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Selection of Oil and best Bio-diesel Blend based on Performance and Emission Characteristics of IC Engine: An Integrated CRITIC-TOPSIS Approach

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Selection of optimum bio-diesel blend for internal combustion (IC) engine is crucial. The process of selecting the ideal blend requires a multidimensional analysis. In order to tackle the challenge, an efficient decision-making strategy is required. This paper uses the Multi-Criteria Decision-Making (MCDM) method to offer the selection of a suitable oil and bio-diesel blend based on the performance of the diesel engine under various load circumstances. In order to measure the weights of evaluating criteria, Criteria Importance Through Intercriteria Correlation (CRITIC) and Technique for Order of Preference by Similarity to an Ideal Solution (TOPSIS) are used. At first, seven different oils and seven assessment parameters, namely kinematic viscosity, cetane number, heating value, cloud point, pour point, flash point and density are attempted to select the acceptable oil for making bio-diesel. Next, the ranking of bio-diesel blends is performed based on the evaluation criteria, namely Brake Thermal Efficiency (BTE), Exhaust Gas Temperature (EGT), nitrogen oxide (NOx), smoke, carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbon (HC) emissions. The results show that hemp seed oil is closer to diesel and higher in ranking. The recommended order of blend is B20 > Diesel > B40 > B60 > B80 > B100. The study indicated that B20 is the optimum blend for diesel engines. In order to meet the economy and pollution standards for the green revolution, decision-makers can use the new insights into MCDM approaches described in this article. This study also demonstrates that the suggested methods for choosing the best bio-diesel blend differ from the existing literature.

Keywords: Engine analysis, MCDM, Ranking, Suitability, Vegetable oils

Introduction

Bio-diesel is a type of fuel derived from plants or animals and composed of long-chain fatty acids. It has been considered the best alternative to petroleum fuels and can therefore be utilized without significant change in any compression-ignition engine.[1] The replacement of diesel fuel with other renewable fuels is needed for reasons related to environmental, economic and political factors.[2] Furthermore, the use of fossil fuels to transport vehicles raises greenhouse gas emissions.[3]

The researchers were inspired by these factors to investigate the usage of alternate fuels and to evaluate the performance of bio-diesel in IC engines.[4] The method of processing bio-diesel is the transesterification process.[5] The different types of bio-diesel as an alternative fuel have been analysed by several researchers.[6,7] Research conducted with bio-diesel blends shows an improvement in BTE.[8] Analysis of the IC engine powered by rice bran oil bio-diesel showed a correlation between fuel consumption and BTE. Use of rice bran oil bio-diesel decreased the brake specific fuel consumption by 18.6% with increased BTE of 14.66%.(9) Researchers also stated that lesser BTE exists and higher fuel consumption is registered at B40. Because of the higher peak pressure and higher combustion temperature, the study with a Karanja bio-diesel-diesel blend reported an increase in BTE at B25. Lower BTE was registered at a higher blend and BSFC was also found to be lower with increased load.[10] In contrast with diesel, the production of CO is found to be lower for the B25 blend at all loads. The authors concluded that when compared to diesel, B25 gives better efficiency. Multiple bio-diesel preparations have been documented in this series by many writers, such as Tamanu methyl ester[11], *Garcinia gummi-gutta* methyl ester[12], *Cymbopogon flexuosus*[13]

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and hazelnut kernel oil methyl ester.[14] The bio-diesel that was prepared had also been blended with diesel and used for combustion, efficiency and emission analysis. The authors described the benefits and drawbacks of their research in terms of various engine operating characteristics. A new approach to decision-making has been provided by MCDM methods. It is a sub-discipline of operational research that specifically examines various conflicting decision-making criteria and is also used for solving real problems in different areas where there are many alternatives and criteria, i.e. objectives to solve real problems.[15] For the past three decades, the use of MCDM in the green energy and automotive sectors has been expanded.[16] Poh and Ang suggested the Analytical Hierarchy Method (AHP) for diesel fuel assessment[17] and Winebrake and Creswick demanded hydrogen fuelling systems.[18] In deciding the best alternative fuel for transport, Tzeng *et al.* used TOPSIS.[19] This MCDM technique is also applied to biomass selection[20], bio-diesel production, car body material selection and bumper beam selection.[21]

This study presents the CRITIC-TOPSIS method, which is aimed at determining the relative importance of objective weights in the MCDM problem. The best bio-diesel blend among the various blends cannot be suggested by researchers, because the fuel properties are nearer, creating a flaw to meet the emission standards and economy. So far, no research has been carried out on the selection of oil and bio-diesel blends using the CRITIC weight analysis method. Therefore, this study seeks to employ a novel approach for decision making along with the TOPSIS technique.

Materials and Methods

Sample Collection

This study is aimed at selecting the required oil from rapeseed, hemp seed, soybean, sunflower, cottonseed and sesame for producing bio-diesel, for which seven evaluation criteria were considered. To render different proportions, such as B20, B40, B60, B80 and B100, the produced bio-diesel was blended with diesel. Further attempts are being made to assess the suitable blend using CRITIC-TOPSIS in order to achieve optimum engine performance under various load conditions by reducing noxious emissions according to environmental benefits. The oil samples taken for the analysis were acquired from a merchant in Coimbatore, India. The oils were analyzed as per ASTM test protocols and reported in Table 1.

Experimental Setup

The tests were conducted in a constant-speed single-cylinder, four-stroke, air-cooled compression ignition engine. The bore and stroke are 80 mm and 110 mm respectively. The compression ratio and injection pressure for all experiments were set as 17.5:1 and 210 bar respectively. In order to offer the load, the engine was loaded by a mechanical dynamometer. In order to test the amount of CO, CO_2, NOx, HC and smoke AVL 437 smoke metre and AVL444 DI gas analyser were employed. A series of experiments with 1500 rpm and variable loads were carried out. As engine fuel, multiple blends of biodiesel were used along with clean diesel.

Experimental Methodology

The proposed technique comprises of four phases: (1) the selection of the most acceptable oil among the other oils selected. (2) Selection of the acceptable bio-diesel blend on the basis of engine performance criteria (3) CRITIC and TOPSIS shall rank the oils. (4) Performance and emission characteristics were observed at variable load for different alternatives.

CRITIC Method

By introducing the following stages, objective weights were found using the CRITIC method is carried out.

Table 1 — Properties of the selected bio-oils and diesel

Criteria type	C1	C2	C3	C4	C5	C6	C7
	Min	Max	Max	Min	Min	Min	Min
	Kinematic viscosity (cSt)	Cetane index	Heating value (MJ/kg)	Cloud point (°C)	Pour point (°C)	Flash point (°C)	Density (kg/m^3)
	ASTMD445	ASTM D613	ASTM D20	ASTM D5773	ASTM D97	ASTM D92	ASTM D2217
Diesel	3.04	50.0	43.9	−12	−16.2	78	845
Rapeseed oil	42.8	48.6	43.54	1.8	−14	128	874
Hemp seed oil	37.2	37.5	39.7	−4	−31.8	245	9116
Soya bean oil	32.5	37.8	39.5	−4	−12.3	253	9137
Sunflower oil	33.8	37.2	39.8	7.4	−15.2	276	9162
Cottonseed oil	33.6	41.9	39.6	18	−15.3	235	9149
Sesame oil	35.4	40.4	39.4	−3.8	−9.5	262	9134

Step 1: Determining normalized decision matrix using Eq. (1)

$$r_{ij} = \frac{x_{ij} - x_j}{x_j^{max} - x_j^{min}} \quad \ldots (1)$$

Value x_{ij} shows how an alternative is close to the ideal value x_j^{max} and how far it is from the anti-ideal values. The type of criteria will not be taken into account for normalized matrix.

Stage 2: Based on the value r_{ij} it is probable to form a vector, each vector has a standard deviation σ_j,

$$\sigma_j = \sqrt{\frac{1}{n}\left(\sum_{i=1}^{m} r_{ij} - \overline{r}\right)^2} \quad \ldots (2)$$

where, n is a number of elements and $\overline{r}$ is an mean.

Stage 3: Determining a symmetric matrix nxn with element. R_{ij}, is linear correlation co-efficient between r_j, r_k.

$$R_{ij} = \frac{n\sum r_j r_k - \sum r_j \sum r_k}{\sqrt{n\sum r_j^2 - (\sum r_j)^2} \cdot \sqrt{n\sum r_k^2 - (\sum r_k)^2}} \quad \ldots (3)$$

Stage 4: Determining the objective weight coefficients by normalizing the value by Eqs (4) & (5)

$$C_j = \sigma_j \sum_{k=1}^{n} \left(1 - R_{ij}\right) \quad \ldots (4)$$

$$w_j = \frac{C_j}{\sum_{j=1}^{n} C_j} \quad \ldots (5)$$

TOPSIS Method

Hwang and Yoon (1981)$^{(22)}$ invented TOPSIS technique, considering three types of criteria, such as qualitative benefit, quantitative benefit and cost criteria, this is fast and simple.[23] With respect to each chosen criterion, TOPSIS gives rank. The following step-by-step process for this approach is:

Step 1: Normalization process (z_{ij}):

$$z_{ij} = X_{ij} / \sqrt{\sum_{i=1}^{n} {X_{ij}}^2} \quad \ldots (6)$$

$$\left[x_{ij}\right] = \begin{bmatrix} x_{11} & x_{12} & \cdots x_{1n} \\ x_{21} & x_{22} & \cdots x_{2n} \\ \vdots & \vdots & \vdots \\ x_{mn} & x_{m2} & \cdots x_{mn} \end{bmatrix} \quad \ldots (7)$$

Step 2: Calculating weighted normalized decision matrix (r_{ij})

$$r_{ij} = w_j z_{ij},\ i = 1, 2, \ldots\ldots m \& j = 1, 2, \ldots n, \quad \ldots (8)$$

w_j is weights and $\left[z_{ij}\right]_{m\times n}$ is normalized matrix.

Step 3: Documenting positive and negative ideal solutions:

$$V^+ = \left\{\left(max_i r_{ij} \mid j\epsilon J\right), \left(min_i r_{ij} \mid j\epsilon J'\right) \mid i = 1,2, \ldots m\right\} = \left\{r_1^*, r_2^*, \ldots, r_j^*, \ldots, r_n^*\right\} \quad \ldots (9)$$

For best one

$$V^- = \left\{\left(min_i r_{ij} \mid j\epsilon J\right), \left(max_i r_{ij} \mid j\epsilon J'\right) \mid i = 1,2, \ldots m\right\} = \left\{r_1^-, r_2^-, \ldots, r_j^-, \ldots, r_n^-\right\} \quad \ldots (10)$$

For least one

$$J = \{j = 1,2, \ldots n \mid whennonbeneficialcriteria\}$$
$$J' = \{j = 1,2, \ldots n \mid whenbeneficialcriteria\}$$

Step 4: Calculating separation measures

$$S_{i+} = \sqrt{\sum_{j=1}^{n}\left(\delta_{ij} - \delta_j^*\right)^2}, i = 1,2, \ldots, m \quad \ldots (11)$$

$$S_{i-} = \sqrt{\sum_{j=1}^{n}\left(\delta_{ij} - \delta_j^-\right)^2}, i = 1,2, \ldots, m \quad \ldots (12)$$

Step 5: Calculation of the relative proximity(P_i)

$$P_i = \frac{T_{i-}}{(T_{i*} - T_{i-})}, 0 < C_{i*} < 1, i = 1,2, \ldots m. \quad \ldots (13)$$

P_i used for ranking

Uncertainty Analysis

Finding uncertainty is the lack of confidence in the outcomes of an experiment. It is difficult to assess the functional value of the experiment without an uncertainty analysis. To provide accuracy in the experiment, it's crucial to analyze the uncertainty values and the instrument's precision. According to Imdadul *et al.* the analysis was performed by calculating differences between the mean values at 95% confidence level.[24] To assure the accuracy of the findings, all tests were conducted thrice, and the data was averaged. The uncertainties are enumerated in Table 2.

Results and Discussion

Criteria Weights and Ranking of Oils

The CRITIC technique is employed to find the objective weight of the criterion. First Eq. (1) is used to form the normalized decision matrix (Table 3). The normalisation would not consider the criterion to be beneficial or non-beneficial. The standard deviation is determined using Eq. (2) based on the normalised value of the parameters. The standard deviation value is used to find the correlation coefficient value (Table 4). Finally, the weights for the parameters are assessed by Eq. (5) and represented in Table 4.

The normalization matrix was established in the first step by normalising the properties of the alternatives chosen. To perform the normalisation Eq. (6) was used (Table 5). In the second stage normalised decision matrix weighted is determined and is also tabulated in Table 5. The ideal positive and negative solutions are tabulated in Table 6. The values derived from CRITIC for the objective criteria weights are organized in Table 7. The order of rank is allotted with respect to proximity coefficient, which is diesel = 0.710 > hemp seed oil = 0.700 > soya bean oil = 0.522 > sesame oil = 0.491 > rapeseed oil = 0.434 > sunflower oil = 0.315 > cotton seed oil = 0.140. From this it can be understand that hemp oil was identified as the good one with a closeness coefficient of 0.700.

Table 2 — Uncertainties of the instruments

Instrument	Accuracy	Uncertainty
Kinematic viscometer	< 3%	±1.45
Cetane Number Analyser	±0.5	±0.5
Bomb calorimeter	±0.06%	±1.50
Cloud point apparatus	±1°C	±1.5
Pour point apparatus	±1°C	±2.92
Pensky Martens closed cup apparatus	±2°C	±1.75
Density meter	±0.02 g/cm^3	±0.35
Engine testing		
Brake thermal efficiency	±0.6%	±0.06
CO	±0.01%	±2.5
CO_2	±0.04%	±0.7
HC	±2 ppm	±3
NOx	±2 ppm	±2
Smoke	±0.2%	±1.5
EGT	±3°C	±2.5

Ranking of Best Blend using CRITIC-TOPSIS

Test Fuel

In this session, hemp seed oil is taken for further evaluation, since CRITIC-TOPSIS expressed that hemp seed oil is the best one. Hemp seeds contain around 32.21% oil, which is a strong yellow shade with a dull taste and a lovely nutty smell. The hardening point is 15–72°C. There were 1.4570 and 0.8927 individually in the refractive list and explicit gravity. The collected oils were transformed into bio-diesel using catalytic transesterification process.

Transesterification

A molar proportion of 6:1 is frequently utilized in mechanical procedures to get bio-diesel. In this process, the proportion of alcohol to oil was 0.4 to 0.8 and 0.01–0.03%. The blend was filled with a water shower shaker and mixed for 45 min at 60°C. In this process 93.89% of biodiesel was produced by utilizing 2 gram of KOH. After preparation the bio-diesel was analysed to get its basic properties. The calorific value of the bio-diesel was identified as

Table 3 — Normalized decision-making matrix for weight calculation

Criteria type	C1	C2	C3	C4	C5	C6	C7
Diesel	1.000	1.000	1.000	1.000	0.300	1.000	1.000
Rapeseed oil	0.000	0.891	0.920	0.540	0.202	0.747	0.593
Hemp seed oil	0.141	0.023	0.067	0.733	1.000	0.157	0.065
Soya bean oil	0.259	0.047	0.022	0.733	0.126	0.116	0.035
Sunflower oil	0.226	0.000	0.089	0.353	0.256	0.000	0.000
Cottonseed oil	0.231	0.367	0.044	0.000	0.260	0.207	0.018
Sesame oil	0.186	0.250	0.000	0.727	0.000	0.071	0.039

Table 4 — Correlation coefficient values of criteria and weights

	C1	C2	C3	C4	C5	C6	C7
C1	1.000	0.486	0.482	0.499	−0.054	0.591	0.681
C2	0.486	1.000	0.935	0.257	−0.229	0.957	0.921
C3	0.482	0.935	1.000	0.392	−0.076	0.972	0.964
C4	0.499	0.257	0.392	1.000	0.117	0.417	0.523
C5	−0.054	−0.229	-0.076	0.117	1.000	−0.037	−0.056
C6	0.591	0.957	0.972	0.417	−0.037	1.000	0.982
C7	0.681	0.921	0.964	0.523	−0.056	0.982	1.000
Weights (w_j)	0.133	0.138	0.129	0.152	0.252	0.101	0.096

Table 5 — Normalized and weight normalized decision-making matrix

Criteria type	C1	C2	C3	C4	C5	C6	C7
			Normalized decision-making matrix				
Diesel	0.034	0.448	0.406	−0.502	−0.347	0.132	0.355
Rapeseed oil	0.484	0.435	0.403	0.075	−0.300	0.217	0.368
Hemp seed oil	0.421	0.336	0.368	−0.167	−0.682	0.416	0.383
Soya bean oil	0.368	0.339	0.366	−0.167	−0.264	0.430	0.384
Sunflower oil	0.383	0.333	0.369	0.309	−0.326	0.469	0.385
Cottonseed oil	0.380	0.375	0.367	0.752	−0.328	0.399	0.385
Sesame oil	0.401	0.362	0.365	−0.159	−0.204	0.445	0.384
			Weight normalized decision making matrix				
Diesel	0.005	0.062	0.052	−0.076	−0.088	0.013	0.034
Rapeseed oil	0.064	0.060	0.052	0.011	−0.076	0.022	0.035
Hemp seed oil	0.056	0.046	0.047	−0.025	−0.172	0.042	0.037
Soya bean oil	0.049	0.047	0.047	−0.025	−0.066	0.043	0.037
Sunflower oil	0.051	0.046	0.048	0.047	−0.082	0.047	0.037
Cottonseed oil	0.050	0.052	0.047	0.115	−0.083	0.040	0.037
Sesame oil	0.053	0.050	0.047	−0.024	−0.051	0.045	0.037

Table 6 — Ideal positive and ideal negative solutions

	C1	C2	C3	C4	C5	C6	C7
V^+	0.005	0.062	0.052	−0.076	−0.172	0.013	0.034
V^-	0.064	0.046	0.047	0.115	−0.051	0.047	0.037

Table 7 — Distance of alternative, relative closeness and rank

Criteria type	S_{i+}	S_{i-}	P_i	Rank
Diesel	0.084	0.207	0.710	1
Rapeseed oil	0.143	0.110	0.434	5
Hemp seed oil	0.079	0.185	0.700	2
Soya bean oil	0.130	0.142	0.522	3
Sunflower oil	0.164	0.075	0.315	6
Cottonseed oil	0.218	0.035	0.140	7
Sesame oil	0.144	0.139	0.491	4

42.92 MJ/kg. The flash point, fire point, cloud point and pour point were identified as 132°C, 146°C, −4°C and −17°C. The density and viscosity of the oil were reduced to 886 kg/m^3 and 4.76 cSt during this process.

TOPSIS Computation

The engine operated at 20% load is deliberated to demonstrate proposed TOPSIS computation. Initially the performance readings were taken from Table 8 by using Eq. (6). The experimental analysis for various alternative blends at various load conditions are given in Table 9 and the weights of criteria are displayed in Table 10. To get weighted normalized decision matrix Eq. (8) is employed and listed in Table 11. CRITIC parameters weights are taken from Table 4. Positive and negative ideal solutions are calculated using Eqs (9) & (10), after the formation of a weighted normalized decision matrix (Table 12). In the next step, the Euclidian distance were found and listed in Table 13, using Eqs (11) & (12). The performance score is determined using Eq. (13) and described in Table 14. Finally, based on the performance score, the alternatives are ranked. The ranks of different blends for different loads are also given in Table 14. The same calculation method is used for 0%, 40%, 60%, 80% and 100% load conditions.

To illustrate the result of the TOPSIS analysis, the ranking order obtained at 60% load condition is considered. The ranking order is (B20 = 0.7197 > diesel = 0.6993 > B40 = 0.6919 > B60 = 0.6430 > B80 = 0.6356 > B100 = 0.3075). For load conditions of 40%, 60% and 80%, B20 is found as the optimum blend. For the load conditions of 20% and 100%, B20 obtained rank two and diesel obtained rank one, whereas B100 was ranked last because of its characterization.

Performance Characterization

The BTE versus load for all tested fuel is exposed in Fig. 1. At peak load, B100 achieved 11.79% lower BTE than diesel and this scenario is because of the high viscosity in nature of B100 which results in poor atomization characteristics and a lower combustion rate. Due to this issue, the B100 blend was diversified with diesel to produce various blends and it was tested with the diesel engine. BTE for diesel, B20, B40, B60, B80 and B100 were 33.06%, 33.29%, 29.10%, 27.28%, 26.55% and 24.00% respectively at the rated

Table 8 — Properties of fuels

Properties	Diesel	B20	B40	B60	B80	B100
Density (kg/m^3)	845	849	858	867	876	886
Kinematic viscosity (cSt)	3.04	4.1	4.22	4.36	4.52	4.76
Calorific value (MJ/kg)	43.9	41.80	41.46	40.74	40.84	40.92
Flash point (°C)	78	44	63	96	118	132
Fire point (°C)	84	52	72	90	126	146
Cloud point (°C)	−12	−7.725	−7	−6.5	−4.5	−4

Table 9 — Experimental performance and emission analysis at different loads

Criteria/ Load (%)	Blends	NOx (ppm)	Smoke (%)	BTE (%)	CO$_2$ (%)	CO (%)	HC (ppm)	EGT (°C)
		P1	P2	P3	P4	P5	P6	P7
0	Diesel	73	9.2	0	2	0.07	34	167
	B20	82	10.3	0	2.2	0.065	32	174
	B40	86	12.6	0	2.5	0.059	30	183
	B60	90	14.6	0	3	0.051	29	202
	B80	89	15.8	0	2.9	0.05	28	205
	B100	87	16.4	0	2.3	0.057	32	186
20	Diesel	85	24	16.3865	2.6	0.06	38	228
	B20	138	26	17.36	2.8	0.048	35	237
	B40	165	26.8	15.279	3	0.042	32	246
	B60	172	30.2	14.3695	3.4	0.035	30	264
	B80	187	31.9	13.8238	3.6	0.038	29	272
	B100	192	33.6	11.6411	2.8	0.046	34	254
40	Diesel	184	33.2	24.6517	3.4	0.04	42	312
	B20	176	32.4	26.646	3.6	0.027	38	328
	B40	232	34.5	23.2822	3.8	0.0219	35	342
	B60	266	38.2	21.9726	4	0.0172	36	365
	B80	284	42.3	20.7357	4.1	0.018	34	374
	B100	312	46.7	17.4617	3.5	0.0192	37	334
60	Diesel	308	42.1	30.5091	5.8	0.04	54	396
	B20	272	41.2	30.78	5.2	0.0264	49	419
	B40	432	42.4	26.1925	5.5	0.0219	46	436
	B60	486	43.9	24.7737	6.2	0.0168	44	459
	B80	516	46.4	23.4641	6.1	0.0161	45	462
	B100	541	54.1	21.2814	5.2	0.0186	47.5	440
80	Diesel	534	51.4	33.6355	6.8	0.19	66	454
	B20	494	52.8	33.693	6.8	0.186	62	466
	B40	648	55.4	26.1925	7	0.1623	58	481
	B60	684	58.9	29.8303	7.2	0.153	55	516
	B80	712	60.1	28.9573	7.3	0.148	57	529
	B100	736	62	27.0656	6.6	0.172	59	495
100	Diesel	986	63	33.0606	8.2	0.16	67	520
	B20	988	61	33.29	7.4	0.184	64	536
	B40	966	56	29.1028	7.7	0.163	60	548
	B60	942	58	27.2838	7.7	0.154	58	532
	B80	937	60.2	26.5563	7.7	0.146	57	530
	B100	905	65.9	24.0098	8.2	0.07	59	526

power. The higher drop in BTE for more than 40% bio-diesel blend is stable with other studies[25], since the higher bio-diesel blends have higher fuel consumption due to the presence of oxygenated elements.[26] B20 was revealed to have 33.29% better BTE when associated with other blends due to better energy content and optimum oxygen concentration of B20 enhance the heat level in the cylinder and thereby increase the atomization and homogeneity of the mixture, which results in better combustion.

Emission Characterizations

The various emission characteristics of the engine were illustrated in Fig. 2. The CO emission at 100% load, diesel, 20%, 40%, 60%, 80% and 100% blends exhibited 0.16%, 0.184%, 0.163%, 0.154%, 0.146%

Table 10 — Weights of criteria obtained from CRITIC

Load (%)	P1	P2	P3	P4	P5	P6	P7
20	0.1126	0.1063	0.0995	0.1406	0.2069	0.2194	0.1148
40	0.1147	0.1141	0.1005	0.1476	0.2101	0.1871	0.1259
60	0.1189	0.1137	0.1169	0.1564	0.1910	0.1761	0.1270
80	0.1116	0.1119	0.1280	0.1354	0.2164	0.1852	0.1116
100	0.1300	0.1367	0.1893	0.1508	0.1287	0.1225	0.1419

Table 11 — Weighted normalized decision matrix

Load (%)	Blends	P1	P2	P3	P4	P5	P6	P7
20	Diesel	0.0243	0.0360	0.0446	0.0489	0.1112	0.1027	0.0426
	B20	0.0395	0.0390	0.0473	0.0526	0.0890	0.0946	0.0443
	B40	0.0472	0.0402	0.0416	0.0564	0.0779	0.0865	0.0460
	B60	0.0492	0.0453	0.0391	0.0639	0.0649	0.0811	0.0493
	B80	0.0535	0.0478	0.0376	0.0677	0.0704	0.0784	0.0508
	B100	0.0549	0.0504	0.0317	0.0526	0.0853	0.0919	0.0475
40	Diesel	0.0348	0.0405	0.0446	0.0548	0.1364	0.0865	0.0467
	B20	0.0333	0.0395	0.0482	0.0580	0.0921	0.0783	0.0491
	B40	0.0439	0.0420	0.0422	0.0612	0.0747	0.0721	0.0512
	B60	0.0503	0.0465	0.0398	0.0644	0.0586	0.0741	0.0547
	B80	0.0537	0.0515	0.0375	0.0660	0.0614	0.0700	0.0560
	B100	0.0590	0.0569	0.0316	0.0564	0.0655	0.0762	0.0500
60	Diesel	0.0341	0.0432	0.0552	0.0652	0.1262	0.0814	0.0471
	B20	0.0301	0.0423	0.0557	0.0585	0.0833	0.0739	0.0498
	B40	0.0479	0.0435	0.0474	0.0618	0.0691	0.0693	0.0519
	B60	0.0539	0.0450	0.0448	0.0697	0.0530	0.0663	0.0546
	B80	0.0572	0.0476	0.0424	0.0686	0.0508	0.0678	0.0550
	B100	0.0600	0.0555	0.0385	0.0585	0.0587	0.0716	0.0523
80	Diesel	0.0379	0.0413	0.0585	0.0540	0.0991	0.0837	0.0421
	B20	0.0351	0.0424	0.0586	0.0540	0.0971	0.0786	0.0433
	B40	0.0460	0.0445	0.0456	0.0556	0.0847	0.0736	0.0446
	B60	0.0486	0.0473	0.0519	0.0572	0.0798	0.0698	0.0479
	B80	0.0506	0.0483	0.0504	0.0580	0.0772	0.0723	0.0491
	B100	0.0523	0.0498	0.0471	0.0525	0.0898	0.0748	0.0459
100	Diesel	0.0548	0.0579	0.0879	0.0646	0.0558	0.0550	0.0566
	B20	0.0549	0.0560	0.0885	0.0583	0.0642	0.0525	0.0583
	B40	0.0537	0.0514	0.0773	0.0606	0.0569	0.0493	0.0596
	B60	0.0524	0.0533	0.0725	0.0606	0.0538	0.0476	0.0579
	B80	0.0521	0.0553	0.0706	0.0606	0.0510	0.0468	0.0577
	B100	0.0503	0.0605	0.0638	0.0646	0.0244	0.0484	0.0573

Table 12 — Ideal solutions

Load (%)	P1	P2	P3	P4	P5	P6	P7
Positive ideal solutions (V^{+})							
20	0.0243	0.0360	0.0473	0.0489	0.0649	0.0784	0.0426
40	0.0333	0.0395	0.0482	0.0548	0.0586	0.0700	0.0467
60	0.0301	0.0423	0.0557	0.0585	0.0508	0.0663	0.0471
80	0.0351	0.0413	0.0586	0.0525	0.0772	0.0698	0.0421
100	0.0503	0.0514	0.0885	0.0583	0.0244	0.0468	0.0566
Negative ideal solution (V^{-})							
20	0.0549	0.0504	0.0317	0.0677	0.1112	0.1027	0.0508
40	0.0590	0.0569	0.0316	0.0660	0.1364	0.0865	0.0560
60	0.0600	0.0555	0.0385	0.0697	0.1262	0.0814	0.0550
80	0.0523	0.0498	0.0456	0.0580	0.0991	0.0837	0.0491
100	0.0549	0.0605	0.0638	0.0646	0.0642	0.0550	0.0596

Table 13 — Euclidian distance of alternatives from PIS (S_{i+})

Blends	Load (%)				
	20	40	60	80	100
			From PIS (S_{i+})		
Diesel	0.0324	0.0219	0.0332	0.0210	0.0271
B20	0.0296	0.0242	0.0296	0.0181	0.0340
B40	0.0392	0.0300	0.0276	0.0197	0.0324
B60	0.0332	0.0366	0.0384	0.0218	0.0408
B80	0.0524	0.0346	0.0335	0.0262	0.0348
B100	0.0450	0.0796	0.0773	0.0264	0.0336
			From NIS(S_{i-})		
Diesel	0.0524	0.0680	0.0772	0.0253	0.0407
B20	0.0423	0.0803	0.0760	0.0251	0.0258
B40	0.0479	0.0774	0.0620	0.0201	0.0185
B60	0.0379	0.0726	0.0692	0.0245	0.0260
B80	0.0416	0.0582	0.0584	0.0226	0.0192
B100	0.0321	0.0352	0.0343	0.0145	0.0178

Table 14 — Performance score and rank for different blends and different load

Blend	20% Load	Rank	40% Load	Rank	60% Load	Rank	80% Load	Rank	100% Load	Rank
Diesel	0.6178	1	0.7566	2	0.6993	2	0.5458	2	0.6002	1
B20	0.5884	2	0.7686	1	0.7197	1	0.5814	1	0.4314	2
B40	0.5503	3	0.7209	3	0.6919	3	0.5056	4	0.3641	4
B60	0.5337	4	0.6647	4	0.6430	4	0.5288	3	0.3894	3
B80	0.4426	5	0.6268	5	0.6356	5	0.4632	5	0.3560	5
B100	0.4162	6	0.3068	6	0.3075	6	0.3543	6	0.3465	6

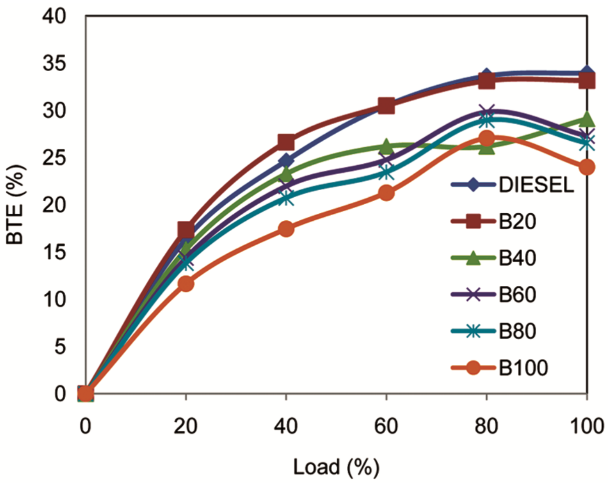

Fig. 1 — Variation of BTE for diesel and various blends under different load conditions

and 0.07% respectively. This reduction of CO for bio-diesel blends was increased by more accessibility of oxygen in hemp bio-diesel improving the combustion rate and thereby its carbon length was lower than diesel that results in low CO emission. These results are agreed with earlier studies.[27] According to Abed *et al.* the higher oxygenated elements in B80 and B100 compared to diesel burn quickly and completely lower the emission of CO. The release of lower CO is caused by enhanced fuel oxidation and more oxygen in the higher blends.[27] This is also the result of fuel mixing ratio, fuel vaporization followed by supplemented oxygen presence, which in turn promotes CO_2 conversion. Sudalaiyandi *et al*. claimed that the generation of CO_2 enhanced as a result of the larger load mass being linked to chemical processes by the higher engine load.[28] HC emission graph exhibits that all the bio-diesel blends show a minimal range of HC emissions up to 75% engine load. This is caused by the optimal quantity of oxygen supplied at a lower load and it also helps to complete the oxidation of fuel. At peak load, the HC for all fuels attained its maximum level. At higher loads, the minimum of HC emission for B20, B40, B60, B80 and B100 was detected by 64 ppm, 60 ppm, 58 ppm, 57 ppm and 59 ppm respectively. Bio-diesel blends have adequate oxygen concentration and better cylinder temperature showed a better reduction rate of HC emissions.[9] According to Gad and Jayaraj, the higher HC emission with a higher load is related to the presence of lower oxygen, when a greater quantity of fuel is injected.[29]

The increases in load condition the all fuel blends possess higher NOx emission by enhance cylinder temperature during the combustion. At 100% load,

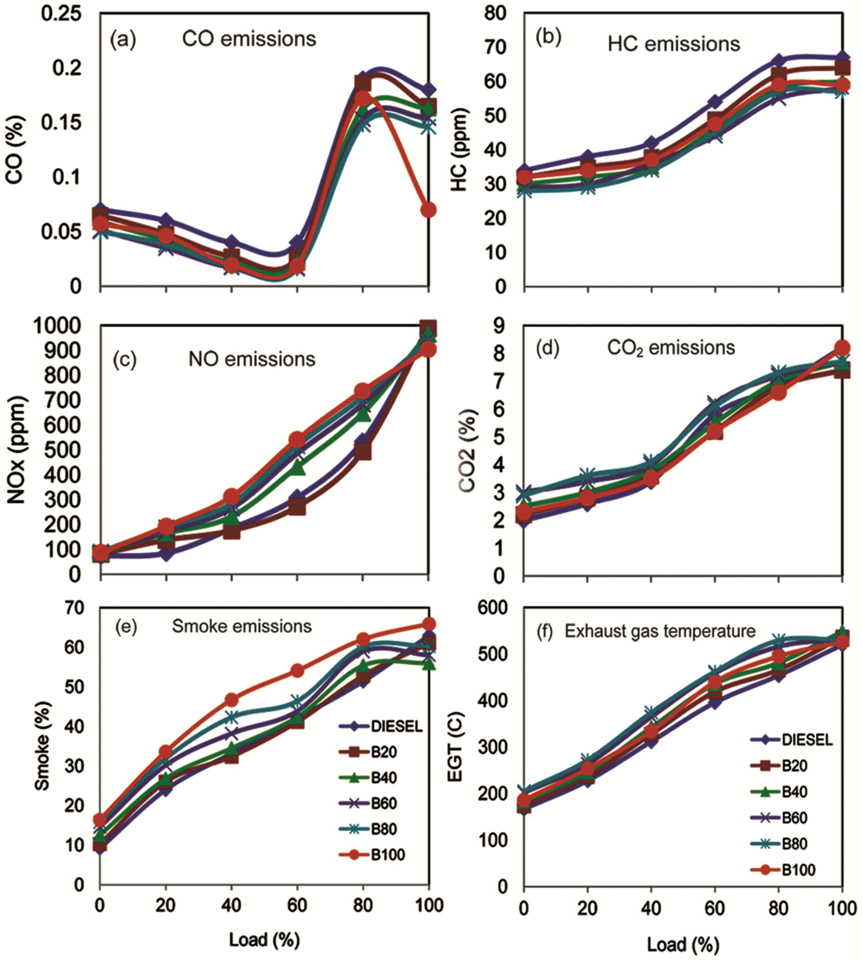

Fig. 2 — Various emission parameters of the engine: (a) CO emissions, (b) HC emissions, (c) NO emissions, (d) CO_2 emissions, (e) Smoke emissions, and (f) Exhaust gas temperature

NOx of B100, B80, B60, B40, B20 and diesel were noticed as 905 ppm, 937 ppm, 942 ppm, 966 ppm 988 ppm and 986 ppm respectively. Moreover, the NOx emission of B20 was 988 ppm, which is higher than other bio-diesel blends and diesel at constant speed. This is due to the medium level of O_2 in B20 with a chemically correct A/F mixture, which results in more NOx formation by the Zeldovic mechanism. At peak load, the least amount of NOx emissions was recorded for diesel fuel. This might have occurred due to low in-cylinder pressure. At maximum load, all bio-diesel blends displayed higher NOx than diesel due to the availability of O_2 molecules available in the fuel and peak flame temperature. It also occurred because of thorough combustion, existence of previous cycle temperature and combustible nature.[30] The CO_2 emissions for B100 is higher than the rest of the blends. This is owing to neat biodiesel had maximum concentration of oxygen which promote CO oxidation process. The CO_2 emissions for biodiesel blends and diesel reached to maximum at rated brake power (BP). This is due to the available resident time for fuel to involve the combustion process.[31] The CO_2 emission for B20, B40, B60, B80, B100, and diesel were observed by 7.4%, 7.7%, 7.7%, 7.7%, 8.2% and 8.2% respectively and it is lowered by 0.8%, 0.5%, 0.5% and 0.5% respectively because of low evaporation of the blends by higher viscous and least energy level of bio-diesel blends that result in poor oxidation of CO. In addition, the B100 and B40 followed a close trend to diesel at maximum load, which is related to a improved cetane index, which enable to produce a shorter ignition delay and better cylinder temperature. By this impact, the fuel oxidation process is enhanced to complete the combustion and increase the CO_2 emissions. From the result, it was found that the CO_2 emission level is lower in B20 blend.

The graph demonstrates that all the blends noticed lower smoke emission for a rise in load condition than diesel fuel, which would be achieved by the low C/H ratio of the blends and enhanced oxygen availability, which would provide more fuel burn in a rich zone. Diesel produced more quantities of smoke emissions than the fuel blends due to the high stoichiometric ratio and the availability of partial unburned hydrocarbons in the fuel. At peak load, the fuel blends B40 and B60 got 56% and 58% lowered smoke emission with diesel. This is attributed to the better ignition of fuel and the higher oxygenated molecules. B20 detected as 61% of smoke emission at rated speed condition. The EGT rises with gradually increasing BP. For diesel the value of EGT is low for all load conditions. B40 showed higher EGT than diesel fuel at peak load conditions. In general, the primary combustion region produces a high cylinder temperature due to the fact that more fuel can burn in this region. From results, the B40 showed highest EGT due to the optimum viscosity which enhance combustion rate. The results of EGT for diesel is 520°C, for B20 is 536°C, for B40 is 548°C, for B60 is 532°C, for B80 is 530°C and for B100 is 526°C. At highest load, B60, B80, B100, and diesel showed 532°C, 530°C, 526°C, and 520°C lowered EGT values, respectively than B20 because of better cetane rating and minimal ignition delay, which results in enhanced cylinder temperature. According to Sjöberg and Zeng, this is because of the joint effect of improved combustion and intrinsic O_2 level.[32]

Conclusions

The investigation indicates that due to the distinct properties of hemp bio-diesel, it can be directly utilized in conventional diesel engine. The least performance was noticed with neat hemp bio-diesel. The BTE of B20 blend was drastically higher than the other blends. Moreover, B20 exhibited a similar BTE trend to diesel and exhibited 9.281% higher BTE than B100 at peak load condition. B100 showed least CO emission at full load condition which is 0.09% lower than diesel. Lesser HC production was observed for all bio-diesel blends may be due to the higher oxygen concentration in bio-diesel. Compared to diesel the CO_2 production of all bio-diesel blends were lower. Raw bio-diesel and diesel observed higher NOx emissions and smoke opacity than the blends. Finally, it is concluded that the B20 fuel showed superior operating characteristics with optimum level of emissions. Furthermore, the study can be extended to find the combustion characteristics of the engine. With the same performance, bio-diesel can be utilised in other type of engines. Under the same operating circumstances, the study can be utilized to construct group decision-making methodologies using other MCDM methods such as VIKOR, EDAS and PROMETHEE. The study utilized different bio-diesel blends with a 20% variation. To obtain more precise results, additional trials can be carried out by adjusting the blending concentrations between 5% and 10%.

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