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Estimating cetane numbers of pure biodiesels through multiple non-linear correlations depending on some fuel properties

Bazı yakıt özelliklerine bağlı olarak çoklu non-linear korelasyonlar yoluyla saf biyodizellerin setan sayılarının tahmin edilmesi

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Abstract

In the literature, multiple linear regression, machine learning methods, and group contribution methods have been employed to estimate the cetane numbers of pure biodiesels based on their properties (composition of fatty acid esters, number of carbon atoms, number of double bonds, chain length, saponification number, iodine value, etc.). However, there has been relatively limited research on the relationship between cetane number and other fuel properties. Therefore, this study purposes to utilize the multiple non-linear regression method to estimate the cetane numbers of pure biodiesels as functions of the density, kinematic viscosity, flash point, and heating value. To establish correlations, experimental data on the fuel properties of 100 different biodiesels (methyl and ethyl esters) were gathered from the literature. The predictive performances of the proposed multiple non-linear correlations were compared with the commonly recommended multiple linear correlation found in the literature. According to the results, reliable non-linear correlations, having relative errors of less than 5% and high coefficient of determination values (r^2) were obtained.

Keywords: Alternative fuels, Biodiesel, Fuel properties, Cetane number, Multiple non-linear regression

Öz

Literatürde saf biyodizellerin setan sayılarını özelliklerine (yağ asidi esterlerinin bileşimi, karbon atomu sayısı, çift bağ sayısı, zincir uzunluğu, sabunlaşma sayısı, iyot değeri, vb.) bağlı olarak tahmin etmek için çoklu doğrusal regresyon, makine öğrenmesi yöntemleri ve grup katkı yöntemleri kullanılmaktadır. Fakat, setan sayısı ile diğer yakıt özellikleri arasındaki ilişki üzerine nispeten sınırlı araştırma bulunmaktadır. Bu nedenle, bu çalışma, yoğunluk, kinematik viskozite, parlama noktası ve ısıl değere bağlı olarak saf biyodizellerin setan sayılarını tahmin etmek için çoklu doğrusal olmayan regresyon yöntemini kullanmayı amaçlamaktadır. Korelasyonları oluşturmak için, 100 farklı biyodizelin (metil ve etil esterler) yakıt özellikleriyle ilişkin deneysel veriler literatürden toplanmıştır. Önerilen çoklu non-linear korelasyonların tahmin performansları, literatürde bulunan ve yaygın olarak önerilen çoklu doğrusal korelasyon ile karşılaştırılmıştır. Sonuçlara göre, %5'ten daha düşük bağıl hatalara ve yüksek determinasyon katsayısı (r^2) değerlerine sahip olan güvenilir non-linear korelasyonlar elde edilmiştir.

Anahtar kelimeler: Alternatif yakıtlar, Biyodizel, Yakıt özellikleri, Setan sayısı, Çoklu doğrusal olmayan regresyon

1 Introduction

Diesel engines have been widely used in various sectors (transportation, agriculture, and industry) owing to their notable advantages of efficiency and durability [1]. Heavy-duty vehicles, construction machinery, agricultural equipment, marine vessels, locomotives, and power generators have been powered by diesel engines for a long time [2]. Currently, petroleum-based fuels are the primary energy source for diesel engines. However, their combustion in diesel engines leads to harmful emissions and greenhouse gases that pose significant environmental challenges [3]. Additionally, the dependence on petroleum-based fuels owing to their non-renewable nature and the gradual decline in their reserves increases concerns about the potential risk of an energy crisis in the future [1]. For these reasons, it is necessary to channel research efforts to address these issues and find renewable alternative fuels.

Biodiesel is one of the renewable alternative fuels that has drawn lots of attention recently. As an alternative to diesel fuel, biodiesel exhibits superior properties, including lower sulfur and aromatic contents, domestic origin, higher flash point, and enhanced biodegradability [4]. The use of biodiesel generally decreases some exhaust emissions owing to the oxygen content in its molecular structure. Moreover, biodiesel can be mixed with diesel fuel at any proportion [5]. Due to these superior properties, biodiesel is used in both the developing and developed countries. However, biodiesel has also some disadvantages that limit its widespread use, including poor cold flow properties and oxidation stability, higher viscosity, and lower heating value [4, 6]. Chemically, biodiesel is a mixture of fatty acid esters. Transesterification is the predominant method used in biodiesel production, involving the transformation of edible or non-edible vegetable oils or animal fats into mono-alkyl esters. The reaction of alcohol (generally methanol or ethanol) with

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vegetable oils or animal fats in the presence of a catalyst (alkalis, acids, or enzymes) results in the formation of esters (biodiesel) and glycerol [7-9]. International standards such as EN 14214 and ASTM D6751 regulate the quality of biodiesel.

Density, viscosity, flash point, heating value, and cetane number are among the most significant fuel properties. Density affects atomization and engine performance. Additionally, density can contribute to engine oil sludge issues [9, 10]. Viscosity influences atomization, fuel droplet size, spray penetration, mixture formation, and consequently, the combustion process. Fuel viscosity must be kept within specified upper and lower limits [11]. Flash point serves as a safety indicator for fuel storage [9]. The heating value (heat of combustion) is equal in magnitude but opposite in sign to the enthalpy of the reaction [12]. A fuel with a higher heating value can offer an extended transportation distance with a smaller storage fuel tank, while also providing greater power output from a smaller engine [13]. The cetane number defines the ignition quality of a diesel fuel and affects the ignition delay, making it a crucial factor in determining various diesel engine operating characteristics (fuel conversion efficiency, smoothness operation, misfire, noise levels, emissions, and ease of starting) [14]. The use of a fuel with a lower cetane number results in a longer ignition delay, higher rates of pressure rise, and higher peak pressures. Moreover, a lower cetane number results in incomplete combustion, reduced engine performance, and poor fuel conversion efficiency. On the other hand, the use of a fuel with a higher cetane number results in a shorter ignition delay, and smoother engine operation [14].

To determine the cetane number of a fuel, a standardized single-cylinder, variable compression ratio engine is used along with specialized loading and accessory equipment and instrumentation. The diesel engine is operated under the specified conditions (the engine speed: 900 rpm; the injection timing: 13 crank angle degree before the top dead center; injection pressure: 10.3 MPa, etc.) [14]. Measurement of the cetane number of a fuel through conventional testing equipment can be both labor-intensive and expensive. That is why establishing a predictive correlation represents a significant undertaking to reduce the amount of experimental effort required. In this context, in the existing literature, correlations to predict cetane number of pure biodiesels from their properties (based on the composition of fatty acid esters, the number of carbon atoms, the number of double bonds, the molecular weight of the fatty acid esters, the chain length, the saponification number, the iodine value, etc.) using different techniques (multiple linear regression, machine learning methods, group contribution methods, etc.) and correlations that are not compared with others have been presented in recent years [15-21]. However, the determination of some of these chemical properties can be expensive. Few studies have derived correlations for predicting the cetane number of pure biodiesels based on other fuel properties with the use of multiple non-linear regressions by comparing with multiple linear regression. Therefore, to fill the gap, correlations are derived based on the density, kinematic viscosity, flash point, and heating value to predict cetane number of pure biodiesels using multiple non-linear regression models in this study. Then, the predictive capabilities of derived non-linear correlations are compared to the multiple linear correlation previously suggested in the literature. In other words, the importance of the study is that it can offer an alternative approach for predicting the cetane number of pure biodiesels depending on density, kinematic viscosity, flash point, and heating value rather than chemical properties, considering some difficulties in experimentally determining the cetane number.

2 Material and methods

2.1 Fuel property data

In this study, to develop predictive correlations, the density, kinematic viscosity, flash point, heating value, and cetane number data of different 100 biodiesels (methyl ester and ethyl ester) measured by various authors are collected from the literature [22-105]. The fuel properties measured by various researchers are listed in Tables 1-3. The density and kinematic viscosity are measured by various researchers at 15℃ and 40℃, respectively. The density (EN ISO 12185, ASTM D-1298, ASTM D-4052, ASTM D-941), kinematic viscosity (EN ISO 3104, ASTM D-445), flash point (EN ISO 3679, UNE 51-023-90, ASTM D-92/93), heating value (ASTM D-240, ASTM D-4809, ASTM D-224, ASTM D-4868, ASTM D-5865), and cetane number (EN 5165, ASTM D-976, ASTM D-613, ASTM D-13) are measured by various researchers according to international standards.

2.2 Multiple correlations

The primary objective of regression analysis is to establish a meaningful association between a dependent variable and one or more independent variables [106]. Multiple correlations offer an examination of the connections between two or more independent variables, and a single dependent variable. Multiple correlations are highly useful in experimental and numerical studies in which more than one key independent variable influences the response [107]. In this study, to predict cetane number (CN) of pure biodiesels, the correlations depending on density (DS, kg/m^3), kinematic viscosity (KV, mm^2/s), flash point (FP, ℃), and heating value (HV, MJ/kg) are derived using multiple non-linear regression by using NCSS software [108]. The fuel property data given in Table 1 are used for the derivation of the correlations, as shown in Equation (1), Equation (2), and Equation (3). In other words, to determine the regression constants in Equation (1), Equation (2), and Equation (3), the fuel property data in Table 1 are used. Equation (3) is derived using the multiple linear regression method previously suggested in the literature [15, 18, 109] to compare with the predictive capabilities of non-linear Equation (1) and Equation (2). The forms of multiple non-linear and linear correlations, including the combination of elements without an interaction term, are given as follows:

$$
\begin{aligned}
CN = {} & -21.3112599332018 \cdot DS - 2312.31524541451 \cdot KV \\
& + 37.2533354365478 \cdot FP \\
& + 547.451387881977 \cdot HV \\
& + 0.0290418849516043 \cdot DS^2 \\
& + 3.07779409006598 \cdot DS \cdot KV \\
& - 0.0301348940346684 \cdot DS \cdot FP \\
& - 0.408104995235988 \cdot DS \cdot HV \\
& + 46.8827777140952 \cdot KV^2 \\
& + 2.26385245460417 \cdot KV \cdot FP \\
& + 29.38975618004 \cdot KV \cdot HV \\
& - 0.017789067470411 \cdot FP^2 \\
& - 1.32139763140522 \cdot FP \cdot HV \\
& - 7.67747467892404 \cdot HV^2 \\
& - 5.38392849642564E-06 \cdot DS^3 \\
& - 0.00119595487066825 \cdot DS^2 \cdot KV \\
& - 9.65432622352794E-06 \cdot DS^2 \cdot FP \\
& - 0.000192907451768466 \cdot DS^2 \cdot HV \\
& - 0.0539751962101155 \cdot DS \cdot KV^2 \\
& - 0.000880107527035711 \cdot DS \cdot KV \cdot FP \\
& - 0.00870194860872772 \cdot DS \cdot KV \cdot HV \\
& - 1.09029992191965E-06 \cdot DS \cdot FP^2 \\
& + 0.00128628761880498 \cdot DS \cdot FP \cdot HV \\
& + 0.00685210780041322 \cdot DS \cdot HV^2 \\
& + 0.348452053904228 \cdot KV^3 \\
& + 0.00184997365599729 \cdot KV^2 \cdot FP \\
& - 0.131721733718501 \cdot KV^2 \cdot HV \\
& - 0.00119659718085975 \cdot KV \cdot FP^2 \\
& - 0.0288451814081449 \cdot KV \cdot FP \cdot HV \\
& - 0.206389277299603 \cdot KV \cdot HV^2 \\
& + 6.80842374504503E-06 \cdot FP^3 \\
& + 0.000522476805678622 \cdot FP^2 \cdot HV \\
& + 0.00205256926976448 \cdot FP \cdot HV^2 \\
& + 0.0169718209195705 \cdot HV^3
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
CN = {} & -0.225871017644765 \cdot DS - 395.113643204447 \cdot KV \\
& - 11.151475420594 \cdot FP \\
& - 19.9678622836044 \cdot HV \\
& + 0.511341386235934 \cdot DS \cdot KV \\
& + 0.0149330565935605 \cdot DS \cdot FP \\
& + 0.0299268771561017 \cdot DS \cdot HV \\
& + 4.88228371209204 \cdot KV \cdot FP \\
& + 14.3452716405883 \cdot KV \cdot HV \\
& + 0.405368189106296 \cdot FP \cdot HV \\
& - 0.00601054507606774 \cdot DS \cdot KV \cdot FP \\
& - 0.0179026617259332 \cdot DS \cdot KV \cdot HV \\
& - 0.000518298783755752 \cdot DS \cdot FP \cdot HV \\
& - 0.149726951787513 \cdot KV \cdot FP \cdot HV \\
& + 0.000182135938485259 \cdot DS \cdot KV \cdot FP \\
& \cdot HV
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
CN = {} & 0.0441923071176599 \cdot DS + 0.484872125545549 \cdot KV \\
& + 0.0247426398693162 \cdot FP \\
& + 0.221822286120976 \cdot HV
\end{aligned} \tag{3}
$$

3 Results and discussions

In this section, the predictive capabilities of non-linear and linear correlations are compared. Tables 1-3 list the measured cetane number data of pure biodiesels by different authors, and the relative errors between the measured cetane number data and the calculated cetane number values from the derived correlations. As shown in Tables 1-3, the density, kinematic viscosity, flash point, heating value, and cetane number data measured by different authors vary between 758-929.9 kg/m^3, 1.921-15.5 mm^2/s, 58-262.34°C, 34.50-45.63 MJ/kg, and 45-70, respectively. Compared to diesel fuel, the densities, kinematic viscosities, flash points, and cetane numbers of biodiesels are generally higher, whereas the heating values of biodiesels are lower. Due to the volumetric measurement of fuel injection into the combustion chamber for diesel engines, the higher density of biodiesel leads to a higher mass flow rate for the same fuel volume, potentially leading to a rise in torque and output [110]. The higher viscosity of biodiesel contributes to poor fuel atomization and incomplete combustion, leading to engine deposits, poor engine performance, and exhaust emissions. Moreover, higher viscosity causes additional challenges under cold weather conditions. The higher flash point of biodiesel reduces the risks associated with handling and the potential fire hazards. The lower heating value of biodiesel generally results in higher specific fuel consumption. The higher cetane number of biodiesel can lead to a lower NO_x formation [111]. As listed in Table 1, for Equation (1), the maximum and the minimum relative errors are computed as 4.9879% and 0.0140%, respectively. The average relative error is computed as 1.6242%. The coefficient of determination (r^2) and root mean square error (RMSE) are determined as 0.9996 and 1.4802, respectively. To use fewer terms than those in Equation (1) for practicality, Equation (2) is also derived. For Equation (2), r^2, RMSE, maximum relative error, minimum relative error, and average relative error are computed as 0.9976, 2.9039, 16.8686%, 0.1334%, and 3.8839%, respectively. The multiple linear correlation (Equation (3)) gives the following regression results: the maximum relative error of 25.6210%, the minimum relative error of 0.1012%, the average relative error of 5.0562%, r^2 of 0.9955, and RMSE of 3.7080. According to the regression results, a significant and satisfactory agreement between the experimental data and the calculated values from Equation (1) is observed, compared to Equation (2) and Equation (3). Equation (3) gives the worst estimates of cetane number. Therefore, to improve the predictive capability of Equation (2), the measured cetane number data, where the high relative errors from Equation (2) are obtained in Table 1, are extracted. Then, Equation (4) is again derived using the remaining cetane number data using the multiple regression method as follows:

$$
\begin{aligned}
CN = {} & -0.496861577688628 \cdot DS - 213.561560511396 \cdot KV \\
& - 17.2240864922622 \cdot FP \\
& - 40.5165814219249 \cdot HV \\
& + 0.343580765865512 \cdot DS \cdot KV \\
& + 0.0237023328304558 \cdot DS \cdot FP \\
& + 0.0597890292658327 \cdot DS \cdot HV \\
& + 5.87261376391831 \cdot KV \cdot FP \\
& + 13.749174866194 \cdot KV \cdot HV \\
& + 0.667248830977058 \cdot FP \cdot HV \\
& - 0.00739238512318715 \cdot DS \cdot KV \cdot FP \\
& - 0.0181139565650781 \cdot DS \cdot KV \cdot HV \\
& - 0.000861464488779323 \cdot DS \cdot FP \cdot HV \\
& - 0.195981897863396 \cdot KV \cdot FP \cdot HV \\
& + 0.000240785011170922 \cdot DS \cdot KV \cdot FP \\
& \cdot HV
\end{aligned} \tag{4}
$$

As listed in Table 2, for Equation (4), r^2, RMSE, maximum relative error, minimum relative error, and average relative error are computed to be 0.9994, 1.4819, 4.9556%, 0.0509%, and 1.9436%, respectively. According to the regression results, the predictive capability of Equation (4) is considered to be better than Equation (2).

Finally, to compare the predictive capabilities of Equation (1) and Equation (4), cetane number data different from those given in Table 1 and Table 2 are used, as shown in Table 3. The minimum, maximum, and average relative errors are determined to be 0.2038%, 4.9695%, 2.2582% for Equation (1), and 0.3731%, 4.7636%, 1.8677% for Equation (4). Figure 1 shows the distribution of relative errors coming from Equation (1) and Equation (4). These regression results and Figure 1 indicate that Equation (4), depending on DS, KV, FP, and HV, is the best predictor for cetane number of pure biodiesels. In other words, the regression results demonstrate the superior effectiveness of Equation (4) in estimating cetane number. This can be attributed to the fact that the structures of terms in Equation (4) better reflect the effect of the fuel properties on the change of cetane number. Moreover, Equation (1) can be thought to be an alternative to Equation (4) owing to the close error and r^2 values of Equation (1) to Equation (4), which shows the structures of terms in Equation (1) adequately reflect the effect of the fuel properties on the change of cetane number.

4 Conclusions

Measurements of biodiesel properties (especially cetane number) can require significant expense and effort. Consequently, presenting predictive correlations is not only valuable for predicting fuel properties but also for enhancing the production of superior biodiesel. Hence, it is essential to propose reliable correlations to predict these properties. In this study, the relationship between cetane number and other vital fuel properties is determined. Multiple non-linear regression is used for the formulation of the predictive correlations for the cetane number of pure biodiesels depending on other fuel properties (density, kinematic viscosity, flash point, and heating value). The fuel property data of different biodiesels are collected from the literature measured by various authors. The predictive performances of the derived correlations (Equations (1-4)) are investigated by computing the regression parameters. The main conclusions are as follows:

Equation (1) yields a maximum relative error of 4.9879% and a minimum relative error of 0.0140%. The average relative error, r^2, and RMSE are determined to be 1.6242%, 0.9996, and 1.4802, as shown in Table 1.

Regarding Equation (2), the regression results are computed as follows: r^2 = 0.9976, RMSE = 2.9039, maximum relative error = 16.8686%, minimum relative error = 0.1334%, and average relative error = 3.8839%, as shown in Table 1.

The multiple linear correlation (Equation (3)) yields a maximum relative error of 25.6210%, a minimum relative error of 0.1012%, an average relative error of 5.0562%, r^2 of 0.9955, and RMSE of 3.7080, as shown in Table 1.

Calculation of Equation (4) yields the following values: r^2 = 0.9994, RMSE = 1.4819, with a maximum relative error of 4.9556%, a minimum relative error of 0.0509%, and an average relative error of 1.9436%, as indicated in Table 2.

For the cetane number data given in Table 3, which are different from Tables 1 and 2, the minimum, maximum, and average relative errors are calculated as 0.2038%, 4.9695%, and 2.2582% for Equation (1); and 0.3731%, 4.7636%, and 1.8677% for Equation (4).

Finally, the regression outcomes underline that Equation (4), as functions of DS, KV, FP, and HV, emerges as the superior predictor for the cetane number of pure biodiesels. Alternatively, Equation (1) also shows a good agreement between the measured data and calculated values because of low relative errors than 5%. In other words, Equation (1) can be also suggested after Equation (4).

This study can contribute to researchers and institutions to develop better biodiesel fuel properties, which will result in enhanced engine performance and reduced exhaust emissions for diesel engines. Further improvement of the cetane number correlations can be obtained using machine learning methods, as a future study.

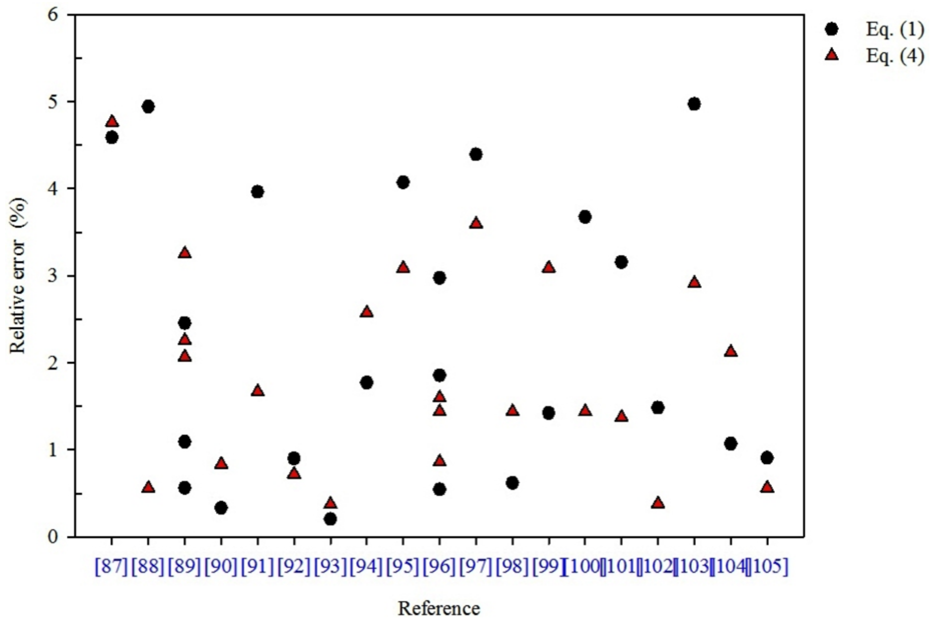

Figure 1. Distribution of relative errors

Table 1. Fuel properties measured by various authors and relative errors coming from Eq. (1), Eq. (2), and Eq. (3)

Biodiesel	Density (kg/m^3)	Viscosity (mm^2/s)	Flash point (ºC)	Heating value (MJ/kg)	Cetane number	Relative error (%)		
						Eq. (1)	Eq. (2)	Eq. (3)
Turkey rendering fat [22]	885.8	4.49	178.1	40.68	52.4	3.1449	3.2142	4.4905
Algae [23]	887	4.23	146	41.24	53.49	4.1973	1.3170	0.9721
Peanut seed [24]	848.5	4.42	166	40.1	53.59	4.0163	1.9564	1.7678
Sesame seed [25]	867.2	4.2	170	40.4	50.48	2.9819	4.9794	6.0378
Lepidium sativum Linn. [26]	845	1.921	176	40.45	49.23	0.9183	4.3303	4.8169
High oleic sunflower [27]	876.6	4.74	167	40.47	53.2	1.3171	1.1758	1.7790
M. nigeriensis [28]	841	2.32	125	41.8	51.4	0.3810	7.1766	1.4482
Sunflower [29]	911	4.33	178.4	45.28	52.9	1.1245	1.9135	7.4043
Canola [30]	878	4.42	172.36	40.748	54	2.0661	0.9449	0.4582
Corn [30]	883	4.19	171	43.1	46.65	4.1690	10.9523	17.5669
Groundnut [30]	920	4.4	132	39.8	59.85	0.1939	8.3207	8.2959
Mustard [30]	879	5.53	169.16	40.4	56	0.8218	1.8407	2.3688
Olive pomace [30]	894	4.26	138	39.96	56.3	1.6855	4.6826	4.3482
Peanut [30]	878.5	4.69	176	35.33	58.24	2.1975	2.9553	8.5016
Rice bran [30]	881	4.4	175	40.87	51.15	3.6126	4.7232	6.4764
Safflower [30]	879	4.18	174	42.2	51.1	1.8920	2.2484	6.7278
Prunus avium [31]	838	3.543	160.56	37.65	50.1	2.5234	3.1708	1.9468
Canola [32]	833	4.7	120.5	38.363	46	0.0140	10.3754	9.9616
Yellow oleander [33]	890	4.81	142	40.42	55	0.6208	2.6091	1.5584
Palm [34]	874	4.7	176.5	39.82	56.3	2.6724	3.6250	3.9023
Semecarpus anacardium [35]	876	4.3	148	39	56	1.4127	4.4294	5.1600
Mesua ferrea [36]	888	4.4	156	38.86	58	0.7066	6.0830	7.1447
Karanja [37]	880.63	5.35	196.18	39.50	54.54	2.6525	2.7919	1.0765
Linseed [37]	886.27	4.76	262.34	38.148	51.24	0.4612	13.4541	10.1237
Reformulated-I [37]	871	3.2	238.61	39.136	60	0.0365	6.9130	8.9531
Jatropha [38]	835	4.8	125	42.97	51	0.9667	1.7907	1.6716
Shea nut butter [39]	877	4.42	171	37.93	58	2.2857	5.1793	7.6819
J. curcus [40]	875	4.97	175	38.83	59.05	3.1537	7.0322	8.5158

Table 1 (Continued)

Biodiesel	Density (kg/m^3)	Viscosity (mm^2/s)	Flash point (ºC)	Heating value (MJ/kg)	Cetane number	Relative error (%)		
						Eq. (1)	Eq. (2)	Eq. (3)
Palm [41]	873	4.5	92	42.144	53	3.2636	3.2790	1.1573
Sesame seed [42]	870	3.9	158	37.60	52	4.0785	3.8981	1.1311
Sunflower [43]	885	4.6	92	43.10	47	1.3488	7.7449	13.1435
Spirulina microalgae [44]	861	5.26	128.2	41	52.2	2.6346	0.9308	1.2772
Waste cooking [45]	898	4.7	73	36.89	53	0.2529	2.4763	1.9758
Microalgae (Botryococcus) [46]	853	5.52	140	40.40	55.4	1.2106	3.8364	4.6965
Microalgae (Spirulina platensis) [47]	863.7	12.4	189	45.63	70	0.0250	0.2652	15.7437
Eruca sativa [48]	870	4.19	185	43.70	47.5	0.9511	7.3487	15.2630
Microalgae (Chlorella vulgaris) [48]	860	3.7	124	38.70	51.4	1.2266	1.2387	0.1012
Calophyllum inophyllum [49]	872	5.76	179	38.532	58.7	2.0528	5.5794	7.4877
Mahua [50]	882	4.2	170	38.5	57	1.5392	3.9801	5.6834
Hazelnut [51]	861.9	4.54	168	40.009	52.2	1.4104	2.0542	2.1500
Amoora [52]	866	4.67	154	38.3	55	0.6608	2.1095	3.9254
Thesz-Boros-Kiraly [53]	905	6.43	221	34.81	50.8	0.4979	0.9897	10.8298
Mango seed [54]	882	4.73	135	40.453	54	0.7566	1.8081	0.7691
Simarouba glauca [55]	865	4.68	165	38.5	56	1.1476	3.3157	5.1460
Waste cooking [56]	890	5.15	120	39	56	4.1545	4.5225	4.5564
Jatropha curcas [57]	864.8	4.723	182.5	40.536	51	3.0509	5.2178	5.9115
Brassica carinata [58]	879	4.5	110	36	52	0.9403	2.9341	0.5110
Pumpkin [59]	787	4.4	138	39.128	51	1.0864	4.8517	3.9084
Prosopis juliflora [59]	758	5.1	74	40.36	54.3	0.1015	0.9101	13.8963
Water hyacinth [60]	887	3.96	212	36.9	52.5	0.8021	9.8582	3.9035
Palm–sesame [61]	881	4.43	151	41.24	53.37	3.2949	0.9497	1.1158
Waste cooking [62]	883	4	120	39.5	52	4.1219	1.5696	1.3315
Soybean [63]	885	4.08	69	39.76	52	0.4868	0.3167	0.7397
Jatropha [64]	848.2	5	76	41.5	53	1.0375	1.6959	3.7843
Waste vegetable cooking [65]	880	4.15	176	37.73	55.1	1.7846	0.4819	2.6760
Rice bran [66]	876	4.46	213	42.21	55.7	1.2164	4.1931	0.3442
Waste cooking [67]	855	4.57	126	40.5	52	0.5830	0.4118	0.1955
Karanja [68]	900	9.6	114	35.9	54.53	0.0681	0.5430	1.2506
Yellow mustard [69]	877.84	5.413	164	39.931	57.23	0.7063	4.4900	5.0607
Unknown type mustard [69]	847	3.8	143	39.124	54	4.6418	5.5995	4.6478

Table 1 (Continued)

Biodiesel	Density (kg/m^3)	Viscosity (mm^2/s)	Flash point (ºC)	Heating value (MJ/kg)	Cetane number	Relative error (%)		
						Eq. (1)	Eq. (2)	Eq. (3)
Kusum (ethyl ester) [70]	872	3.5	95	42.653	47	1.5803	10.0436	10.7334
Palm [71]	880	4.5	175	41.30	52	0.2877	2.7852	4.9276
Safflower [72]	870	3.9	187	40.26	53.14	1.1092	0.2717	1.4222
Trichosanthes cucumerina [73]	856	4.26	158	38.50	53	0.2087	0.1864	1.2384
Cotton seed [74]	864	4.14	128	36.80	52	0.9899	0.4194	0.9238
Cotton seed [75]	848	6.1	200	40.61	53	0.9413	0.1334	2.6217
Soybean [76]	890	4.5	58	37.405	45	0.3724	16.8686	13.8787
Castor bean [77]	920	12.5	135	40.5	47	0.1344	4.9116	25.6210
Castor [78]	929.9	15.5	146	41.17	60.2	0.0291	1.4712	1.9183
Microalgae [79]	885	4.2	191	40.10	54	1.7877	0.4475	1.4214
Palm [80]	872	4.5	94	39.80	53	1.7591	2.7654	2.1284
Mahua [81]	869	4.5	154	37.59	57	2.5198	5.0088	7.4847
Moringa oleifera [82]	869.6	5.05	150.5	40.05	56.3	2.1063	4.9315	4.9983
Jatropha [83]	865	5.2	175	34.50	51	0.7318	10.6896	3.3932
Jatropha [84]	876	4.5	121	38.789	55	0.1556	3.9392	4.5591
Simarouba [85]	868	4.8	165	39.80	52	4.9879	3.3898	3.0719
Pongamia [86]	898	5.46	196	39.15	57.9	2.0022	1.2110	3.5130

Table 2. Fuel properties measured by various authors and relative errors coming from Eq. (4)

Biodiesel	Density (kg/m^3)	Viscosity (mm^2/s)	Flash point (ºC)	Heating value (MJ/kg)	Cetane number	Relative error (%)
Turkey rendering fat [22]	885.8	4.49	178.1	40.68	52.4	3.8418
Algae [23]	887	4.23	146	41.24	53.49	0.5897
Peanut seed [24]	848.5	4.42	166	40.1	53.59	2.5859
Sesame seed [25]	867.2	4.2	170	40.4	50.48	4.6276
Lepidium sativum Linn. [26]	845	1.921	176	40.45	49.23	1.0144
High oleic sunflower [27]	876.6	4.74	167	40.47	53.2	2.2712
Sunflower [29]	911	4.33	178.4	45.28	52.9	2.4563
Canola [30]	878	4.42	172.36	40.748	54	0.7279
Groundnut [30]	920	4.4	132	39.8	59.85	3.3228
Mustard [30]	879	5.53	169.16	40.4	56	0.3974
Olive pomace [30]	894	4.26	138	39.96	56.3	1.9089
Peanut [30]	878.5	4.69	176	35.33	58.24	3.0728
Rice bran [30]	881	4.4	175	40.87	51.15	4.8689
Safflower [30]	879	4.18	174	42.2	51.1	0.3180
Prunus avium [31]	838	3.543	160.56	37.65	50.1	2.3704
Yellow oleander [33]	890	4.81	142	40.42	55	0.4452
Palm [34]	874	4.7	176.5	39.82	56.3	2.3118
Semecarpus anacardium [35]	876	4.3	148	39	56	3.0276
Mesua ferrea [36]	888	4.4	156	38.86	58	3.9436
Karanja [37]	880.63	5.35	196.18	39.50	54.54	4.7769
Reformulated-I [37]	871	3.2	238.61	39.136	60	2.4265
Jatropha [38]	835	4.8	125	42.97	51	2.8806
Shea nut butter [39]	877	4.42	171	37.93	58	2.1726
J. curcus [40]	875	4.97	175	38.83	59.05	4.3962
Spirulina microalgae [44]	861	5.26	128.2	41	52.2	3.7367
Waste cooking [45]	898	4.7	73	36.89	53	0.5197
Microalgae (Botryococcus) [46]	853	5.52	140	40.40	55.4	0.7109
Microalgae (Spirulina platensis) [47]	863.7	12.4	189	45.63	70	0.0744
Eruca sativa [48]	870	4.19	185	43.70	47.5	0.5727
Microalgae (Chlorella vulgaris) [48]	860	3.7	124	38.70	51.4	4.7815
Calophyllum inophyllum [49]	872	5.76	179	38.532	58.7	1.8854
Mahua [50]	882	4.2	170	38.5	57	1.6641
Hazelnut [51]	861.9	4.54	168	40.009	52.2	2.5526
Amoora [52]	866	4.67	154	38.3	55	0.5119
Thesz-Boros-Kiraly [53]	905	6.43	221	34.81	50.8	0.7250
Mango seed [54]	882	4.73	135	40.453	54	0.8642

Table 2 (Continued)

Biodiesel	Density (kg/m^3)	Viscosity (mm^2/s)	Flash point (ºC)	Heating value (MJ/kg)	Cetane number	Relative error (%)
Simarouba glauca [55]	865	4.68	165	38.5	56	0.6195
Waste cooking [56]	890	5.15	120	39	56	1.2927
Brassica carinata [58]	879	4.5	110	36	52	2.1310
Prosopis juliflora [59]	758	5.1	74	40.36	54.3	0.2805
Palm–sesame [61]	881	4.43	151	41.24	53.37	0.2496
Waste cooking [62]	883	4	120	39.5	52	2.8664
Soybean [63]	885	4.08	69	39.76	52	2.3552
Jatropha [64]	848.2	5	76	41.5	53	1.3917
Waste vegetable cooking [65]	880	4.15	176	37.73	55.1	3.9317
Waste cooking [67]	855	4.57	126	40.5	52	0.6018
Karanja [68]	900	9.6	114	35.9	54.53	0.1037
Yellow mustard [69]	877.84	5.413	164	39.931	57.23	1.9529
Palm [71]	880	4.5	175	41.30	52	2.5223
Safflower [72]	870	3.9	187	40.26	53.14	0.0833
Trichosanthes cucumerina [73]	856	4.26	158	38.50	53	1.5250
Palm [41]	873	4.5	92	42.144	53	1.0875
Cotton seed [74]	864	4.14	128	36.80	52	0.0509
Cotton seed [75]	848	6.1	200	40.61	53	1.9268
Castor bean [77]	920	12.5	135	40.5	47	1.4807
Castor [78]	929.9	15.5	146	41.17	60.2	0.7800
Microalgae [79]	885	4.2	191	40.10	54	0.9563
Palm [80]	872	4.5	94	39.80	53	1.1394
Mahua [81]	869	4.5	154	37.59	57	2.3177
Moringa oleifera [82]	869.6	5.05	150.5	40.05	56.3	2.8329
Jatropha [84]	876	4.5	121	38.789	55	2.5207
Simarouba [85]	868	4.8	165	39.80	52	4.9556
Pongamia [86]	898	5.46	196	39.15	57.9	1.1372

Table 3. Fuel properties measured by various authors and relative errors coming from Eq. (1) and Eq. (4) for the validation

Biodiesel	Density (kg/m^3)	Viscosity (mm^2/s)	Flash point (ºC)	Heating value (MJ/kg)	Cetane number	Relative error (%)	
						Eq. (1)	Eq. (4)
Animal fats [87]	887	4.241	180	39.64062	58	4.5876	4.7636
Peanut [88]	883	4.9	176	41.71	54	4.9400	0.5573
Mahua [89]	869	4.90	136	39.95	56	2.4543	3.2504
Jatropha [89]	895	5.25	85	38.88	53	0.5620	2.0669
Jojoba [89]	895	5.05	85	38.88	53	1.0910	2.2565
Waste cooking [90]	879.4	4.651	172.5	36.49349	58.031	0.3324	0.8362
Safflower [91]	870	4.1	136	38.52	52	3.9624	1.6680
Kusum [92]	857	4.5	138.5	39.07	52.4	0.9002	0.7218
Canola [93]	881.1	4.63	163	40.102566	55	0.2038	0.3731
Grilled chicken waste [94]	876	4.3	177	39.9	53	1.7707	2.5737
Palm [95]	877	4.56	196	39.72	57.3	4.0708	3.0866
Corn [96]	885.8	4.363	167	39.87	55.4	0.5437	0.8595
Rapeseed [96]	884.9	4.585	177	39.9	54.5	1.8531	1.5957
Waste fried [96]	884.2	4.869	167	39.68	55	2.9739	1.4372
Fish (ethyl) [97]	885	4.741	114	40.057	52.6	4.3923	3.5919
Ceiba pentandra [98]	882	4.58	148	40.016	55.4	0.6190	1.4389
Cottonseed [99]	874	4.2	142	40.6	51.2	1.4218	3.0889
Palm [100]	859.2	4.6175	188.5	39.907	55	3.6746	1.4372
Camelina sativa [101]	872.6	5.01	159.5	40.86	55	3.1564	1.3731
Waste [102]	858	4.49	125	40.7	51.4	1.4821	0.3826
Rapeseed [103]	874	4.8	140	37.6	54	4.9695	2.9137
Jatropha [104]	869.2	4.75	180	40	53.5	1.0697	2.1201
Soapstock [105]	892.7	4.554	180.4	39.30	56.7	0.9076	0.5639

Conflict of interest

The author declares that there is no conflict of interest.

Similarity rate (iThenticate): %12

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