand changes.

By reducing carbon dioxide emissions and other greenhouse gases, biofuel additives can dramatically lessen the carbon footprint of transportation. Biofuels are sustainable and renewable, derived from various biomass sources, in contrast to fossil fuels. Utilizing biofuel additives to diversify fuel sources can lessen reliance on foreign oil imports and improve energy security. High octane values in biofuel additives, such as ethanol, isopropanol, isobutanol, and methanol, enhance engine efficiency and performance. However, adopting biofuel additives comes with challenges, including changes in land use, the need for infrastructural adjustments to accommodate larger biofuel blends, and potential impacts on the food supply in the case of food-based biofuels.

One of the most often utilized biofuel additives in gasoline is ethanol, a type of alcohol. The main sources of biomass used in its production include cellulosic feedstocks, maize, and sugarcane. Adding ethanol to gasoline offers numerous advantages, such as better fuel quality, lower emissions, and increased energy security. The most common method for producing ethanol is through the fermentation of sugars from biomass by yeast or bacteria. In the United States, corn is the primary ingredient used to produce ethanol, while sugarcane serves as the main feedstock in Brazil. Additionally, non-food biomass, such as woody materials, grasses, and agricultural waste, is also used to produce ethanol. It entails dissolving complicated carbs into sugars that can ferment. Additionally, ethanol can be chemically produced, although this is less frequently done for fuel uses. Because ethanol contains oxygen, it helps gasoline burn more completely, which lowers hazardous pollutants including carbon monoxide, hydrocarbons, and particulate matter. Compared to fossil fuels, ethanol has a smaller carbon footprint, lowering greenhouse gas emissions over its life cycle [2].

Another type of alcohol that can be used as an addition to gasoline is isopropanol, also referred to as isopropyl alcohol. Even though isopropanol isn't as widely utilized as ethanol, it still has several advantages and special qualities that make it a good option for improving gasoline. Emerging biotechnological technologies ferment biomass utilizing genetically modified microbes to manufacture isopropanol, providing a sustainable manufacturing route. Because of its high-octane number, isopropanol helps gasoline's anti-knock qualities, which improves engine efficiency and performance. Additionally, using isopropanol can help minimize greenhouse gas emissions and dangerous pollutant emissions, which will encourage cleaner air and less environmental effects. Isopropanol is a sustainable substitute for fossil fuels since it can be made from renewable biomass sources. It can be produced chemically by reactions using feedstocks sourced from biomass or through fermentation techniques. The use of isopropanol as an additive in gasoline is still being under investigation. It presents a robust option for next fuel formulations due to its potential advantages in pollution reduction, combustion efficiency, and renewability. Research is concentrated on cost-effectiveness, production technique optimization, and engine-type performance evaluation of isopropanol-gasoline blends [3].

There is growing interest in isobutanol as a possible addition to gasoline. Compared to more conventional biofuels like ethanol, this advanced biofuel has several benefits. Microbial fermentation of biomass, such as agricultural wastes, maize stover, or switchgrass, using strains of yeast or bacteria that have been specifically designed to create isobutanol. Catalyst-based solutions are being explored to convert products of biomass gasification into isobutanol. Because of its high-octane rating, isobutanol helps gasoline's anti-knock qualities, boosts engine performance, and increases fuel efficiency. Compared to the manufacture of gasoline, isobutanol synthesis can have lower greenhouse gas emissions, particularly when it is derived from cellulosic biomass. Because isobutanol has a lower vapor pressure than ethanol, it minimizes the possibility of vapor lock in engines and lowers evaporative emissions. Because isobutanol has a greater energy density than ethanol, internal combustion engines can produce more power and use less fuel. The likelihood of gasoline lines, seals, and other engine parts being damaged is decreased by isobutanol's lower corrosiveness level than ethanol. This eliminates the need for major changes and increases its compatibility with current fuel infrastructure and automobiles.

The effects of adding di-isopropyl ether to gasoline in a twin-cylinder spark ignition engine were investigated by Sathyanarayanan et al. [4]. At 2500 rpm engine speed and 10:1 compression ratio, using 25% di-isopropyl ether/75% gasoline resulted in 4% and 12% increases in brake thermal efficiency and NO levels, respectively, when compared to pure gasoline. Di-isopropyl ether and gasoline mixes were studied by Dhamodaran et al. [5] in a 993 cm^3 spark ignition engine with a multi-point fuel injection system. At 2800 rpm engine speed and 25 N-m load, the brake thermal efficiency was 4% greater with 30% di-isopropyl ether added to gasoline than with pure gasoline. Furthermore, alcohol/gasoline surrogate blends, including ethyl alcohol, isopropyl alcohol, n- and isobutanol, have been studied by Lu et al. [6], Saisirirat et al. [7], and Boehman and colleagues [8,9] under homogeneous charge compression ignition (HCCI) operation. These studies discovered that alcohol blending can inhibit low-temperature heat release (LTHR), leading to delayed timings and larger initial exothermicity values. Furthermore, overall reactivity was decreased to the point that combustion phasing was slowed; in order to obtain equivalent phasings, the engine's compression ratio had to be raised. Moreover, the methanol–gasoline blend with hydrogen enrichment and a total input energy of 5% were reported by Sarikoc [10]. Additionally, they saw a decline in performance with the addition of methanol but an improvement in the environment when methanol and hydrogen were mixed. Finally, another study applied Co-optima in conjunction with traditional and reformulated blendstock for oxygenate blending (BOB) at concentrations of 10, 20, and 30% di-isobutylene. They observed inconsistent mixing of motor octane number (MON) but research octane number (RON) blends linearly, increasing octane sensitivity when the blend level is raised [11].

Recently, Multi-Criteria Decision-Making (MCDM) approaches have gained significant attention across various domains, including biofuel sustainability assessment, due to their ability to handle multiple conflicting criteria. In the biofuel sector, these methods have been applied to evaluate different feedstocks, production processes, and policy impacts by incorporating stakeholder perspectives and addressing uncertainties. In [12], a range-based multi-actor multi-criteria analysis was applied to assess the sustainability of microalgae biodiesel compared to first- and second-generation biofuels in France. By incorporating stakeholder perspectives and using Monte Carlo simulations to account for uncertainties, the study found that microalgae biodiesel could contribute to sustainability objectives in the transport sector. Haase et al. [13] compared gasoline from straw, wood, and conventional sources, considering ecological, economic, and social factors. TOPSIS results showed that economically focused stakeholders prefer conventional gasoline, while those prioritizing ecological and social aspects favor gasoline from wood. Akhtari et al. [14] proposed a risk-based MCDM approach to evaluate biofuel production from construction and demolition wood waste, using the mini-max regret method to rank alternatives under uncertainty. Applied to Vancouver's waste management options, results recommend installing a large facility, with sensitivity analysis confirming the robustness of this choice. A hybrid MCDM approach, integrating TOPSIS, ARAS, and WASPAS with ranking aggregation methods, was used in [15] to prioritize biomass resources for biofuel production in Guilan, Iran. The results reveal that municipal solid waste and sewage, forest and wood farming wastes, and livestock and poultry wastes are the most significant resources for second-generation biofuels.

The MCDM techniques offers a methodical approach for assessing and ranking distinct biofuel additives based on specific criteria. These techniques assist in making well-informed judgments by taking into account several variables at once. The Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are common MCDM approaches used in this area for evaluating the criteria weights and alternatives rankings, respectively. By including these methods in the selection process, this paper aims to apply MCDM to select renewable and sustainable gasoline biofuel additives based on an integrated AHP-TOPSIS model to produce high-octane gasoline with high engine performance and low exhaust emissions. Biofuel additives are evaluated thoroughly, considering all related technical criteria, which include research octane number, motor octane number, density, Reid vapor pressure, boiling point temperature, auto-ignition temperature, heat of evaporation at 25 °C, Flashpoint, stoichiometric air-fuel ratio (AFR), and laminar flame speed. The compared alternatives as gasoline biofuel additives are isopropanol, ethanol, methanol, isobutanol, di-isobutylene, n-butanol, and DIPE.

2. Methodology

An integrated AHP-TOPSIS model within the MCDM approach is adopted to evaluate the selection of biofuel additives, as shown in Figure 2. This procedure has demonstrated its effectiveness in selecting optimal solutions for renewable energy systems, as evidenced by recent research studies [16]. Initially, the key factors influencing the selection are identified and alternatives to be compared are determined. Subsequently, a pair-wise comparison matrix is distributed to experts to compare the identified criteria. The resulting matrices are processed through the AHP model to calculate the weight of each criterion, reflecting its relative importance. These weights, combined with the collected data, are then utilized in the TOPSIS model to evaluate and rank the alternatives based on their performance across all criteria.

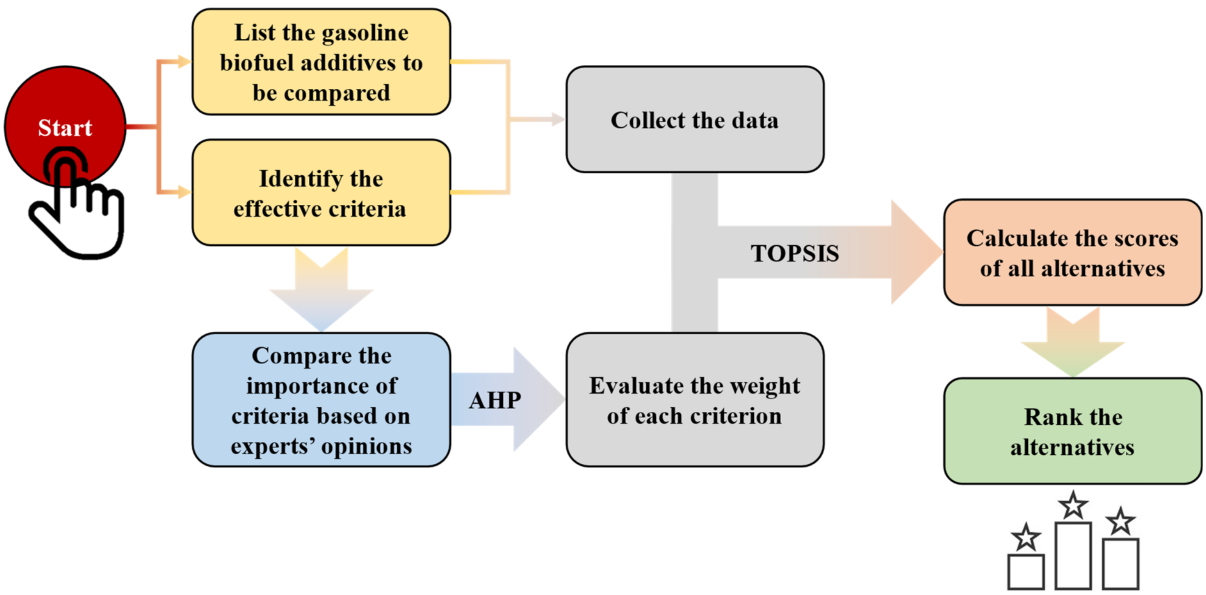

Figure 2. Research methodology flowchart.

2.1. Criteria and Alternatives

2.1.1. Alternatives

In MCDM, alternatives refer to the various choices or courses of action available to a decision-maker. Several technical criteria are taken into consideration while evaluating these alternatives, which will be discussed in detail in the next section. Finding and evaluating these options is an essential step since it makes it possible to compare them all in detail and choose the best one. To ensure a well-informed and logical decision, the alternatives are quantified and prioritized in a way consistent with the decision-makers preferences and objectives. The alternatives used as gasoline biofuel additives are isopropanol, ethanol, methanol, isobutanol, di-isobutylene, n-butanol, and DIPE. Figure 3 exhibits the schematic illustration of gasoline biofuel additives as octane enhancers, including the primary resources for gasoline biofuel additives, production processes of biofuel gasoline additives, and studied renewable and sustainable gasoline biofuel additives as octane enhancers.

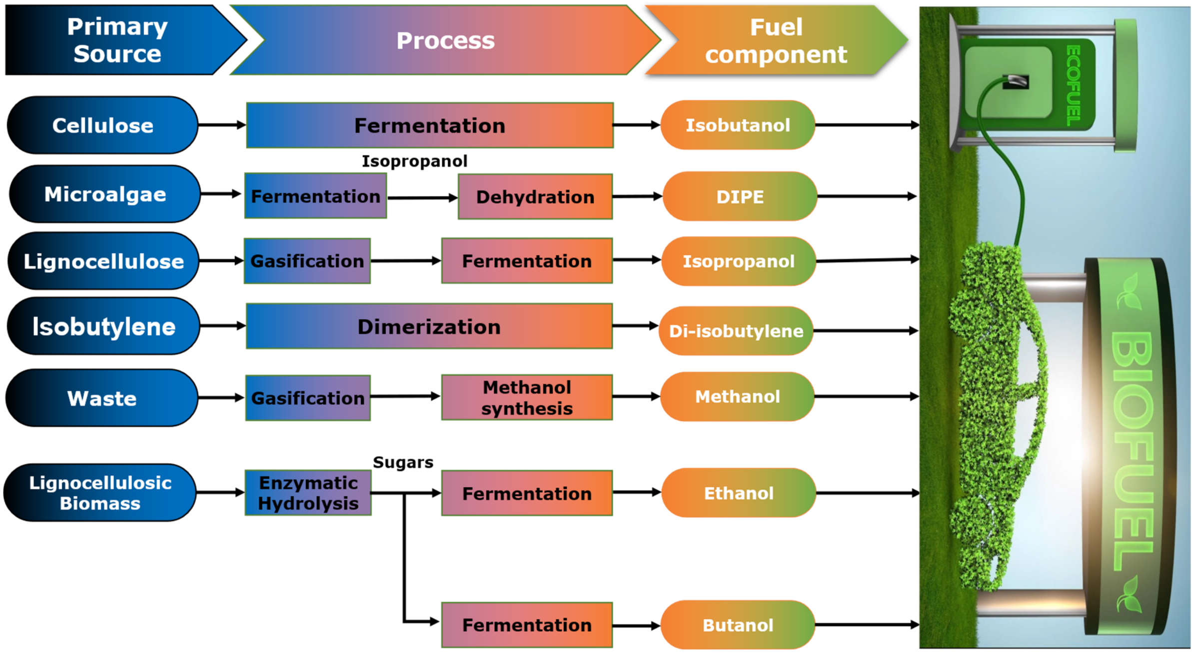

Figure 3. Schematic diagram of alternatives' production processes.

Several important elements are considered while rating gasoline additives since they affect the fuel's sustainability and performance. Figure 4 shows the justification for positive and negative factors. While negative variables call attention to possible hazards such as engine knock, incomplete combustion, emissions, and safety issues, positive aspects emphasize the significance of additives that enhance fuel performance, safety, and sustainability. Choosing the most efficient and environmentally friendly gasoline additives requires balancing these variables.

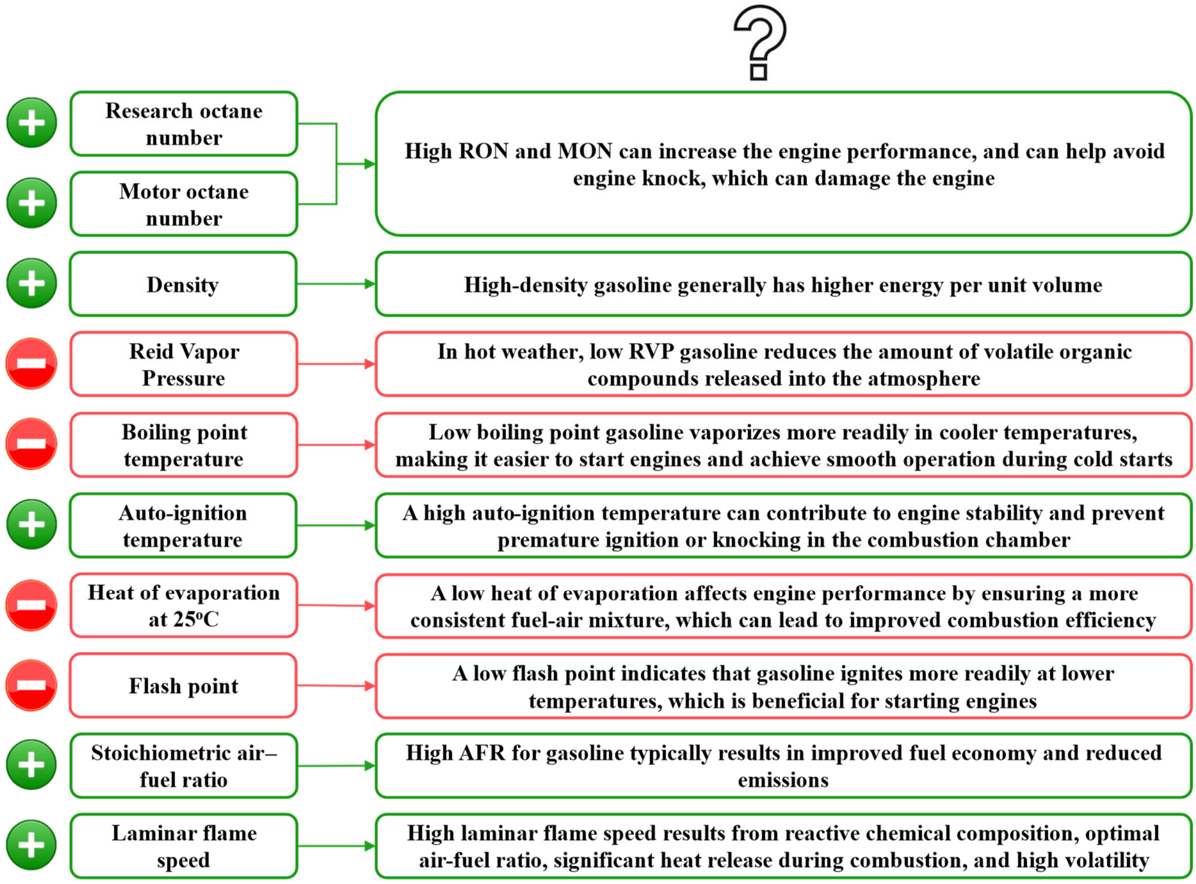

Figure 4. Justification for positive and negative factors.

2.1.2. Criteria Description

The practice of assessing and prioritizing several competing criteria in scenarios involving decision-making is known as MCDM. It entails assessing alternatives methodically while considering a range of influencing elements. With the use of MCDM approaches, decision-makers can choose the best option by considering each criterion's relative relevance. These methods can be used to streamline complicated decision-making processes in a variety of industries, including engineering, business, healthcare, and environmental management. MCDM's main purpose is to offer a thorough framework that takes into consideration all of a problem's aspects, allowing decision-makers to make better-educated and balanced choices that are in line with the interests and overarching goals of all parties involved. In this study, ten criteria that address various elements such as research octane number, motor octane number, density, Reid vapor pressure, boiling point temperature, auto-ignition temperature, heat of evaporation at 25 °C, Flashpoint, stoichiometric AFR, and laminar flame speed are used in MCDM. Furthermore, the definition of these criteria considered in the current study is shown in Table 1.

Table 1. Definition of the different criteria considered in the current study.

	Criteria	Description
C1	Research Octane Number (RON)	This property assesses its resistance to engine knocking, a phenomenon where uncontrolled combustion occurs in the engine's cylinders. RON can be measured when the engine is performed at a low rpm of 600 and correlates best with low-speed and mild-knocking conditions.
C2	Motor Octane Number (MON)	This property is used to assess its resistance to engine knocking, a phenomenon where uncontrolled combustion occurs in the engine's cylinders. MON can be measured at much more severe conditions of around 900 rpm and MON correlates best with high-speed and high temperature-knocking conditions
C3	Density [kg/m^3]	Fuel density is a significant property because it affects the fuel economy and controls the amount of fuel burned in the combustion chamber. The higher the fuel density is, the more energy is acquired.
C4	Reid Vapor Pressure (RVP) [kPa]	The objective of measuring RVP is crucial for ensuring the safe handling and transportation of gasoline, reducing environmental impacts, and optimizing engine performance.
C5	Boiling Point Temperature [°C]	The objective of determining the boiling point temperature for gasoline is to understand the temperature at which gasoline transitions from a liquid to a vapor phase under standard atmospheric pressure.

Table 1. *Cont.*

	Criteria	Description
C6	Auto-ignition temperature [°C]	The objective of determining the auto-ignition temperature for gasoline is to understand the temperature at which gasoline will spontaneously ignite without an external ignition source.
C7	Heat of evaporation at 25 °C [kJ/kg]	The objective of determining the heat of evaporation at 25 °C for gasoline is to understand the energy required to change the state of gasoline from liquid to vapor at that specific temperature.
C8	Flash point [°C]	The objective of determining the flash point for gasoline is to assess its flammability and safety during handling, storage, and transportation.
C9	Stoichiometric air–fuel ratio (AFR)	The objective of determining the stoichiometric AFR is to identify the precise ratio of air to fuel required for the complete combustion of a given fuel.
C10	Laminar flame speed [cm/s]	The objective of determining the laminar flame speed for gasoline is to understand how quickly a flame propagates through a gasoline-air mixture under certain conditions. Laminar flame speed refers to the speed at which a flame front advances through a stationary mixture without any turbulence.

2.2. AHP-TOPSIS

A schematic diagram presenting the AHP-TOPSIS model employed in the current study is depicted in Figure 5. The figure indicates the main objective of the study and the technical criteria utilized and the compared alternatives. In the subsequent subsections, we will explain in detail the steps followed to apply the AHP and TOPSIS models for evaluating the criteria weights and alternatives' scores, respectively.

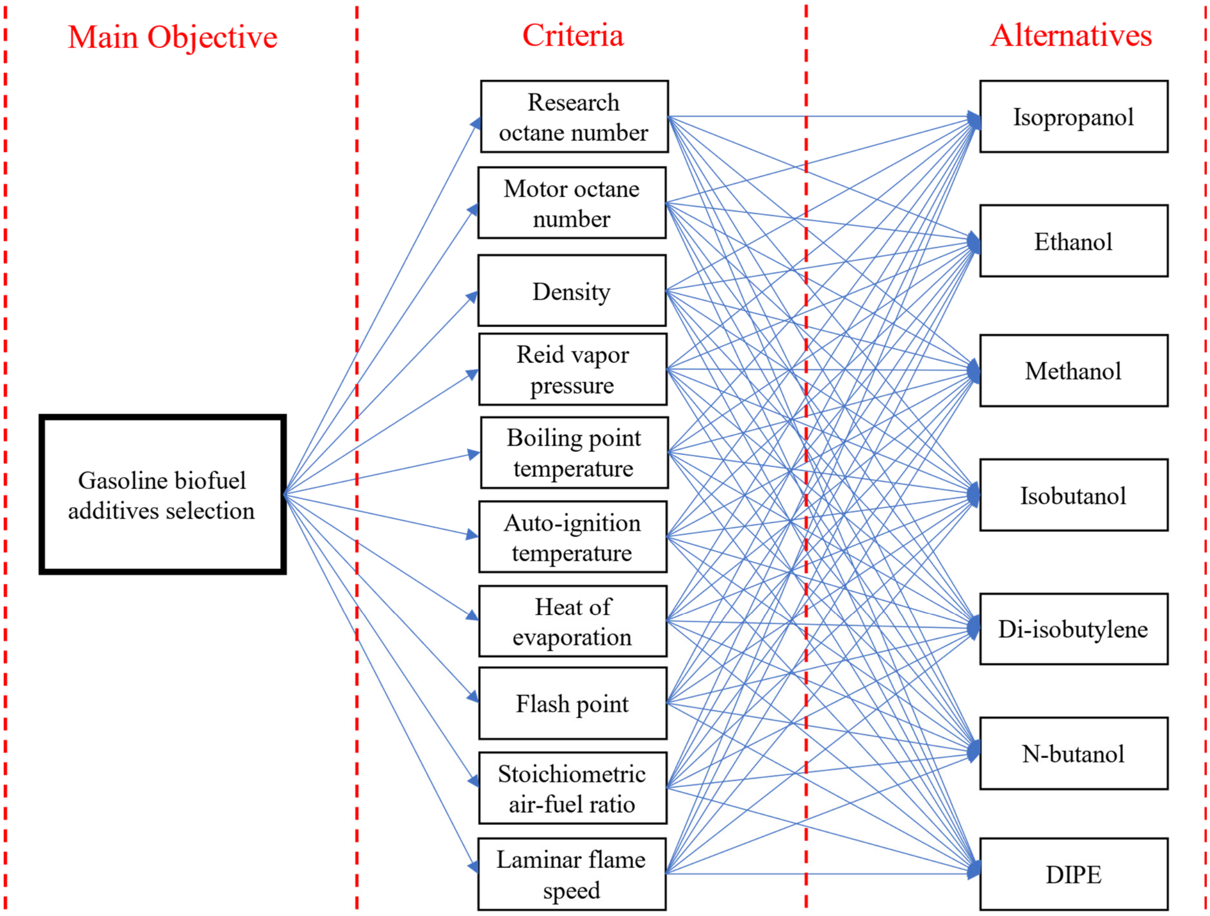

Figure 5. Hybrid analytical hierarchal process-TOPSIS model.

2.2.1. AHP Weighting Model

Saaty [17] proposed the Analytic Hierarchy Process (AHP) to facilitate decision-making in complex scenarios by analyzing multiple criteria based on a hierarchical structure and their relative importance. AHP helps rank options for decision-making, with sensitivity analysis applied to criteria and standards to assess outcomes. Additionally, it assesses consistency in decisions, simplifying calculations and evaluations [18]. A key advantage of AHP is its ability to structure the decision problem by establishing criteria, sub-criteria, and alternatives in a logical way [19]. AHP ensures the weights assigned to criteria and sub-criteria accurately reflect the decision-maker's preferences, validated through consistency checks. This step is crucial as the quality of decision-making depends on how well the weights reflect the importance of each criterion [20].

The steps followed to calculate the weights of the criteria using the AHP method are presented below:

- **Prepare the pair-wise comparison matrix:**

The pair-wise comparison matrix (D) is presented in Equation (1) where d_{ij} represents the decision maker's preference for the *i*-th criterion over the *j*-th criterion, as follows:

$$D = \begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nn} \end{bmatrix} \tag{1}$$

where *n* denotes the number of independent matrix rows.

The values of the pair-wise comparison matrix d_{ij} are assigned based on experts' judgment. Decision-makers compared each criterion's relative importance using Saaty's fundamental scale, which ranges from 1 (equal importance) to 9 (extreme importance). These comparisons are then structured into the matrix to reflect the decision-maker's preferences objectively.

- **Normalize the pair-wise comparison matrix:**

$$A_{norm} = \frac{d_{ij}}{\sum_{i=1}^{n} d_{ij}} \tag{2}$$

- **Calculate the weights (w_i):**

$$w_i = \frac{1}{n}\sum_{j=1}^{n} a_{ij} \tag{3}$$

where a_{ij} is the normalized value of the pairwise matrix, A_{norm}, estimated in the previous step.

- **Check the consistency:**

After the weights of the criteria are estimated, the consistency of the matrix needs to be evaluated, meaning the matrix elements must be linearly independent. This can be measured using the Consistency Index (*CI*), calculated after determining the highest eigenvalue of the matrix (λ_{max}) [17].

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{\sum_{j=1}^{n} d_{ij} \times w_i}{w_i} \tag{4}$$

The *CI* is then computed as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5}$$

As the number of pairwise comparisons increases, the likelihood of inconsistency also rises. To account for this, Saaty [17] introduced the Consistency Ratio (*CR*), estimated as follows:

$$CR = \frac{CI}{RI} \tag{6}$$

where *RI* denotes the average *CI* obtained from random simulations of pair-wise comparison matrices. The acceptable CR value should not exceed 0.1, as recommended by Saaty [17], to ensure the validity and consistency of the pair-wise comparisons. A CR value ≤ 0.1 indicates that the judgments are sufficiently consistent, whereas a higher value suggests the need to reassess the comparisons.

2.2.2. TOPSIS

Once the weights are determined using AHP, TOPSIS is applied to rank the alternatives. TOPSIS focuses on the distance of each alternative from the ideal solution (the best possible scenario) and the negative ideal solution (the worst-case scenario). By comparing the alternatives based on how close they are to the ideal solution, TOPSIS provides a clear ranking considering the trade-offs between criteria. Even if an alternative performs poorly in one criterion, strong performance in another criterion can still make it favorable. This makes the decision process more flexible and realistic in real-world scenarios.

Combining AHP and TOPSIS leverages the strengths of both methods: AHP's ability to break down and prioritize complex problems and TOPSIS's capacity to rank alternatives based on closeness to the ideal solution [21]. AHP focuses on establishing clear, consistent weights, while TOPSIS uses objective calculations to rank the alternatives, leading to well-rounded decisions. This hybrid approach ensures more robust, reliable, and justifiable decision-making, especially in situations where multiple criteria with varying importance need to be considered [22].

The TOPSIS ranking technique is a common method used to calculate the scores for the different alternatives. It can be divided into five main steps as shown below:

- **Compute Normalized Matrix:**

The original decision matrix is normalized to enable effective comparisons among criteria, as follows:

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X^2{}_{ij}}} \tag{7}$$

where X_{ij} is the value of alternative *i* for criterion *j*, and *m* is the number of alternatives.

- **Estimate the weighted normalized matrix:**

The weighted normalized matrix (V_{ij}) is determined by multiplying each column of the matrix ($\bar{X}_{ij}$) by the corresponding weight (W_j) of the criterion, obtained by the AHP method previously.

$$V_{ij} = \bar{X}_{ij} \times W_j \tag{8}$$

- **Ideal values calculation:**

This step involves evaluating the ideal best (V_j^+) in Equation (9) and ideal worst values (V_j^-) in Equation (10) based on the target of each criterion. For instance, if the criterion is considered a positive factor, then the ideal best will be the maximum value, while if it is a negative factor, then the ideal best will be the minimum value and vice versa.

$$V_j^+ = \left\{max_i\, V_{ij} \middle|\, j \in J^+, min_i\, V_{ij} \middle| j \in J^+\right\} \tag{9}$$

$$V_j^- = \left\{min_i\, V_{ij} \middle|\, j \in J^+, max_i\, V_{ij} \middle| j \in J^-\right\} \tag{10}$$

- **Estimate the Euclidean distances from the ideal best ($\boldsymbol{S_i}^+$) and worst ($\boldsymbol{S_i}^-$):**

$$S_i{}^+ = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j{}^+\right)^2} \tag{11}$$

$$S_i{}^- = \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j{}^-\right)^2} \tag{12}$$

where *n* is the number of criteria as defined in the AHP method.

- **Compute Final score ($\boldsymbol{P_i}$):**

$$P_i = \frac{S_i{}^-}{S_i{}^+ + S_i{}^-} \tag{13}$$

3. Data Collection

Liquid biofuels reduce carbon emissions while preserving the majority of the present fleet of vehicles, easing the transition to a more sustainable transportation industry. There are several options available today to generate biofuels; the choice of fuel type, mix, conversion method, and carbon source will determine the product's ultimate cost and environmental effect. Ethers and alcohols are examples of gasoline biofuel additives, and their performance is evaluated based on several factors, including cost, environmental impact, efficiency, and compatibility with existing engines. Ethers, such as di-isopropyl ether (DIPE), are frequently commended for their high-octane ratings and capacity to lower emissions. Alcohols that mix well with gasoline, such as methanol, isopropanol, isobutanol, and ethanol, are widely used since they are renewable resources. In this context, MCDM techniques can be employed to systematically compare various additives. Decision-makers can choose the additions that best fulfill their objectives by prioritizing them based on criteria, such as the energy content, greenhouse gas emissions, manufacturing cost, and infrastructure needs. For example, ethers may be preferred for their better engine performance and reduced volatility, whereas ethanol may be rated higher due to its renewability and lower greenhouse gas emissions. Ultimately, the ranking will be based on the specific needs and constraints of the stakeholders involved, ensuring a balanced and efficient selection of biofuel additives.

The current MCDM focuses solely on technological considerations, with Table 2 illustrating the criteria scores for the different alternatives. Given that each alternative has its benefits and drawbacks, comparing all options based on specific features and criteria should precede the selection of a single solution. The most important parameter to rank the selected gasoline biofuel additives and alternatives is evaluating anti-knock characteristics in terms of RON and MON. The octane value, which indicates the fuel's resistance to engine knocking or pinging during combustion, is an important consideration when assessing gasoline biofuel additives. Better resistance to knocking is indicated by higher octane levels, which result in smoother and more efficient engine operation. RON values for selected alternatives, including isopropanol, ethanol, methanol, isobutanol, di-isobutylene, n-butanol, and DIPE were 109, 130, 109, 105, 106, 92, and 129, respectively, indicating that ethanol has the highest octane number, as shown in Table 2.

Table 2. Criteria scores for the different alternatives.

	Criteria	Isopropanol "A1"	Ethanol "A2"	Methanol "A3"	Isobutanol "A4"	Di-Isobutylene "A5"	n-Butanol "A6"	DIPE "A7"
C1	Research Octane Number, (RON)	109	130	109	105	106	92	129
C2	Motor Octane Number, (MON)	97	96	88.6	90	87	78	94
C3	Density, kg/m^3	786	795	794	802	715	809.5	723
C4	Reid Vapor Pressure (RVP), kPa	9.7	17	31.7	3.3	11	2.2	35
C5	Boiling Point Temperature, °C	84	78	64.5	108	101.5	118	69
C6	Auto-ignition temperature, °C	399	434	464	415	420	340	443
C7	Heat of evaporation at 25◦C, kJ/kg	758	904	1146	690	318.2	710	340
C8	Flash point, °C	12	13	12	28	1.7	37	-22
C9	Stoichiometric air—fuel ratio (AFR)	10.3	9	6.3	11.2	14.7	11.2	12.1
C10	Laminar flame speed, cm/s	45	48	52.3	46	35	48	38.9
References		[2,3,11]	[2,23–26]	[27–31]	[11,26,32–34]	[11,35]	[2,26,34]	[5,36,37]

4. Results and Discussion

4.1. Criteria Weights

A pair-wise comparison matrix is used in decision-making techniques such as the Analytical Hierarchy Process (AHP) to examine the relative relevance of several criteria for assessing renewable gasoline additives. The matrix facilitates the expert judgment-based weighting of each criterion. The relative weight of each criterion in relation to the others is represented by each member of the matrix. Table 3 presents an example of a pair-wise comparison matrix. According to the AHP model outlined in the methodology section, the matrix is normalized, allowing for the computation of weights accordingly.

Table 4 exhibits the average criteria weights based on the AHP model. It is crucial to considered several factors when assessing sustainable and renewable gasoline additives, such as how they operate in fuel systems, damage the environment, and alter the characteristics of gasoline combustion. In high-compression engines especially, these octane levels must be maintained or increased by renewable gasoline additives to guarantee effective combustion and avoid engine knocking. Improved engine performance is a result of higher RON and MON values, making this criterion one of the most crucial for additive evaluation. Moreover, for effective blending and performance, renewable additives need to have a density that is compatible with regular gasoline. Densities of additives that fall within gasoline-acceptable parameters guarantee seamless integration into current fuel systems and preserve energy efficiency. Besides, the RVP should be adjusted or kept within allowable bounds by renewable additives to ensure secure and effective functioning throughout a broad temperature range. This is particularly crucial in warm regions because increased volatility may result in excessive emissions from evaporation. Additionally, beneficial boiling point additives improve fuel atomization and combustion efficiency. Although this is significant, the overall gasoline mix often affects the boiling point; therefore, a modest weight is assigned to this criterion.

Table 3. Example of pair-wise comparison matrix.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1	5	6	4	3	8	8	8	8	8
C2	1/5	1	2	2	1	6	8	8	8	8
C3	1/6	1/2	1	1	1/6	6	6	6	6	6
C4	1/4	1/2	1	1	1	7	7	7	7	7
C5	1/3	1	6	1	1	8	8	8	8	8
C6	1/8	1/6	1/6	1/7	1/8	1	1	1	1	1
C7	1/8	1/8	1/6	1/7	1/8	1	1	1	1	1
C8	1/8	1/8	1/6	1/7	1/8	1	1	1	1	1
C9	1/8	1/8	1/6	1/7	1/8	1	1	1	1	1
C10	1/8	1/8	1/6	1/7	1/8	1	1	1	1	1

Table 4. Average criteria weights based on the AHP model.

Criteria	Average Weight—AHP Model
Research Octane Number (RON)	0.321287
Motor Octane Number (MON)	0.165399
Density [kg/m^3]	0.116399
Reid Vapor Pressure (RVP) [kPa]	0.119018
Boiling Point Temperature [°C]	0.155774
Auto-ignition temperature [°C]	0.029432
Heat of evaporation at 25 °C[kJ/kg]	0.028327
Flash point [°C]	0.022273
Stoichiometric air-fuel ratio (AFR)	0.021538
Laminar flame speed [cm/s]	0.020552

Higher auto-ignition temperature gasoline additives derived from renewable resources aid in preventing engine knock, or early combustion. Though this element is slightly less important than octane ratings, a higher auto-ignition temperature is preferred, especially for high-performance engines. Similarly, engine performance can be enhanced, and the probability of knocking decreases by cooling the intake charge using renewable gasoline additives that have good evaporation properties. This characteristic is crucial to additive performance, particularly for high-performance and turbocharged engines. Furthermore, to guarantee safety during the handling, storage, and consumption of fuel, renewable gasoline additives must have a suitable flash point. Although crucial for safety, it has less weight since gasoline additives usually have a flash point that is within a safe range. Furthermore, gasoline additives that keep or slightly modify the AFR within permissible bounds guarantee efficient burning and lower emissions. Renewable fuel additives must match the AFR of gasoline to provide the best possible engine performance and emissions control. Lastly, increasing flame speed in gasoline additives can minimize unburned hydrocarbons, increase combustion efficiency, and improve engine performance. A balanced flame speed is a critical performance characteristic since it is necessary to achieve complete combustion.

4.2. Scores and Rankings

Evaluating several factors instead of just one specific criterion is necessary for making effective decisions. When faced with a multi-criteria decision dilemma, decision-makers should determine the best possibilities (alternatives). Table 5 displays the scores and ranking of gasoline biofuel additives based on the TOPSIS technique. The results of this MCDM study showed that based on the factors that were looked at, isopropanol and ethanol have the highest degree of favorability, which is consistent with the significant advantages and technical characteristics of renewable and sustainable gasoline biofuel additives in comparison with other alternatives.

The order of “isopropanol > ethanol > isobutanol > di-isobutylene > n-butanol > DIPE > methanol” probably indicates how useful or preferred these substances are as additives for gasoline. A popular gasoline additive, isopropanol comes in first place presumably because of its high anti-knock properties, which assist in producing high-octane gasoline. Next is ethanol, a popular biofuel which increases octane ratings and lowers greenhouse gas emissions. Another biofuel that is known for its compatibility with current engines and increased energy content is isobutanol. Di-isobutylene is an olefin that is used to improve fuel stability because of its anti-knock qualities. N-butanol has good blending qualities; it is comparable to isobutanol but has a distinct branching. The oxygenate DIPE aids in increasing combustion efficiency. Methanol is less desirable than other alcohols since it is more corrosive and has a lower energy content, even if it is good at raising octane and lowering pollutants.

Figure 6 illustrates the normalized score and ranks of the investigated alternatives. The highest-ranked additive is indicated in red, while the lowest is highlighted in grey. The normalized scores and ranks of the alternatives show various performance characteristics when analyzing gasoline biofuel additives. From this figure, it can be noticed that the scores of the top three alternatives are close to each other (isopropanol, ethanol, and isobutanol), while methanol and DIPE score significantly lower than all other options. The small difference between isopropanol and ethanol suggests that both additives are highly favorable and may be viable choices depending on specific priorities, such as cost, availability, or blending requirements. This closeness in scores may lead to a trade-off in decision-making, where secondary factors like production feasibility, infrastructure compatibility, and environmental policies influence the final selection.

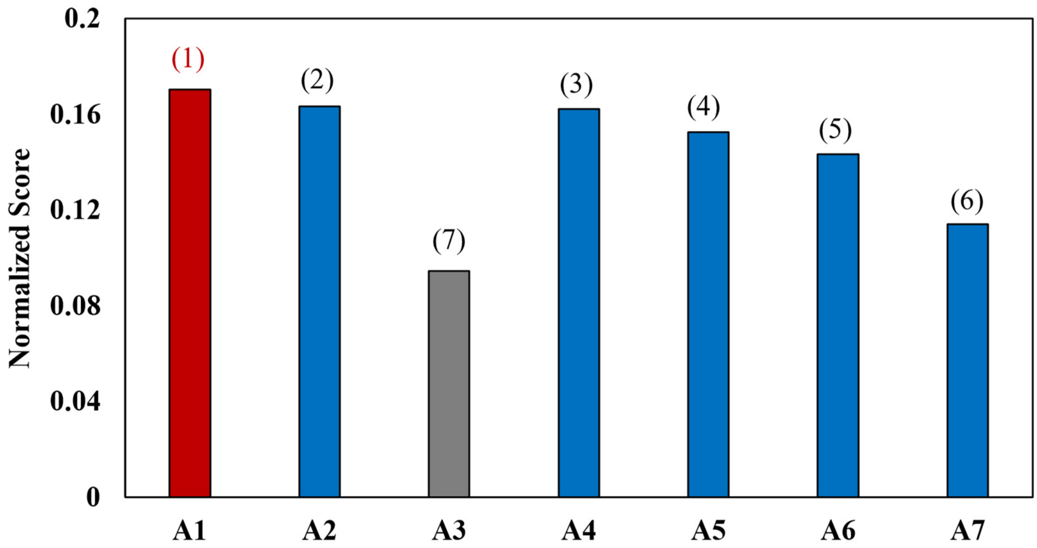

Figure 6. The normalized score and ranks of the investigated alternatives using AHP-TOPSIS, with the highest and lowest ranked alternatives marked red and grey, respectively.

Table 5. Scores and rankings of biofuel additives based on the TOPSIS technique.

	RON	**MON**	**Density**	**RVP**	**Boiling Point Temperature**	**Auto-Ignition Temperature**	**Heat of Evaporation at 25 °C**	**Flash Point**	**Stoichiometric Air–Fuel Ratio**	**Laminar Flame Speed**	**Score**	**Rank**
Isopropanol “A1”	0.118	0.0672	0.0446	0.022	0.0544	0.0106	0.0109	0.0048	0.0077	0.0078	0.6576	1
Ethanol “A2”	0.1408	0.0665	0.0451	0.0386	0.0505	0.0115	0.013	0.0052	0.0067	0.0083	0.6301	2
Methanol “A3”	0.118	0.0613	0.045	0.0719	0.0417	0.0123	0.0164	0.0048	0.0047	0.009	0.3652	7
Isobutanol “A4”	0.1137	0.0623	0.0455	0.0075	0.0699	0.011	0.0099	0.0112	0.0083	0.0079	0.626	3
Di-isobutylene “A5”	0.1148	0.0602	0.0405	0.025	0.0657	0.0112	0.0046	0.0007	0.0109	0.006	0.5886	4
n-butanol “A6”	0.0996	0.054	0.0459	0.005	0.0764	0.009	0.0102	0.0148	0.0083	0.0083	0.5532	5
DIPE “A7”	0.1397	0.0651	0.041	0.0794	0.0446	0.0118	0.0049	-0.009	0.009	0.0067	0.44	6

Ultimately, we infer that the proposed selection model provide a knowledge-based framework that can be used by different decision-makers under diverse scenarios. This approach, which is adaptable to specific local conditions, can effectively identify the most appropriate technology options. In general, the results of MCDM can be used to develop efficient strategies for the use of biofuels that provide the highest performance while minimizing environmental concerns. However, to address the potential influence of bias in the weighting process, particularly due to political or environmental considerations that may favor specific configurations, the No-Priority weighting criteria are applied in this study. The No-Priority method ensures that all criteria are treated equally, eliminating the subjective influence that could arise from predefined preferences or sector-specific priorities. Under this approach, equal weights are assigned to all criteria, preventing any individual factor from having an excessive impact on the final decision. This analysis provides a more neutral and objective evaluation of biofuel additives, aligning with the principle of fairness in MCDM applications. The corresponding scores and rankings obtained using this approach are presented in Figure 7, highlighting the impact of an unbiased weighting scheme on the decision-making process.

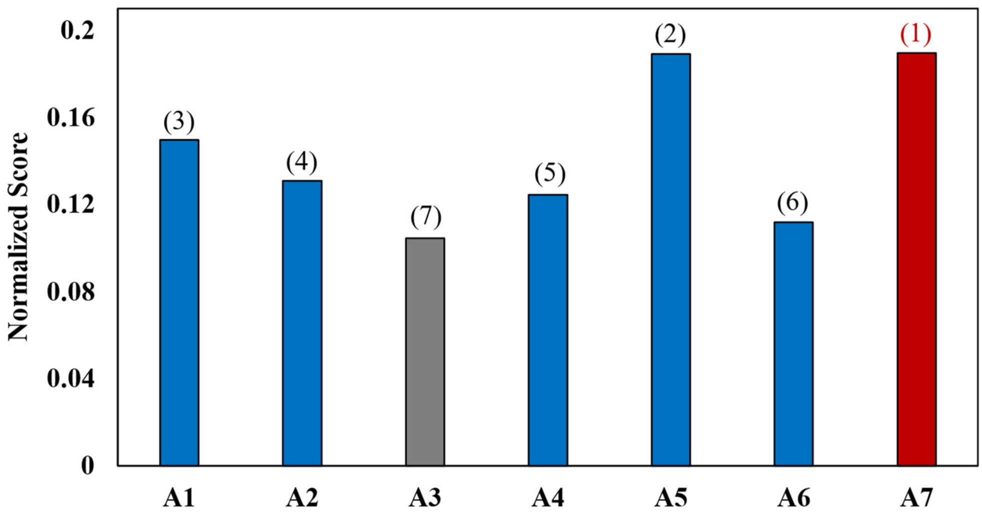

Figure 7. The normalized score and ranks of the investigated alternatives using No-Priority TOPSIS, with the highest and lowest ranked alternatives marked red and grey, respectively.

4.3. Sensitivity Analysis

To assess the robustness of decision outcomes while changing the weights or preferences assigned to different criteria in MCDM for sustainable and renewable gasoline biofuel additives, sensitivity analysis is performed and the results are shown in Figure 8. This study sheds light on how modifications to variables like energy efficiency and gasoline compatibility impact the ranking of additives. The feasibility of any addition depends on its compatibility with the current gasoline infrastructure. Higher compatibility may result from the blending qualities and ease of integrating additives such as Di-isobutylene (A5) and Isopropanol (A1) into existing distribution systems. On the other hand, less compatible but more sustainable choices like ethanol (A2) or methanol (A3) may become increasingly popular in situations where compatibility is not as important. Additionally, the sensitivity analysis can be used to evaluate the robustness of an additive's performance in light of infrastructure adaptability. Each criterion's weight was adjusted from 0 to 0.9, and the remaining weight was split evenly among the remaining criteria. Moreover, the sensitivity analysis serves as a guideline for further studies and assessments, allowing for changes in the weight of each criterion based on specific objectives or limitations. For example, these renewable and sustainable additives can be used as fuel additives in diesel engines to enhance performance and reduce exhaust emissions. In summary, sensitivity analysis in MCDM for sustainable and renewable biofuel additives provides valuable insights into how changes in the weighting of criteria influence selection outcome. By evaluating the various factors, the analysis identifies which additives, such as ethanol (A2), isobutanol (A4), or n-butanol (A6), offer the best balance for sustainable gasoline production under different conditions.

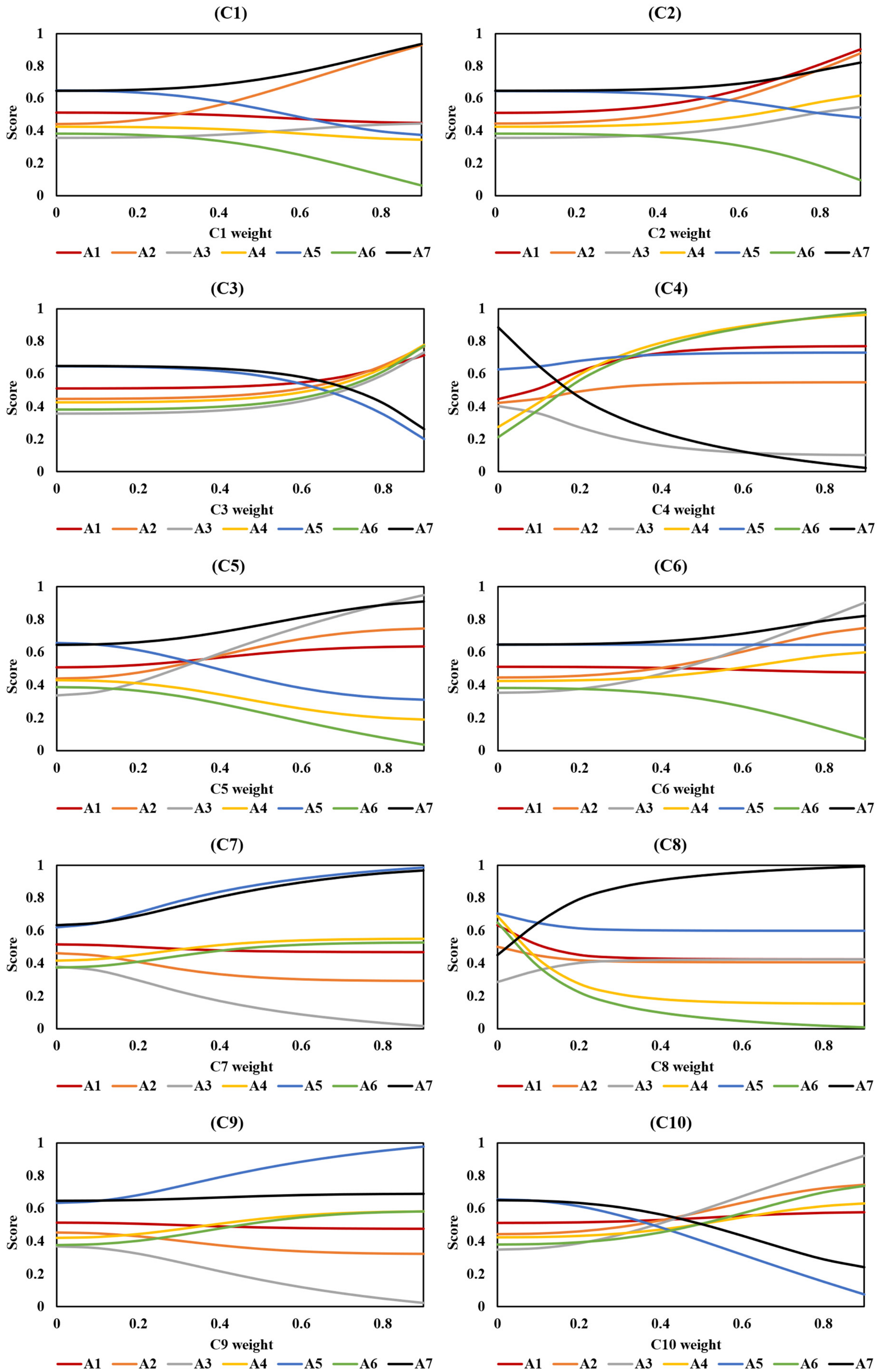

Figure 8. Effect of criteria weights on alternatives' scores.

5. Conclusions

Finding the most sustainable and renewable gasoline biofuel additives was the subject of a quest. To enhance the selection process, an MCDM approach utilizing an integrated AHP-TOPSIS model was employed to assess optimal options. The compared alternatives as gasoline biofuel additives are isopropanol, ethanol, methanol, isobutanol, di-isobutylene, n-butanol, and DIPE. Ten technical criteria considered, namely research octane number, motor octane number, density, Reid vapor pressure, boiling point temperature, auto-ignition temperature, heat of evaporation at 25 °C, Flashpoint, stoichiometric air-fuel ratio (AFR), and laminar flame speed.

The overall MCDM results reported that isopropanol and ethanol achieved the highest rankings, which is consistent with the significant advantages and technical characteristics of the gasoline biofuel additives. In general, the results of MCDM can be used to develop efficient strategies for the use of biofuels that provide the highest performance while minimizing environmental concerns. Furthermore, the results indicated that isopropanol ranks at the top among gasoline additives, with a score of 0.6576, due to its antiknock properties that contribute to a high-octane, environmentally friendly fuel blend. This is ethanol and isobutanol, each offering distinct characteristics for fuel performance, with scores of 0.6301 and 0.626, respectively. In contrast, methanol was ranked lowest, with a score of 0.3652.

The current paper fills in a research gap by developing an MCDM method for sorting renewable gasoline additives to produce high-octane gasoline with excellent engine performance and low exhaust emissions. Due to the diverse technical criteria considered and the reliability of the integrated model applied, it is recognized as a prominent approach. The proposed selection methodology can facilitate various decision-makers, as it offers a knowledge-based framework for choosing the most appropriate alternative from a wide range of options, considering local conditions and constraints. As a follow-up to this study, experimental validation through real gasoline engine tests is recommended to assess the practical performance of the biofuel additives under real-world conditions. Such tests would provide critical insights into engine efficiency, emissions, and long-term fuel compatibility, further validating the MCDM-based selection process.

Author Contributions

M.M.: conceptualization, methodology, writing—original draft preparation, writing—reviewing and editing, visualization; T.M.M.A.: data curation, conceptualization, writing—original draft preparation, writing—reviewing and editing, investigation; R.A.: conceptualization, methodology, writing—original draft preparation, writing—reviewing and editing, visualization; M.A.A.: data curation, conceptualization, writing—original draft preparation, writing—reviewing and editing, Supervision. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data will be available upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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