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Statistical analysis on prediction of biodiesel properties from its fatty acid composition

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ABSTRACT

The present work deals with the statistical analysis to determine the relationship between the vital biodiesel properties (cetane number, density, viscosity, heating value) and fatty acid compositions of nine different types of biodiesels originated from edible oil non-edible oil, waste oil, and animal oil. Multiple linear regression analysis (MLR) was used to develop the mathematical models to predict the properties from the saturated (lauric, myristic, stearic) and unsaturated fatty (oleic, linoleic, linolenic) acids composition. The developed models were then validated with experimental data from the literature to determine their predictive capability. The models developed for cetane number and density were highly statistical and successfully predicted the respective properties of randomly selected biodiesel from the literature. On the other hand, predictive models for kinematic viscosity and heating value were ineffective; however, the error between experimental and predicted values was sufficiently minimal for heating value.

1. Introduction

Extensive research is being conducted on biodiesel application for internal combustion engines [10,24,25]. This is due to the fact that biodiesel is made from agricultural or animal sources, which reduces the necessity on the oil and helps maintain the environmental CO_2 balance as biodiesel combustion produces lower carbon emissions [3,24,26]. Biodiesel is generally made using a transesterification reaction wherein the triglycerides present in oil reacts with reacts with alcohol in the company of acid or alkali catalyst to produce the fatty acid esters [21,22]. Biodiesel is prepared from various oils/feedstocks and raw materials with varying chemical compositions. A peculiar aspect of the feedstocks used for biodiesel production is that each oil/fat in the fatty acid has a different structure and varies depending on its origin, physical and chemical properties (density, viscosity, cetane number, calorific value) [2]; [33]). This variation in biodiesel's fatty acid contents is responsible for the variation in performance and emission levels when used as engine fuel. Hence, it is a question of utmost importance: which biodiesel feedstock and what Fatty Acid Composition (FAC) would be best to obtain better engine performance and lower emissions. The amount of fatty acid present in the biodiesel molecule affects its chemical properties. In contrast, the physical properties depend on the chain length and the number of double bonds in fatty acids [12].

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The transesterification reaction does not alter the FAC of the biodiesel; thus, the FAC of biodiesel plays a vital role in properties such as cetane number, viscosity, density, and calorific value.

The available literature on the FAC and its effect on biodiesel chemical and physical properties is scarce. In a study conducted by Ref. [12], the high concentration of saturated fatty acids was responsible for the high cloud point of biodiesel produced from beef oil [7]. concluded that the linolenic acid content present in the FAC is responsible for the oxidation stability of biodiesels. The FAC of biodiesel and its effect on the physio-chemical proprieties are reported in various literature wherein critical properties such as cetane number, density, viscosity, calorific value is discussed (V. S [19]. Much state-of-the-art research has experimented on diesel engines fuelled with biodiesel derived from various ranges of feedstocks. The fuel properties such as cetane number, additional oxygen content, and absence of sulfur compounds reveal biodegradable, cleaner combustion, and relatively more minor exhaust emission profiles of biofuels. The engine performance investigation results of both short and long terms indicate the biofuel's potential. However, during the long-term engine endurance experimentation, a few critical problems such as lubricating oil thickening, injector deposition, gum formation, and rubber component softening are primarily attributed to biodiesel's high viscosity and density.

According to Ref. [8] comprehensive investigations, the FAC of biodiesel feedstock, such as long-chain saturated factor (LCSF), degree of unsaturation (DU), significantly affects their physio-chemical properties. Further, biodiesel quality is influenced by contaminants such as unreacted glycerides and non-fatty acid fractions present either in a feedstock or due to side reactions in the course of transesterification reaction. This can be explained by the greater lengths of the fatty acid chain, which contributes to a high cetane number of biodiesels, leading to lower NOx emissions. Thus, the FAC of biodiesel directly relates to its physicochemical properties, which can further affect engine performance and emissions [17]. reported the prediction of biodiesel properties from its FAC. It was concluded that the higher heating value, oxidation stability, and viscosities of biodiesel produced from animal fats and oils were higher than the vegetable oils [13]. conducted a statistical study to investigate biodiesel properties from its fatty acid weight composition. A wide range of data was chosen to predict and develop the mathematical models using the regression technique [5]. using a least-square support vector machine coupled with particle swarm optimization and developed a model to predict the cetane number from the FAC of biodiesel. However, although the developed mathematical models predict biodiesel properties, their reference values may vary [6]. reported that the variation of prediction and reference values could be attributed to the sources of variability such as impurities, storage time, and conditions, a chemical reaction used which do not reflect in the developed models. The biodiesels with a high degree of unsaturation, branching showed excellent cold flow properties [1]. In contrast, the chain length and degree of saturation influenced cetane number, viscosity, and heating values of biodiesel [4]. correlated the viscosity of biodiesel with its FAC, while saponification and iodine value of biodiesel was correlated with FAC using multiple linear regression analysis [9].

The present work focuses on the production and determination of properties of biodiesel, particularly Cetane number, density, kinematic viscosity, and calorific value, intending to develop predictive correlations concerning the FAC employing multiple linear regression methodologies. The established predictive correlations are validated to forecast the properties of the biodiesel based on the FAC. Though the experimental measurements of these biodiesel properties are not complex, they do involve substantial expense and effort. Thus, the relevance of presenting the predictive correlations is not limited to predicting the fuel properties but may also help manufacture higher-quality biodiesel. As a result, it is necessary to propose dependable and precise correlations to predict the properties.

2. Methodology

In this study, nine different biodiesels (B100) originated from edible oil (soybean rapeseed, rice bran), non-edible oil (Jatropha *(Jatropha Curcas)*, Karanja *(Pongamia Pinnata)*, Mahua Indica *(Madhuca longifolia)*, Tamarind seed *(Tamarindus Indica)*, waste oil (waste cooking oil), and animal oil (Chicken fat oil) were selected. The raw feedstock was transesterified into biodiesel using a transesterification reaction. To prepare the biodiesel, the raw oil was preheated at around 50–55 °C for 10 min. Methanol in the ratio 9:1 was mixed in the preheated raw oil. Potassium hydroxide (KOH) 1.5% of oil was added as catalyst. The mixture was then heated and simultaneously stirred in a magnetic stirrer for 60 min at 55–60 °C temperature. The mixture was then poured into a separating funnel to separate the glycerol which is a by-product of the transesterification process. Glycerol is kept to settle down for overnight. The resulting solution was washed three times with a boiling water to remove excess KOH and methanol. Properties of biodiesel, including cetane number (CN), density, kinematic viscosity (KV) and calorific value (CV), were measured as per ASTM D6751

Table 1
FAC and percentage unsaturation of biodiesel.

Biodiesel	Lauric	Myristic	Palmitic	Stearic	Oleic	Linoleic	Linolenic	% US
	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	
Soyabean	0.1	0.2	10.5	3.8	23.7	54.5	6.3	84.5
Rapeseed	0.1	0.2	4.07	1.55	62.24	20.61	8.72	91.57
Rice Bran	0	0	18.8	2.4	43.1	33.2	0.6	76.9
Jatropha	0.12	0.1	13.2	6.11	43.86	35.4	0.3	79.56
Karanja	0	0	10.6	6.8	49.4	19	0.3	68.7
Mahua Indica	0	0	21.53	18.9	39.1	19.55	0.3	58.95
Tamarind seed	0	1.59	12.67	15.93	47.48	18.34	0.63	66.45
Waste Cooking oil	0	0	13	4	24	52	0.2	76.2
Chicken fat oil	0	0	22.2	5.1	42.5	19.3	1	62.8

standards shown in Table 2.

To proceed to the development of a correlation between the properties of biodiesel and the respective composition by weight of fatty acids, the first step was to determine the FAC of the selected biodiesels. The FAC (FAC) of the biodiesel was measured using a gas chromatograph (GC-2010, Shimadzu) equipped with a flame ionization detector and capillary column. The essential fatty acids that were measured were Lauric (C12:0), Mystric (C14:0), Palmitic (C16:0), Stearic (C18:0), which are saturated fatty acids, while unsaturated fatty acids include Oleic (C18:1), Linoleic (C18:2), and Linolenic (C18:3). The saturated fatty acids have no carbon-carbon, while the unsaturated fatty acids have one or more carbon-carbon double bonds with *cis* or *trans* configuration [12]. The FAC of biodiesel significantly influences its fuel properties. The FAC of biodiesel considered under is summarized in a Table 1. The percentage unsaturation (%US) consists of composition of three unsaturation fatty acids which are oleic, linoleic, and linolenic.

The regression equation chosen for the Multiple Linear Regression (MLR) analysis is of the type which [14] previously studied. Statistical package Minitab 19.0 was used to perform the MLR analysis.

$$\text{Property} = A + a_1x_1 + a_2x_3 + a_3x_3 + a_5x_5 + a_6x_6 + a_7x_7 + a_8x_8 \quad (1)$$

where *A* and *a* are the coefficients of constants and x_1 to x_8 corresponds to the FAC of (1: Lauric, 2: Mystric, 3: Palmitic, 5: stearic, 6: oleic, 7: linoleic, and 8: linolenic acid). The mathematical model obtained from regression analysis will then be used to predict the properties of different biodiesel other than the present study.

3. Results and discussion

3.1. Cetane number

Cetane number (CN) of fuels signifies its combustion and ignition quality; besides, a higher cetane number results in incomplete fuel combustion (A. K. [28], better engine performance over cold operating conditions, and less white smoke emissions. Higher CN of biofuel results in shorter ignition delay time (V. [20]; however, biodiesel CN closely associates with the FAC of their base feedstock utilized for production. Higher CN results in higher saturated fatty acids and aggregate long fatty acid chains; conversely, cetane number lowers with a higher degree of Monounsaturated fatty acids (MUFAs) and polyunsaturated fatty acids (PUFA). Further lower long chain saturation factor and increase of DU leads to rising NOX emission [31]. Experimental determination of CN is time-consuming and requires precision; thus, several prediction models have been developed in the past. The CN for biodiesel ranges from lower to much higher than that of diesel fuel (Table 3). These variations in CN are attributed to the different FAME structures and FACs. A correlation was observed between % US and CN, as illustrated in Fig. 1.

$$CN = -0.3852(US) + 80.277 \quad (2)$$

It is evident that increasing the %US results in lower CN. Feedstocks with lower unsaturation levels such as Karanja, Mahua Indica, Tamarind seed result in higher CN in the range of 60. Various authors have reported correlations between CN and chain length, molecular weight, double bonds, and straight-chain saturated factor [34,36].

The regression model fitness coefficient for CN is obtained as follows:

$$CN = 65.80 - 7.91x_1 + 0.774x_2 - 0.0608x_3 + 0.0768x_5 + 0.1406x_6 - 0.2887x_7 - 0.369x_8 \quad (3)$$

Where x_1, x_2, x_3, x_5, x_6, x_7, x_8, are fatty acid weight compositions of lauric, myristic, palmitic, stearic, oleic, linoleic, and linolenic, respectively.

The regression equation (3) shows that the saturated fatty acids (lauric, myristic, palmitic) contributes to the increasing of CN. The magnitude of the coefficient of saturated fatty acids decreased with an increase in carbon number, i.e., from C12:0 to C16:0. On the other hand, the unsaturated fatty acids (stearic, oleic, linoleic, and linolenic) contributed towards the decrease of predicted CN with the magnitude of coefficients increasing with increase in carbon number, i.e., from C18:0 to C18:3. The regression model fitness coefficients of the developed model are presented in Table 4. The R^2 was found 99.54%, which is relatively high for the analyzed data set. The model's predictive capability was checked by randomly selecting the different biodiesel from literature; the CN from literature and those obtained using the developed regression model are presented in Table 5. The magnitude of the error is not high, and this model can predict the CN's success, which proves the reliability of the developed model.

Table 2
Properties of biodiesel considered in study.

Biodiesel	CN	Density, kg/m^3	KV, cSt	CV, MJ/Kg
Soyabean	44.4	881.2	4.31	39.12
Rapeseed	47.83	878.4	4.64	38.61
Rice Bran	50.96	873.4	4.72	38.6
Jatropha	49.78	874.8	4.74	38.71
Karanja	54.21	871.47	4.97	37.21
Mahua Indica	57.34	867.37	4.87	37.64
Tamarind seed	56.83	867.21	4.84	37.31
Waste Cooking oil	48.92	880.14	4.78	37.97
Chicken fat oil	55.83	872.6	4.85	37.77

Table 3
FAC and CN for analyzed data set.

Biodiesel	Lauric	Myristic	Palmitic	Stearic	Oleic	Linoleic	Linolenic	CN
	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	
Soyabean	0.1	0.2	10.5	3.8	23.7	54.5	6.3	44.4
Rapeseed	0.1	0.2	4.07	1.55	62.24	20.61	8.72	47.83
Rice Bran	0	0	18.8	2.4	43.1	33.2	0.6	50.96
Jatropha	0.12	0.1	13.2	6.11	43.86	35.4	0.3	49.78
Karanja	0	0	10.6	6.8	49.4	19	0	54.21
Mahua Indica	0	0	21.53	18.9	39.1	19.55	0.3	57.34
Tamarind seed	0	1.59	12.67	15.93	47.48	18.34	0.63	56.83
Waste Cooking oil	0	0	13	4	24	52	0	48.92
Chicken fat oil	0	0	22.2	5.1	42.5	19.3	1	55.83

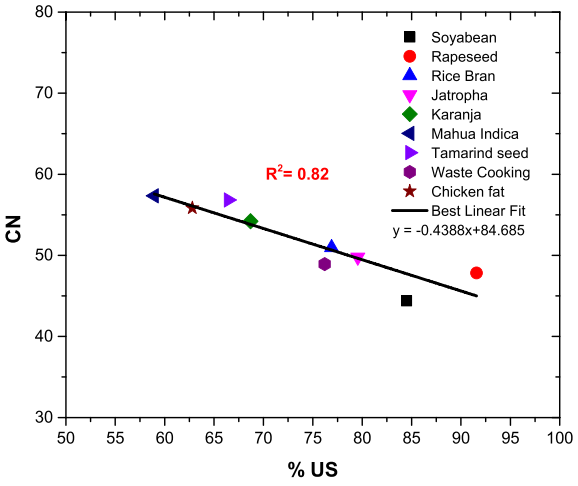

Fig. 1. Relation between % US and CN.

Table 4
Statistical coefficients for MLR for CN model.

Statistics	Multiple regression model
R^2 (%)	99.66
Std. Deviation (±)	0.7435
Observations	9
P-Value	0.137

The model established in the present study was compared with those developed in previous studies:

(a) Bamgboye and Hansen [27].

$$CN = 61 + 0.088x_2 + 0.133x_3 + 0.152x_4 - 0.101x_5 - 0.039x_6 - 0.243x_7 - 0.369x_8 \quad (4)$$

(b) Giakoumis and Sarakatsanis [13].

Table 5
Prediction of CN of random biodiesel taken literature [14].

Biodiesel	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	Exp. CN	Pred. CN	Error (%)
Olive	0	11.6	3.1	75	7.8	0.6	57	53.7	5.74
Peanut	0.1	8	1.8	53.3	28.4	0.3	53	50.6	4.34
Rapeseed	0	4.9	1.6	33	20.4	7.9	55	52.7	4.04
Grape	0.1	6.9	4	19	69.1	0.3	48	43.8	8.59
HO Sunflower	0	4.6	3.4	62.8	27.5	0.1	53	49.5	6.53
Corn	0	6.5	1.4	65.6	25.2	0.1	53	49.7	6.09
Jatropha	0.1	15.6	10.5	42.1	30.9	0.2	54	52.7	2.37

$$CN = 55.87 + 0.0747x_1 + 0.098x_2 + 0.164x_3 + 0.176x_4 - 0.050x_5 + 0.001x_6 - 0.140x_7 - 0.273x_8 \quad (5)$$

(c) Gopinath et al. [15].

$$CN = 62.2 + 0.017x_1 + 0.074x_2 + 0.115x_3 + 0.177x_4 - 0.103x_6 - 0.279x_7 - 0.366x_8 \quad (6)$$

Fig. 2 shows the graphs for experimental against predicted CN for four models. The model developed by Gopinath et al. and Bamgboye and Hansen resulted in high R^2 values of 0.84 and 0.82. At the same time, that of Giakoumis and Sarakatsanis is slightly lower at 0.72. In contrast, the newly developed model had an R^2 of 0.99, showing its predictive capability for the measured data set.

3.2. Density

Biodiesel standards EN 14214 states fuel's density limits over 860–900 kg/m^3 at 15 °C. While operating the diesel engines, both the fuel injection and air-fuel mixing systems operate at temperature ranges 300–350 K and pressure of 150-50 Mpa. Further, the fuel injection rate depends directly on the density of the corresponding fuel; hence the density of biodiesel is a primary concern on their use in diesel engines (A. K [29]. Greater SFA and DU of feedstock contribute higher density; on the other hand, the values decrease with increasing the fatty acid molecular chain length [16,35].

The ASTM standards include no specifications for density. For the biodiesel that meets all other specifications, it is stated that no determination of density is required as it will have densities in the desired range. Most of the studies have shown that the density of biodiesel does not vary a lot because the density of oil and alcohol used for biodiesel production is nearly the same. The density of biodiesel depends on the FAC as well as its purity. The density increases with decreasing the chain length and increasing the double bonds. Thus, fuels with rich unsaturated compounds such as soyabean oil (881.2 kg/m^3), rapeseed oil (878.2 kg/m^3) have high density (Table 6).

Fig. 3 represents the density values for different biodiesel with slight variation due to variation in the FAC of the feedstock used to produce biodiesel. The relationship between the %US and density (R^2 =0.65) is obtained as,

$$\rho = 0.3244(US) + 849.36 \quad (7)$$

The biodiesel chain length and bonds have a significant effect on the density. The density tends to increase with increasing the double bonds and decrease with decreasing the chain length. The correlation of density with double bonds and the molecular weight is developed by Ramirez Vedrizco et al. [35], while Lapuerta et al. [23] correlated density with the DU and chain length. In the present work, the density is correlated with the FAC, and the regression equation (8) is developed as,

$$Density = 877.47 + 21.35x_1 + 0.619x_2 - 0.0367x_3 - 0.3740x_5 - 0.0599x_6 + 0.0007x_7 + 0.3532x_8 \quad (8)$$

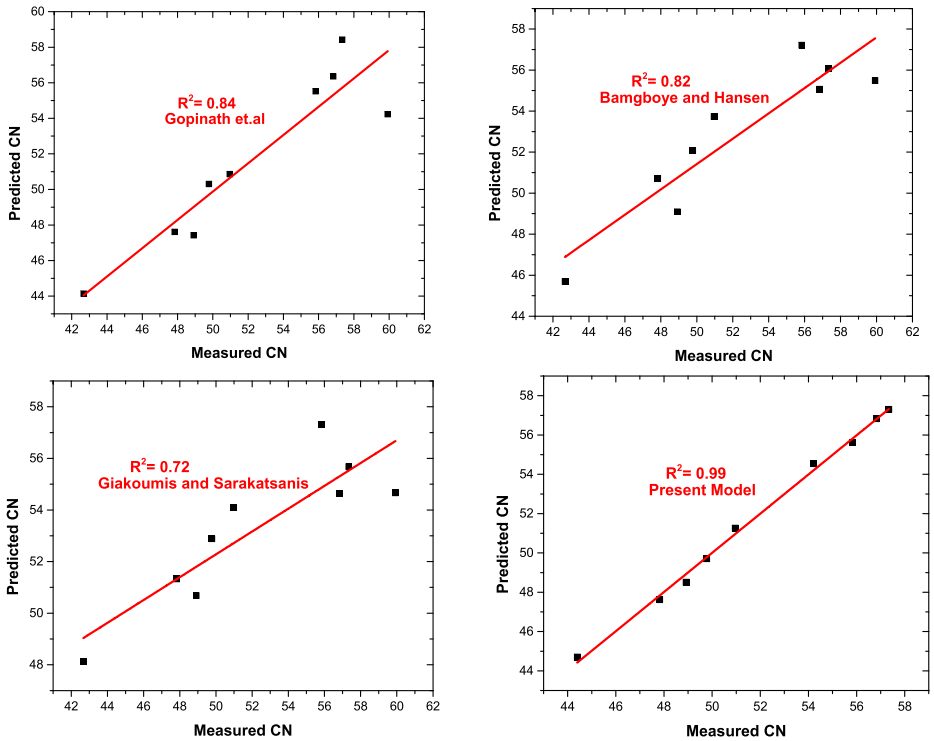

Fig. 2. The predictive capability of the present model with previously developed models for CN.

Table 6
FAC and density for analyzed data set.

Biodiesel	Lauric C12:0	Myristic C14:0	Palmitic C16:0	Stearic C18:0	Oleic C18:1	Linoleic C18:2	Linolenic C18:3	Density, kg/m^3
Soyabean	0.1	0.2	10.5	3.8	23.7	54.5	6.3	878.6
Rapeseed	0.1	0.2	4.07	1.55	62.24	20.61	8.72	878.4
Rice Bran	0	0	18.8	2.4	43.1	33.2	0.6	873.4
Jatropha	0.12	0.1	13.2	6.11	43.86	35.4	0.3	874.8
Karanja	0	0	10.6	6.8	49.4	19	0	871.47
Mahua Indica	0	0	21.53	18.9	39.1	19.55	0.3	867.37
Tamarind seed	0	1.59	12.67	15.93	47.48	18.34	0.63	869.4
Waste Cooking oil	0	0	13	4	24	52	0	874.14
Chicken fat oil	0	0	22.2	5.1	42.5	19.3	1	872.6

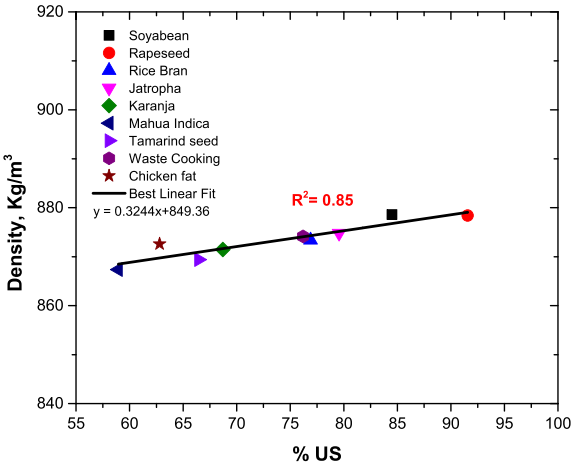

Fig. 3. Relation between % US and density.

Where x_1, x_2, x_3, x_5, x_6, x_7, x_8, are fatty acid weight compositions of lauric, myristic, palmitic, stearic, oleic, linoleic, and linolenic, respectively. The saturated fatty acids (lauric, myristic, palmitic) have higher coefficients than unsaturated fatty acids, which is the reason for the high coefficient of the constant term. The developed regression model coefficients show an excellent R^2 value of 99.18%, indicating the strong correlation between the derived equation and data points (Table 7).

The reliability of the developed model is checked with the experimental density values of random biodiesel taken from literature. Table 8 gives the experimental and predicted values of density from the developed regression equation. The percentage error between experimental and predicted values was comparable, and thus the model can predict the density values from the FAC. Further, the established regression model is checked with one developed by Giakoumis and Sarakatsanis. An R^2 value of 0.75 was obtained, which is entirely satisfactory, as shown in Fig. 4.

Giakoumis and Sarakatsanis [13].

$$\text{Density} = 923 + 1.01x_1 - 0.99x_2 - 0.54x_3 - 0.62x_4 - 0.70x_5 + 0.44x_6 + 0.37\ \ x_7 + 0.24x_8 \tag{9}$$

3.3. Kinematic viscosity

Kinematic viscosity (KV) is a measure of internal fluid's resistance to shearing flows under gravity at 40 °C. Biodiesel standards EN 141214 specifies KV over 3.5–5.0 mm^2/s (Table 9). The KV influences primary fuel injection, lubrication, blending atomization, volatility, and combustion (V [19]. Hence, the KV of combustive fuel oil is a prominent decisive flow feature for their usage. The lower KV of fuel indicates its poor lubrication, resulting in increased wear of moving engine parts, subsequently increasing engine durability and power losses due to leakage issues. Conversely, higher KV causes soot deposition on engine components such as inlet and outlet

Table 7
Statistical coefficients for MLR for density model.

Statistics	Multiple regression model
R^2 (%)	99.96
Std. Deviation (±)	0.2162
Observations	9
P-Value	0.334

Table 8
Prediction of density of random biodiesel taken literature [32].

Biodiesel	Experimental Density	Predicted Density	% Error
Soybean	880	876.61	0.39
Rapeseed	876.6	875.96	0.30
Palm	870.4	876.71	0.73
SME + RME	878.3	876.75	0.18
RME + PME	874	878.01	0.46
SME + PME	874.5	878.12	0.41

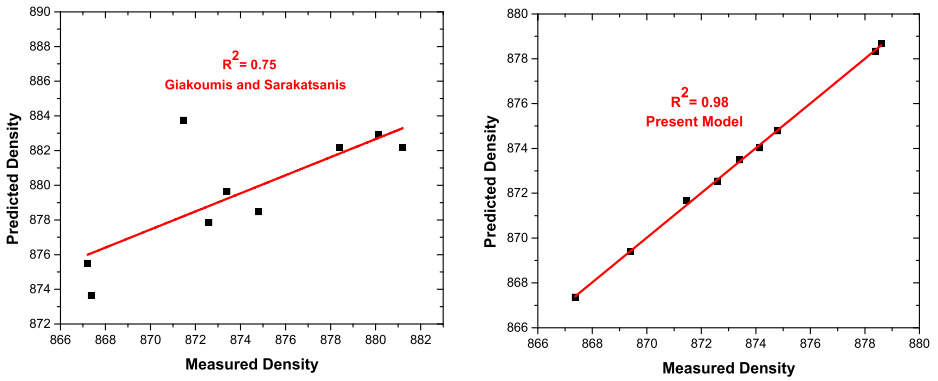

Fig. 4. The predictive capability of the present model with previously developed models for density.

Table 9
FAC and KV for analyzed data set.

Biodiesel	Lauric	Myristic	Palmitic	Stearic	Oleic	Linoleic	Linolenic	KV, cSt
	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	
Soyabean	0.1	0.2	10.5	3.8	23.7	54.5	6.3	4.31
Rapeseed	0.1	0.2	4.07	1.55	62.24	20.61	8.72	4.64
Rice Bran	0	0	18.8	2.4	43.1	33.2	0.6	4.72
Jatropha	0.12	0.1	13.2	6.11	43.86	35.4	0.3	4.74
Karanja	0	0	10.6	6.8	49.4	19	0	4.97
Mahua Indica	0	0	21.53	18.9	39.1	19.55	0.3	4.87
Tamarind seed	0	1.59	12.67	15.93	47.48	18.34	0.63	4.84
Waste Cooking oil	0	0	13	4	24	52	0	4.78
Chicken fat oil	0	0	22.2	5.1	42.5	19.3	1	4.85

valves, fuel injectors piston rings, and higher exhaust emissions due to inadequate fuel injection (A. K [28].

The correlation between KV and %US is represented in Fig. 5. The R^2 =0.66 for the established was found to be moderate,

$$\mu = -0.00969(DU) + 5.491 \tag{10}$$

Several studies have reported that biodiesel's kinematic viscosity increases with an increase in carbon atoms and decreases with the degree of unsaturation [18]. Viscosity increases with increasing the chain length and degree of saturation. The configuration of double bonds can also influence the viscosity of biodiesel. Biodiesel consisting of the cis double-bond configuration has a lower viscosity than the trans configuration [35]. Statistical analysis was performed to correlate the viscosity and CN, which showed high R^2 =0.92. The correlation between the viscosity and CN is given in Eq. 11

$$KV = 0.00002(CN)^3 - 0.0089(CN)^2 + 0.7657CN - 14.176 \tag{11}$$

MLR analysis was performed to develop the model for viscosity equation (2). The R^2=0.95 was found for the same, which is quite comparable as represented in Table 10. Fig. 6 represents the predicted and measured viscosity from the developed equation; R^2 was found 0.97, which is satisfactory for the analyzed data set.

$$KV = 5.32 - 0.83x_1 - 0.086x_2 - 0.0133x_3 + 0.0006x_5 - 0.0002x_6 - 0.0082x_7 - 0.0435x_8 \tag{12}$$

The model's predictive capability was checked by selecting the random biodiesel from previous work. The experimental and predicted viscosity values from the developed model are given in Table 11. The percentage error between experimental and predicted viscosity was found to be significant, up to 13%. The uncertainties associated with experimentation can be the reason for such an error.

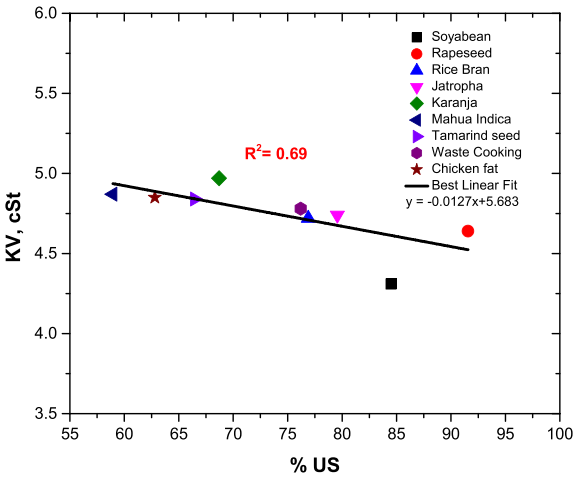

Fig. 5. Relation between % US and kinematic viscosity.

Table 10
Statistical coefficients for MLR for KV model.

Statistics	Multiple regression model
R^2 (%)	95.63
Std. Deviation (±)	0.1122
Observations	9
P-Value	0.411

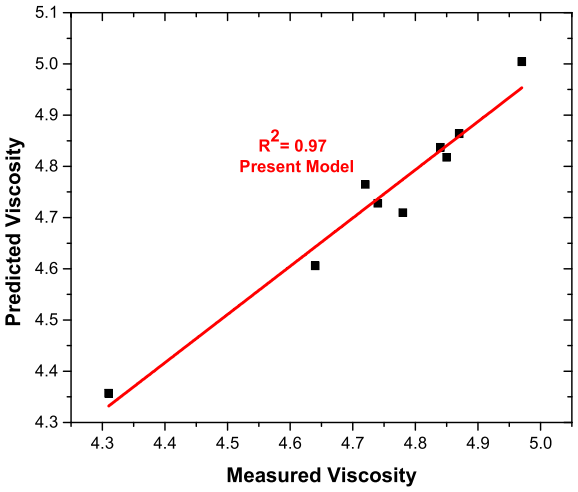

Fig. 6. The predictive capability of the present model for KV.

Table 11
Prediction of KV of random biodiesels taken literature [13].

Biodiesel	Experimental KV	Predicted KV	% Error
Beef tallow	4.83	4.59	4.96
Canola	4.4	4.66	5.9
Chicken fat	4.81	4.65	3.32
Corn	4.32	4.66	7.87
Cottonseed	4.7	4.45	5.31
Olive	5.05	5.05	0
Palm	4.61	4.25	7.8

Other factors such as oxygen content in biodiesel can also be responsible for the variation in the viscosity.

3.4. Heating value

The heating value is the extent of energy measured by combustion of a unit fuel and indicates their suitability for a specific use. The heating value of the biodiesel depends on the hydrogen and oxygen elements present in its configuration (A [30]. Biodiesel is known for its additional oxygen content, which assists in complete combustion; however, it also hampers oxidation stability. Further to more significant cumulative oxygen portions proportionately lowers other elements, including carbon and hydrogen, consequently lowering biodiesel's energy efficiency. Various authors have correlated the calorific value of biodiesel with molecular weight and the number of double bonds [8,11].

Fig. 7 shows the calorific value distribution of biodiesel considered under study concerning its unsaturation percentage. The statistical correlation between the HV and % US was equally modest with R^2 of 0.62, as shown by prior research.

$$HV = 0.0506(US) + 34.364 \tag{13}$$

The heating value increases with increased unsaturation levels; however, the increase in chain length decreases the heating value. Biodiesel with a high amount of oleic and linoleic fatty acids is observed to have a high heating value (Table 12). The heating value increases by increasing the carbon atoms and the chain's hydrogen and nitrogen atoms.

The linear regression analysis yields the following model to predict the heating value; Fig. 8 shows the relationship between measured and predicted heating values which shows satisfactory R^2=0.86, which shows the predictive capability of the developed model. The developed model shows that saturated fatty acids have more significant coefficients than unsaturated fatty acids, although their influence on HV is not monotonous. More specifically, lauric acid reduces the HV, while myristic, palmitic, and stearic acids enhance it. Statistical coefficients for the model are shown in Table 13 which indicated high R^2 value for the measured data set.

$$HV = 31.42 + 4.18x_1 + 0.011x_2 + 0.0916x_3 + 0.0112x_5 + 0.0656x_6 + 0.0740x_7 + 0.0947x_8 \tag{14}$$

The predictive capability of the developed model for heating value was tested from the data considered from the literature shown in Table 14. As can be seen, the error between experimental and predicted heating values was small (less than 7%). This demonstrates that the developed model has a relatively high predictive capability, even though the R^2 value between the model and the data on which it was developed.

4. Conclusion

To relate the FAC to biodiesel properties, a complete statistical analysis was carried out. Nine different types of biodiesels are derived from edible. Non-edible waste oil and animal oil were considered. The biodiesel's cetane number, density, kinematic viscosity, and heating value were investigated properties. The saturated fatty acids (lauric, myristic, palmitic, and stearic) and unsaturated fatty acids (oleic, linoleic, and linolenic) were used in the analysis. Multiple linear regression techniques were used for the formulation of the predictive models. Established models for CN and density were both highly statistically significant compared to the data set on which they were developed. More crucially, the developed models are moderately successful when used to predict the properties of other biodiesel taken from the literature. For both KV and heating values, the developed correlations were not statistically significant, with R^2 values of 0.69 and 0.62. In terms of predictive ability, the relative error for the viscosity was 3–13%, while for heating value was less up to 6%.

According to the findings of this study, researchers and institutions can benefit from the results of this study in the area of biodiesel. Furthermore, the results can be used to guide the development of better biodiesel feedstocks with desired characteristics, which will

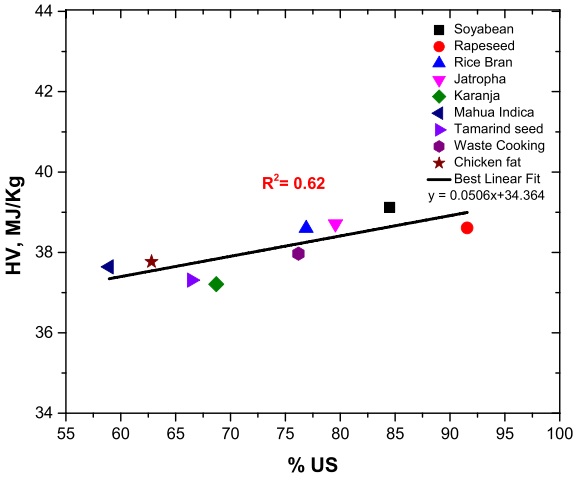

Fig. 7. Relation between % US and heating value.

Table 12
FAC and HV for analyzed data set.

Biodiesel	Lauric	Myristic	Palmitic	Stearic	Oleic	Linoleic	Linolenic	KV, cSt
	C12:0	C14:0	C16:0	C18:0	C18:1	C18:2	C18:3	
Soyabean	0.1	0.2	10.5	3.8	23.7	54.5	6.3	39.12
Rapeseed	0.1	0.2	4.07	1.55	62.24	20.61	8.72	38.61
Rice Bran	0	0	18.8	2.4	43.1	33.2	0.6	38.6
Jatropha	0.12	0.1	13.2	6.11	43.86	35.4	0.3	38.71
Karanja	0	0	10.6	6.8	49.4	19	0	37.21
Mahua Indica	0	0	21.53	18.9	39.1	19.55	0.3	37.64
Tamarind seed	0	1.59	12.67	15.93	47.48	18.34	0.63	37.31
Waste Cooking oil	0	0	13	4	24	52	0	37.97
Chicken fat oil	0	0	22.2	5.1	42.5	19.3	1	37.77

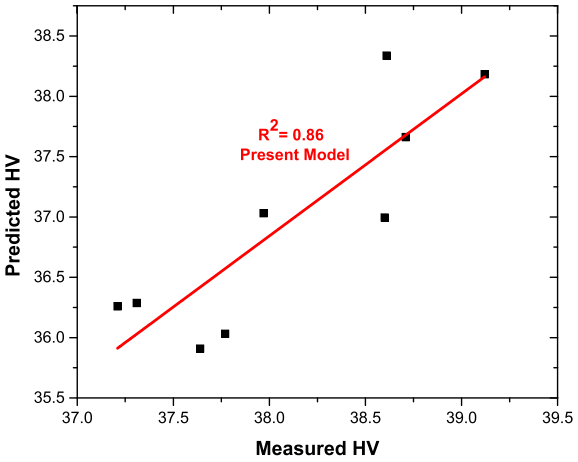

Fig. 8. The predictive capability of the present model for HV.

Table 13
Statistical coefficients for MLR for HV model.

Statistics	Multiple regression model
R^2 (%)	98.83
Std. Deviation (±)	0.2072
Observations	9
P-Value	0.218

Table 14
Prediction of HV of random biodiesels taken literature [11].

Biodiesel	Experimental	Predicted	% Error
Cottonseed	39.50	39.33	0.43
Linseed	39.30	39.75	1.14
Peanut	39.80	38.06	4.37
Rapeseed	39.70	38.29	3.55
Safflower	39.50	38.82	1.72
Sesame	39.30	38.36	2.39
Soybean	39.60	38.69	2.35
Sunflower	39.60	38.59	0.02
Canola	40.64	38.17	6.07

result in improved diesel engine performance and emissions in the future.

Data availability

Data available on request from the authors.

Author statement

Vishal Kumbhar: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing – review & editing; Anand Pandey: Conceptualization, Investigation, Resources, Data curation, Writing - review & editing, Supervision, Project administration; Funding acquisition; Chandrakant R Sonavane Methodology, Data curation, Writing - review & editing. Mohamed E. Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition **A. S. El-Shafay** Methodology, Data curation, Writing - review & editing; **Hitesh Panchal**: Methodology, Data curation, Writing - review & editing; **Ali Chamkha**: Methodology, Data curation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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