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Selection of the Most Suitable Alternative Fuel Depending on the Fuel Characteristics and Price by the Hybrid MCDM Method

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Abstract: In recent years, in order to increase the quality of life of people, energy usage has become very important. Researchers are constantly searching for new sources of energy due to increased energy demand. Engine tests are being conducted to investigate the feasibility of the new sources of energy such as alternative fuels. In the engine tests, engine performance, combustion characteristics and exhaust emissions are evaluated by obtaining the results. The effect of newly developed fuels on engine lifetime, safe transport and storage are also examined for fuel availability. In addition, the potential and the price of fuels are important in terms of sustainability. In these studies, laboratory environments are needed for experimental setups. It is difficult to determine the availability of the most suitable alternative fuel since numerous results are obtained in the engine tests and studies. This integrated model provides a great advantage in terms of time and cost. The physical and chemical properties of the fuel affect experimental results such as engine performance, combustion, and exhaust emission. The suggested model can be making the most efficient and eco-friendly fuel choice without the need for experimental studies by using physical and chemical properties of the fuel. It also can offer the best fuel for cost, safety and maintenance processes. In this study, animal fat biodiesel derived from waste animal fats and vegetable oil biodiesel produced from aspir-canola oils were investigated. Biodiesel fuels are mixed with diesel at 5%, 20%, and 50%, and nine different fuels prepared with three pure fuels, and six different fuel blends are compared. Before using these fuels in an experimental study, estimates are made about which fuels may be more advantageous in terms of many criteria. In the process, nine varied fuel specifications are taken as references such as calorific value, cetane number, oxygen content rate, fuel price, flash point, viscosity, lubricity, iodine number and water content. The criteria weights are determined with SWARA (Step-Wise Weight Assessment Ratio Analysis) from multi-criteria decision-making models, and MULTIMOORA (Multi-Objective Optimization on the basis of Ratio Analysis) is ranked according to fuels' characteristics from the best to the worst. While theoretically, the best fuel is ultimately VOB20, VOB50 and AFB20 were selected as the second fuel and the third fuel.

Keywords: multi-criteria decision making (MCDM); vegetable oil biodiesel; animal fat biodiesel; ANP; SWARA; MOORA; MULTIMOORA; fuel characteristics

1. Introduction

Over the past few decades, energy has taken its place as the essential supply for humanity, contributing to improving our living quality. The primary energy demand of the world is anticipated to enlarge by 1.6% for each year until 2030. Nowadays, most of the global energy consumption consists of fossil-based crude oil (35%), whereas a very small rate of its (5%) is also renewable resources [1].

Due to the fact that fossil oil is widely used, it is leading to gradual deterioration of the global environment, such as global warming, the greenhouse effect, and haze. In addition, the damage to the environment caused by carbon emissions during the production and use of fossil fuels is so important that it cannot be neglected [2,3]. For this reason, many studies have been undertaken to develop sustainable liquid fuel alternatives thanks to the global efforts to encourage a shift from fossil fuels to renewable and cleaner biofuels. These studies have resulted in the identification of biodiesel as a sustainable and environmentally safe fuel alternative [2]. It also has the advantage of being of photosynthetic origin, eco-friendly, renewable and a part of the carbon cycle [4]. Biodiesel is safe to store, transport and operate compared to commercial diesel due to being non-toxic, biodegradable and having a high flash point. Biodiesel reduces dependence on imported petroleum. Therefore, it is very advantageous compared to petroleum [5]. The other advantages are renewability, oxygen content and better lubricity [6]. The price of feedstock is one of the major worries for biodiesel production. Waste cooking oils or animal fats are one of the cheapest options to produce biodiesel. When utilizing these sources, the price of biodiesel price is significantly reduced [7]. Therefore, researchers focus on alternative fuel development from waste sources.

Some fuel properties, such as the viscosity, calorific value, cetane number, oxygen content rate, flash point, and iodine number, play an important role in the formation of thermal efficiency and exhaust emissions in internal combustion engines. The effects of them and the best blend rate are investigated by researchers. Although there are many studies on evaluations of empirical results in terms of performance, combustion and emission of alternative fuels in the literature, statistical and decision-making methods related to fuels are limited.

When alternative fuels produced from different sources are used, the performance, exhaust emissions and combustion characteristics of the engines are varied depending on the fuel properties. The reason for these differences is that the physical and chemical properties of each fuel are different from other fuels. Researchers working on alternative fuels are investigating the effects of physical and chemical properties of fuels on the engine performance, combustion characteristics and emission characteristics. Through experimental studies, it is possible to predict how a change in the performance, combustion and emission results can be expected if each fuel property increases and decreases. In this study, a group decision-making method was preferred, and a group that consisted of five expert academicians engaged in experimental studies on alternative fuels. The aim of this study is to estimate the most suitable fuel in terms of engine performance and exhaust emissions without any experimental work. In order to make this prediction, the opinions of experts who can evaluate the effects of fuel properties on engine combustion, performance and emission characteristics have been consulted. According to expert opinions, the criteria that affect the engine performance, combustion characteristics and emission characteristics have been determined. In addition to the criteria affecting the experimental results, criteria were taken into account that could affect the consumers' fuel choice decision (like fuel price). The study is performed to choose the best fuel for the compression ignition (CI) engine using an application of Multi-Criteria Decision Making (MCDM) techniques. The best fuel was chosen among the alternatives such as ultra-low-sulfur diesel (ULSD), vegetable oil biodiesel (VOB) produced from canola and aspire oil mixture, animal fat biodiesel (AFB) obtained from waste animal fats, and the blend fuels (5%, 20% and 50% by volume biodiesels in diesel) by using a hybrid MCDM model. This model includes a SWARA method for detecting importance weights of criteria and the MULTIMOORA method for making a selection from alternative fuels.

2. Literature Review

Multi-Criteria Decision Making (MCDM) techniques are mostly utilized to figure out problems in the field of business operations, but they have begun to be used in automobile engineering in recent years. Tzeng et al. preferred VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) and TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution) procedures to determine the most suitable alternative fuel bus used in the urban area of Taiwan. The weights of the evaluation criteria were determined by the AHP (Analytic Hierarchy Process) method [8]. Kumar et al. used MCDM methods to determine the most suitable biodiesel production process according to both economic and environmental criteria (such as the acid value, conversion, viscosity, glycerol separation, emission characteristics, sulfur content, and cost). The results indicate that the most appropriate process for biodiesel production is the Supercritical method according to the established model using the fuzzy AHP approach [9]. In another study, the most appropriate fuel selection problem was resolved by the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) method in terms of cost, technical, social and policy criteria for the transportation sector. The results show that compressed natural gas and liquid petroleum gas are the most convenient fuel for light commercial vehicles [10]. Wang et al. investigated the best trigeneration systems for residential buildings were assessed from the social, economic, technical and environmental aspects. AHP and the fuzzy MCDM models were applied by combining. For the residential building, the gas engine plus lithium bromide absorption water heater/chiller unit was selected as the best trigeneration system in the five alternatives [11]. In a study conducted by Durairaj et al., weights to the criteria were obtained by GRA (Gray-Relational Analysis), and the obtained results were ranked. It was evaluated by the TOPSIS method for the purpose of fuel selection. Pongamia oil-based biodiesel was chosen as the best fuel by the GRA-TOPSIS hybrid MCDM method [12]. In another study, the feasible location areas of wind farms are selected and ranked using the WASPAS (Weighted Aggregates Sum-Product Assessment) method by assessing the types of wind turbines in the Baltic Sea offshore area [13]. In a study conducted by Baležentis, a telecommunication company intends to choose a manager for the R&D department from four volunteers named A1, A2, A3 and A4 by using the MULTIMOORA (Multi-Objective Optimization on the basis of Ratio Analysis) method. The decision-making committee composed for a choice process assesses the four concerned volunteers based on criteria [14]. SWARA and ARAS (Additive Ratio Assessment) methods were used to solve a real case study of oil and gas well drilling projects evaluation in a paper [15]. In a similar work on fuels, the most suitable fuel combination was chosen among the alternatives such as blends with biodiesel, ethanol, and hydrogen. The most appropriate duel fuel combination out of ten alternatives was discerned through AHP-VIKOR and AHP-PROMETHEE II methods. The evaluation criteria were selected as NO_x, exhaust gas temperature, CO, hydrocarbon, soot, and brake specific energy consumption [16]. In a study, SWARA and Fuzzy MULTIMOORA methods were used together for pharmacological therapy selection of Type 2 Diabetes (T2D), and a sensitivity analysis was conducted [17]. It is seen in the literature that SWARA and MULTIMOORA methods can be used together in a hybrid way.

In addition to the MCDM techniques, a literature search has also been conducted on engine tests using biodiesel. Godiganor et al. have studied the effect of biodiesel–diesel blends on the performance and the exhaust emissions of a diesel engine. In their study, blended fuels were prepared by using biodiesel obtained fish oil methyl esters at the volumetric ratios of 10%, 20%, 40%, 60%, and 80%. According to the results, it was determined that the most convenient fuel was biodiesel–diesel blends of biodiesel containing 20% in the terms of the best brake thermal efficiency and specific fuel consumption [18]. Behcet has experimentally analyzed the effects of blends of diesel with the biodiesels produced by methyl esters from fish and chicken oil/fat on the engine performance, and exhaust emissions. The results showed that the CO, CO_2, UHC, engine power and torque obtained from the biodiesel–diesel blends (ratio of 20% on the volume basis) reduced when compared with diesel fuel [19]. Buyukkaya experimentally investigated performance and emissions of a diesel engine by using rapeseed oil and 5%, 20% and 70% of its blends with diesel fuel. The test results indicated that there could be potential particularly for the B20 blend in terms of performance efficiency and environmentally friendly emissions. In addition, the B20 blend gave the best brake thermal efficiency of the engine [20]. As seen in the literature, 20% of biofuel use seems to be the optimum point in terms of performance and emissions. In this study, the result of the suggested model was that low-rate biodiesel use was the best fuel. It is seen that the results obtained with the suggested model are similar to the experimental results in the literature.

It is seen that, in order to determine the importance of the criteria, one of the methods such as ANP (Analytic Network Process), AHP and SWARA was preferred, and, in order to make a selection, different methods such as TOPSIS, PROMETHEE, VIKOR, ARAS, and MOORA were used. However, it can be seen that hybrid models are used in small quantities for decision-making problems. In addition, in the literature, it is seen that there are a few studies using MCDM techniques with respect to biodiesel fuels.

3. Materials and Methods

3.1. The Step-Wise Weight Assessment Ratio Analysis (SWARA) Method

Experts have a crucial role in the assessment of criteria and weights. All criteria are compared with each other, and importance ratings are determined. The knowledge and experience of the experts are a very important factor in the decision-making stage [21]. The computational technique of the SWARA method was suggested by Kersuliene et al. According to this method, the most important criterion was the first row, and the insignificant criterion was the last row. The essential principle of SWARA method is its talent to evaluate the expert's perspective concerning the accuracy of the weighted criteria [22]. Moreover, experts can work together on the same problem using this approach, which produces more accurate results than other approaches. In this study, weights obtained by using group decision-making techniques with the experience of five different academicians who are experts in internal-combustion engines have been used in the decision-making process of alternative fuels. In order to determine the relative weights of the criteria, the SWARA method can be used by performing as follows:

Stage 1: Sort the evaluation criteria in the descending sequence, situated on their expected significances.

Stage 2: The academician expresses the relative importance of criterion j related to the previous $(j-1)$ criterion, for each criterion, launching from the second criterion. This proportion is called the comparative importance of average value, s_j.

Stage 3: Define the coefficient k_j as in the following equation:

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases}. \tag{1}$$

Stage 4: Define the recalculated weight q_j as in the following equation:

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{k_{j-1}}{k_j} & j > 1 \end{cases}. \tag{2}$$

Stage 5: Define the relative weights of the evaluation criteria as in the following equation:

$$w_j = \frac{q_j}{\sum_{k=1}^{n} q_k}, \tag{3}$$

where w_j indicates the relative weight of the j-*th* criterion, and n indicates the number of such criteria.

3.2. Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) Method

MOORA method was originally developed by Brauers and Zavadskas [23]. MOORA, a new multi-purpose optimization method, has been used in different areas during recent years. The MOORA method is a superior method than other multi-criteria decision-making techniques in terms of the calculation time, technical simplicity, the number of mathematical operations, and data types used in the analysis [24].

The MULTIMOORA method, consolidating all approaches, is comprised of three components: the ratio system approach, the reference point approach, and the full multiplicative form approach. These approaches can be presented in the following manner.

3.2.1. The Ratio System (RS) Approach

The primary idea of the MOORA RS approach is to determine the overall performance indicator (ranking index) of an alternative as the difference between its sums of the weighted normalized performance degree of the benefit and cost criteria. Normalizing performance value is the square root of the sum of squares of each alternative per objective, as follows:

$$x_{ij}^{*} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}}, \tag{4}$$

where x_{ij}^{*} indicates the normalized performance value of the *i-th* alternative to the *j-th* criterion; x_{ij} is the response of alternative j on criterion i; m is the number of alternatives (j = 1, 2, ..., m); n is the number of criteria (i = 1, 2, . . . n). The ranking index is also defined as follows:

$$y_i = \sum_{j=1}^{k} w_j x_{ij}^{*} - \sum_{j=k+1}^{n} w_j x_{ij}^{*}, \tag{5}$$

where y_i indicates the ranking index of the *i-th* alternative, w_j indicates weight of the *j-th* criterion; j = 1, 2, . . . , k show maximized (benefit) criteria, and j = k + 1, k + 2, ..., n show minimized criteria (cost) respectively.

According to the RS approach, the compared alternatives are ranked on the basis of their y_i in ascending order, and the highest value of the ranking index is the best-ranked one. The best-ranked alternative, A_{RS} can be determined as follows:

$$A_{RS} = max_i\{y_i\}. \tag{6}$$

3.2.2. The Reference Point (RP) Approach

In addition to the RS approach, in the MOORA RP approach, reference points are determined as r_i for each criterion. The distance for each criterion is defined as follows:

$$d_{ij} = \left| w_j r_j - w_j x_{ij}^{*} \right|. \tag{7}$$

"Min-Max metric of Tchebycheff" operation is performed on the new matrix formed [25], and the best-ranked alternative, A_{RP} can be determined as follows:

$$A_{RP} = min_i\{max_j(d_{ij})\}. \tag{8}$$

3.2.3. The Weighted Full Multiplicative form (FMF) Approach

In the MOORA FMF approach of Brauers and Zavadskas, the weights are not taken into account as multiplying coefficients [24]. Instead, a new approach (the weighted full multiplicative form) was developed by Hafezalkotob and Hafezalkotob for situations where the importance weights differ [26]. The weights should be utilized as exponents. The weighted FMF ranking index can be formulated, as follows:

$$u_i = \frac{\prod_{j=1}^{k} \left(x_{ij}^{*}\right)^{w_j}}{\prod_{j=k+1}^{n} \left(x_{ij}^{*}\right)^{w_j}}. \tag{9}$$

According to the weighted FMF approach, the compared alternatives are ranked by virtue of their u_i in ascending order, and the highest value of the ranking index is the best-ranked one, which can be determined as follows:

$$A_{FMF} = max_i\{u_i\}. \tag{10}$$

3.2.4. The Theory of Dominance

MULTIMOORA is not only a stand-alone method but is also based on the comparison of the results of the RS approach, the RP approach, and the FMF approach. In other words, three approaches make up the whole. The Theory of Dominance, developed by Brauers and Zavadskas, is used in order to sort with MULTIMOORA [27]. This theory includes dominance, transitivity, equality and circular reasoning.

3.2.5. The Sensitivity Analysis

The priorities among the criteria are largely dependent on the subjective judgments of the decision-makers. Therefore, the stability of the final sequences under varying weights of the criteria should be tested. Sensitivity analysis is a technique that performs a series of scenarios to test the relative importance of the criteria. It is recommended that weights be carefully watched if the sorting is fairly sensitive to minor changes in the criteria [28].

4. Methodology, Criteria, and Alternatives

The supposed integrated approach involves two MCDM procedures: SWARA and MULTIMOORA. In the first level, the SWARA method is utilized to calculate from the weight of a criterion, and MULTIMOORA is operated to rank fuel alternatives from the best to the worst.

The proposed methodology consists of three fundamental phases: (a) identification of the criteria for the best fuel selection, (b) weight computation using SWARA method, and (c) ranking the alternative fuels using the MULTIMOORA method. In the first phase, the evaluation criteria and alternative fuels are identified. The SWARA method is used for measuring the weights of the criteria. The alternative fuel ranks are detected by using MULTIMOORA at the last phase. The process of this study, which comprises three phases, is defined as follows in Figure 1.

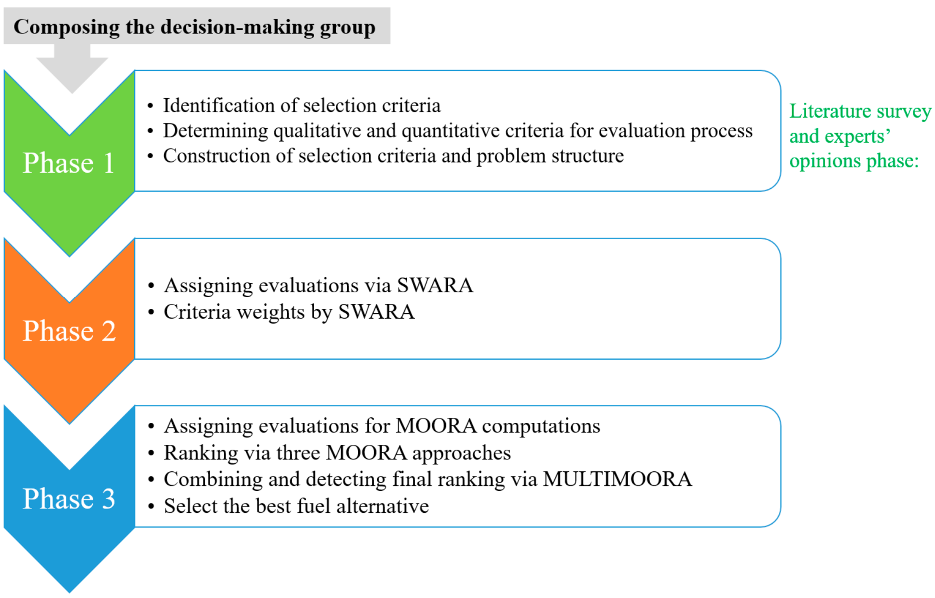
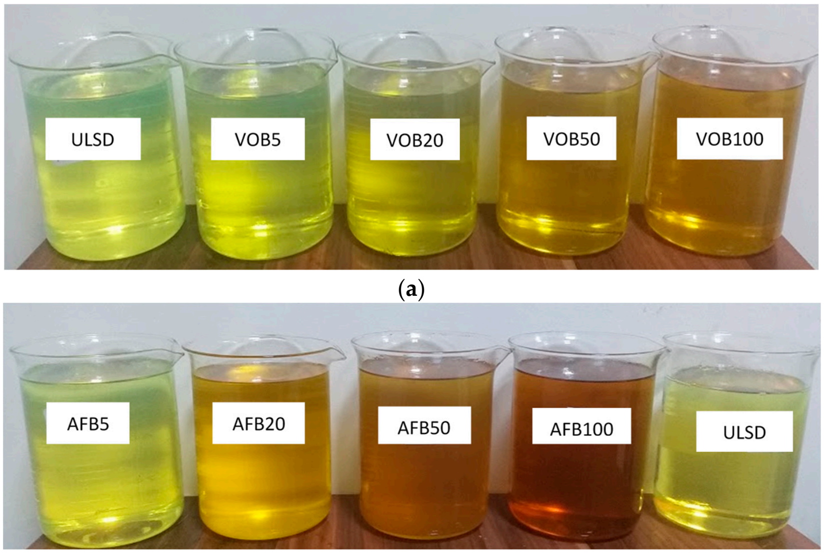


Figure 1. The process of the best fuel selection.

4.1. Alternative Fuels

In this study, the animal fat biodiesel (AFB) was derived from waste animal fats by transesterification for the experimental study of the chemical plant in Istanbul (TR). The inedible animal tallow is a mixture of slaughtered sheep and cattle fats, and these fats are marketed for soap production. The vegetable oil biodiesel (VOB) produced from the aspir-canola oil mixture was obtained from a commercial facility in Kocaeli (TR), and ultra-low-sulfur diesel (ULSD) was purchased in a Shell petrol station in Batman (TR).

The purpose of blending diesel with biodiesel is to research the optimum percentages of biodiesel in diesel engines. Therefore, test fuels were prepared by blending 95% of the diesel–5% of biodiesel, 80% of the diesel–20% of biodiesel and 50% of the diesel–50% of biodiesel. Pure vegetable oil biodiesel and blends were indicated as VOB100, VOB50, VOB20, VOB5 and pure animal fats biodiesel and blends are indicated as AFB100, AFB50, AFB20, and AFB5. They are presented in Figure 2. In the meantime, the resulting blends are quite similar to commercial diesel fuel (ULDS) in its main physical and chemical characteristics that affect the diesel combustion process. Therefore, the test fuels were measured in the Marmara Research Center–The Scientific and Technological Research Council of Turkey (MRC-TUBITAK) and the Petro Chemical Technology Laboratory in Batman University. These features are presented in Table 1.



(**a**)

(**b**)

Figure 2. Alternative fuels and their blends: (**a**) ultra-low-sulfur diesel (ULSD), vegetable oil biodiesel (VOB) and its blends, respectively; (**b**) animal fat biodiesel (AFB), its blends and ultra-low-sulfur diesel (ULSD), respectively.

Table 1. The features of the fuels.

Alternatives	Density (kg/m^3)	Kinematic Viscosity (mm^2/s)	Cetane Number	Flashpoint (°C)	Iodine Value (gI/100 g)	Water (mg/kg)	Calorific Value (kj/g)
ULSD	840	2.80	52	78	~0	~0	43.3
VOB5	842.20	3.01	52	83.5	5.8	10.1	43.1
VOB20	848.78	3.14	52.1	100	23.2	40.4	42.4
VOB50	861.95	3.52	52.3	133	58	101	41
VOB100	883.90	4.01	52.6	188	116	202	38.6
AFB5	842.15	3.11	52.3	82.2	2	19.4	43.1
AFB20	848.58	3.79	53.0	94.7	8	77.6	42.8
AFB50	861.45	4.98	54.5	119.8	20	194	41.7
AFB100	882.90	9.81	57	161.5	40	388	40
Standards [29]	860–900 kg/m^3 [1]	3.5–5.0 mm^2/s [1]; 1.9–6.0 mm^2/s [2]	51, min [1]; 47, min [2]	101 °C, min [1]; 93 °C, min [2]	120 gI/100 g, max [1]	500 mg/kg [1]	-

[1] EN 14214, EU biodiesel standards, [2] ASTM D6751, US biodiesel standards.

Researchers have encountered a varies of problems, which are such as engine deposits, injector coking, and piston ring sticking with the use of mere animal fats or vegetable oils in diesel engines. These problems are obstructed by mixing vegetable oil with diesel fuel, which can also advance the combustion characteristics. In addition, biodiesel can achieve nearly the same performance as diesel fuel and prevent these problems partially with the transesterification process [30].

4.2. Criteria for the Best Fuel Selection

The evaluation criterion for the best fuel selection was identified with the opinion of experts through literature [20,21]. These criteria can be described in the following manner.

4.2.1. Calorific Value (C1)

Calorific value is defined as the amount of heat produced by the complete combustion of a fuel. In order to release higher heat and higher efficiency, it is requested to have high calorific value of the fuel. Consequently, it improves engine performance during combustion [31].

4.2.2. Cetane Number (C2)

The cetane number is an important feature showing the quality of fuel ignition. Low cetane number will boost gaseous and particulate exhaust emissions because of incomplete combustion. Furthermore, the lower cetane number causes prolonged ignition delay, which provokes unacceptable diesel knocking [32]. The use of biodiesel fuel allows the engine to run more smoothly and with less noise [33].

4.2.3. Oxygen Content Rate (C3)

The burning efficiency is improved while the high rate of oxygen content in biodiesel causes a drop in unburned hydrocarbon, carbon monoxide and particulate matter. Meanwhile, it is produced excessive NO_x emissions [34]. The highest oxygen content helps to transform CO into CO_2 [35]. The oxygen content of the biodiesel leads to a reduction of the calorific value of around 10–13% compared to diesel fuel. The oxygen composition of biodiesel derived from different feedstocks is between 10% and 13% [36]—for example: oxygen content of canola oil biodiesel 10.8% [37], safflower oil biodiesel 10.95% [38], waste pork lard methyl ester (ME) from inedible animal tallow 11.2 [39], rapeseed oil ME 10.8%, soybean oil ME 10.8%, and palm oil ME 12.39% [36]. In a different paper by the National Renewable Energy Laboratory (NREL), which conducts an investigation of various biodiesel fuels produced from waste oils, oxygen content rates are 11.16% of methyl soy, 11.74% of edible methyl tallow, 11.08% of inedible methyl tallow, 11.04% of methyl canola, 11.82% of methyl lard, 11.10% of methyl low free fatty acid grease, and 11.28% of methyl high free fatty acid grease [40]. In the present paper, oxygen content rates are as accepted zero, 11.04%, and 11.08% for ULSD, VOB100, and AFB100, respectively, as data of the evaluation criteria. Data is taken as reference for fuels named "inedible methyl tallow" and "methyl canola" of NREL.

4.2.4. Fuel Price (C4)

The main reason for limited trade of the biodiesel is the high cost of production. The raw material price comprises 70–95% of the total biodiesel cost [41]. It is required to use cheap oil feedstocks for biodiesel making, due to the uneconomical food-class oils. The use of inexpensive non-edible oils, residual animal fats, and waste cooking oils can decrease the production cost of biodiesel. In this way, sustainable and eco-friendly fuels can be produced. Biodiesel is more expensive (0.92 US $/L) compared to diesel fuel (0.78 US $/L) according to the report of alternative fuel prices by the U.S. Energy Information Administration in January 2018 [42]. Similarly, the price of diesel fuel in U.S. (average) closed at 2.97 US $/gallon (0.78 US $/L) on 10 April 10 2018 [43]. Even though biodiesel depends on various factors, such as the geographic area, production of crops, and the price of crude petroleum, the primary economic parameter defining the sales price is the cost of raw material [44]. Due to a favorable price of animal fats compared to vegetable oils, they offer an economic advantage. Soy Methyl Ester (SME) biodiesel price and FAME (Fatty Acid Methyl Ester) biodiesel price are just about 1.02 US $/L and 0.88 US $/L, respectively, according to the Neste Report combined from Datasource Thomson Reuters, Starsupply, and OPIS databases on 5 April 5 2018 [45]. In the present paper, fuel prices are accepted 0.78 $/L, 1.02 $/L, and 0.88 $/L for ULSD, VOB100, and AFB100, respectively, as data of the evaluation criteria.

4.2.5. Flashpoint (C5)

The flash point is defined as the lowest temperature in which the fuel–vapor concentration ignited. Whereas this criterion does not directly affect combustion, it is important for storage, fuel usage and transport. Flashpoint is taken into account as the primary indicator in terms of shipping and safety regulations for flammable materials [32].

4.2.6. Viscosity (C6)

Viscosity plays a predominant role in the mixture formation, combustion process and fuel spray. The atomization quality, the size of fuel drop and the penetration are affected by viscosity [46]. In cold weather, high viscosity causes more troubles because viscosity rises as the temperature reduces. In addition, the reason of the leakage in the fuel system is low viscosity [47].

4.2.7. Lubricity (C7)

Lubricity defines the ability of the fuel in order to decrease the friction between surfaces under load. HFRR (High Frequency Reciprocating Rig) is used for measuring the lubricity. Biodiesel may be used as a lubricity improver due to the excellent lubricity characteristic. The lubricity ability of blend varies on biodiesel concentration in the blend [36]. Among the biodiesels, the results of the average wear scars produced by HFRR reveal that neat animal tallow biodiesel display slightly enhanced lubricity over biodiesels from canola oil and blended feedstocks [48]. Exclusively, biodiesel fuels have excellent lubricity, and just 1–2% biodiesel content in a diesel blend can increase the lubricity to an reasonable level [49]. Since the lubricity does not change linearly with the fuel mixture ratios, the value of this criterion is subjectively determined using a 1–9 scoring scale. The rating scale is represented with 1 as the lowest value, while 9 represents the highest value.

4.2.8. Iodine Number (C8)

For the degree of unsaturation, the number of double bonds is a measure for the iodine number, which is a good index [50]. As it is known, animal fats have a high content of saturated fatty acids. There is a strong connection between NO_x emissions and iodine number [51]. It has been reported that NO_x emissions fall down when using more saturated biodiesel fuels [52].

4.2.9. Water Content (C9)

The existence of water is a sign that the fuel is not pure. Biodiesel should be dried after washing with water. Therefore, the water characteristic must be below 500 mg/kg. In fact, when biodiesel is dehydrated properly in the manufacturing process, during storage and transportation water can accumulate. Due to the moisture, metal parts in the fuel system of the engine can be exposed to corrosion by the rising of free fatty acid [36].

5. Computation

The fuels used in diesel engines have advantages over each other in terms of different criteria. After establishing the decision-making group, considerable criteria for fuel selection are identified by using group decision-making techniques, which take into account the experience of different academicians who are experts in internal-combustion engines. Next, the criteria are described. Finally, the selection criteria and problem structure are constructed by the group. The evaluation criteria are calorific value, cetane number, oxygen content rate, fuel prices, flash point, viscosity, lubricity, iodine number, and water content.

5.1. Computation of Criteria Weights Using SWARA

In this technique, a decision-making group member plays an important role in determination of weights. The decision-making group consists of five different academicians, and each group member is called a decision-maker (DM). In addition, each DM chooses the significance value of each criterion. Next, each DM puts in order nine criteria from the first to the last. The ability to estimate the DMs' opinion about the significance ratio of the criteria in the procedure of their weight's determination is the main principle of this method. The weights, obtained on the basis of first DM, are shown in Table 2.

Table 2. The replies of the first DM and the weights of the criteria.

Criteria	s_j	k_j	q_j	w_j
C1—Calorific value		1.000	1.000	0.219
C2—Cetane number	0.30	1.300	0.769	0.168
C3—Oxygen content rate	0.20	1.200	0.641	0.140
C4—Fuel price	0.20	1.200	0.534	0.117
C5—Flash point	0.10	1.100	0.486	0.106
C6—Viscosity	0.40	1.400	0.347	0.076
C7—Lubricity	0.05	1.050	0.330	0.072
C8—Iodine number	0.40	1.400	0.236	0.052
C9—Water content	0.05	1.050	0.225	0.049
				1.000

Priority rankings are found for each DM, and the geometric averages of these are taken. The final weights of evaluation criteria according to the SWARA method are shown in Table 3.

Table 3. The replies of the first DM and the weights of the criteria.

Criteria	w_j of 1st DM	w_j of 2nd DM	w_j of 3rd DM	w_j of 4th DM	w_j of 5th DM	Geometric Average	Normalized Weights of Criteria
C1	0.219	0.257	0.232	0.268	0.232	0.241	24.2%
C2	0.168	0.146	0.166	0.129	0.166	0.154	15.5%
C3	0.140	0.160	0.150	0.168	0.107	0.144	14.5%
C4	0.117	0.086	0.116	0.107	0.118	0.108	10.9%
C5	0.106	0.095	0.085	0.083	0.102	0.094	9.4%
C6	0.076	0.104	0.089	0.072	0.079	0.083	8.4%
C7	0.072	0.062	0.058	0.065	0.065	0.064	6.5%
C8	0.052	0.047	0.061	0.052	0.072	0.056	5.6%
C9	0.049	0.043	0.044	0.057	0.059	0.050	5.0%

5.2. Computation of Ranking Using MULTIMOORA

The initial decision-making matrix is constructed, and data of the evaluation criteria for fuels and fuel blends are given in Table 4, where the maximization direction and minimization direction of the criteria are also indicated.

In the full multiplicative form, a problem may emerge for zero and negative values when illogical results are obtained. There are some data whose values are zero, among C3, C8, and C9 criteria. Hence, zero is replaced by 100. At that moment, the other values are also converted. For instance; 96.6 takes the place of the value of minus 3.4 (negative). Similarly, 103.4 represents the value of 3.4 (positive). Consequently, this operation has to be done for the entire column concerned [53].

Table 4. The initial decision-making matrix for the best fuel selection.

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9
ULSD	43.3	52.0	100.00	0.78	78.0	2.80	1.00	100.0	100.0
VOB5	43.1	52.0	100.55	0.79	83.5	3.01	4.00	105.8	110.1
VOB20	42.4	52.1	102.21	0.83	100.0	3.14	6.00	123.2	140.4
VOB50	41.0	52.3	105.52	0.90	133.0	3.52	7.00	158.0	201.0
VOB100	38.6	52.6	111.04	1.02	188.0	4.01	9.00	216.0	302.0
AFB5	43.1	52.3	100.55	0.78	82.2	3.11	4.00	102.0	119.4
AFB20	42.8	53.0	102.22	0.80	94.7	3.79	6.00	108.0	177.6
AFB50	41.7	54.5	105.54	0.83	119.8	4.98	7.00	120.0	294.0
AFB100	40.0	57.0	111.08	0.87	161.5	9.81	9.00	140.0	488.0
	Max.	Max.	Max.	Min.	Max.	Min.	Max.	Min.	Min.
w_j	24.2%	15.5%	14.5%	10.9%	9.4%	8.4%	6.5%	5.6%	5.0%

Ranking of the alternative fuels is made in accordance with the three approaches of the MULTIMOORA method. Initially, the decision matrix is normalized using Equation (4) and the normalized decision matrix is weighted for the RS approach. The overall performance and the rankings of the alternatives are obtained as seen in Table 5. VOB20 is the best fuel alternative with respect to the RS approach of MOORA. In order to sort by applying the RP approach, reference points are defined among the weighted normalized data. The ranking indexes of fuels are calculated and sorted by applying Equations (7) and (8). VOB100 is the optimum fuel for the RP approach. For the weighted FMF approach, the initial decision matrix shown in Table 3 is taken into consideration. The weights are employed as exponents. The best fuel is VOB20 for the weighted FMF approach. Ranking indexes of alternatives are calculated for the RS approach, RP approach, and weighted FMF approach one by one, as shown in Table 5.

Table 5. The ranking of the fuels obtained for the three approaches of MULTIMOORA.

Alternatives	RS	Rank	RP	Rank	FMF	Rank	MULTIMOORA Final Ranking
ULSD	0.13334	8	0.02843	8	7.79952	9	8
VOB5	0.14158	4	0.02701	6	8.45322	2	4
VOB20	0.14538	1	0.02275	4	8.56300	1	1
VOB50	0.14206	3	0.01422	1	8.42104	4	3
VOB100	0.13841	6	0.01604	2	8.25594	6	6
AFB5	0.14121	5	0.02736	7	8.41822	5	5
AFB20	0.14279	2	0.02412	5	8.42710	3	2
AFB50	0.13557	7	0.01764	3	8.23115	7	7
AFB100	0.10846	9	0.04161	9	7.84806	8	9

According to the Theory of Dominance, the MULTIMOORA final rank is obtained by combining three ranks. If the order of the alternative is the same for the three approaches, absolute dominance exists (1-1-1). In this case, 1 is assigned for the final order. If two of the three approaches achieve the same result, there is general dominance.

5.3. The Sensitivity Analysis for the Integrated Method

The evaluation criteria can be divided into three sets. Calorific value (C1), cetane number (C2), oxygen content rate (C3), and iodine number (C8) constitute the first cluster affecting combustion, performance and emissions (CPE). Fuel price (C4) and flash point (C5) constitute the second cluster affecting safety and cost of consumption (S&CoC). The final cluster affects engine life and maintenance process (EL&MP). Its criteria are viscosity (C6), lubricity (C7), and water content (C9).

In order to perform sensitivity analysis, it is first evaluated separately to find the effect of each cluster on the ranking. The weight of each cluster is selected 100% separately and the order is recorded.

The weights of the criteria in the cluster are determined equally. The clusters are simulated as binary and triplicate, and the effects on ranking are analyzed. Eight scenarios with different criteria weights were simulated. VOB20 fuel blend ranked first in four scenarios. ULSD fuel ranks first in one scenario, VOB100 fuel ranks first in one scenario, and AFB100 ranks first in the two scenarios. As a result, decision-makers' experience is very important because the ranking is highly sensitive to changes in the criteria weights. These scenarios are presented in Table 6.

Table 6. The sensitivity analysis for the integrated method.

Scenarios	Weights of Cluster	Weights of Criteria	The Rank of Alternatives
Set 1	CPE (100%), S&CoC (0%), EL&MP (0%)	C1, C2, C3, C8 (25%); Others (0%)	ULSD > AFB5 > AFB20
Set 2	CPE (0%), S&CoC (0%), EL&MP (100%)	C6, C7, C9 (33.3%); Others (0%)	VOB20 > VOB5 > VOB50
Set 3	CPE (0%), S&CoC (100%), EL&MP (0%)	C4, C5 (50%); Others (0%)	AFB100 > VOB100 > VOB50
Set 4	CPE (50%), S&CoC (0%), EL&MP (50%)	C1, C2, C3, C8 (12.5%); C4, C5 (0%); C6, C7, C9 (16.7%)	VOB20 > VOB5 > AFB5
Set 5	CPE (50%), S&CoC (50%), EL&MP (0%)	C1, C2, C3, C8 (12.5%); C4, C5 (25%); C6, C7, C9 (0%)	AFB100 > AFB50 > VOB100
Set 6	CPE (0%), S&CoC (50%), EL&MP (50%)	C1, C2, C3, C8 (0%); C4, C5 (25%); C6, C7, C9 (16.7%)	VOB100 > VOB50 > VOB20
Set 7	CPE (33.3%), S&CoC (33.3%), EL&MP (33.3%)	C1, C2, C3, C8 (8.3%); C4, C5 (16.7%); C6, C7, C9 (11.1%)	VOB20 > VOB50 > VOB100
Set 8	CPE (44.4%), S&CoC (22.2%), EL&MP (33.3%)	C1-9 (11.1%) weighted equally	VOB20 > VOB5 > AFB5
Group Decision	CPE (58.6%), S&CoC (20.2%), EL&MP (21.2%)	C1 (23.4%), C2 (15.5%), C3 (13.7%), C8 (6.0%); C4 (10.5%), C5 (9.7%); C6 (8.8%), C7 (7.0%), C9 (5.4%)	VOB20 > AFB20 > VOB50

6. Conclusions

In this paper, the MCDM problem for the fuel selection is dealt with by the SWARA and MULTIMOORA methods. This study is the first in the literature for solving the fuel selection problem by SWARA and MULTIMOORA methods taking into account characteristics of the fuel.

Moreover, the operation of the MOORA technique generates the overall performance of alternatives with respect to varied criteria. The MOORA method can integrate the criteria weights to the computational procedure. It is easily understandable because the mathematical phase of the MOORA method is not complicated. The phase does not require a long time to be completed. The number of the alternatives and criteria are unlimited in the problem. Therefore, the MOORA method is made easy to apply due to these advantages.

Consequently, the ideal alternatives are VOB20, AFB20, and VOB50 in accordance with the RS approach calculation results. The optimum fuels with respect to the RP approach calculation results are VOB100, VOB50, and AFB50. In addition, the top order fuels according to the FMF approach calculation results are VOB20, VOB5, and AFB20. The MULTIMOORA results are obtained using

Theory of Dominance. According to MULTIMOORA results, VOB20 is the best fuel, AFB20 is the second, and VOB5 is the third alternative fuel. It is also shown that biodiesel from waste animal fats is more sustainable than biodiesels produced from vegetable oils.

The problem is to estimate the most suitable fuel in terms of fuel properties and price before experimental work is done. By using this model, the researchers developing new alternative fuels will be able to easily compare the available fuels with the new ones. This model will provide the researchers with an idea of the usability of newly developed alternative fuels without conducting any experimental work. From a different point of view, this hybrid model can be further developed for future research by defining new criteria.

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