

The Influence of Chemical Structure of Fatty Acid Alkyl Ester on Properties, Combustion Characteristics, and Emissions: A Review

¹K G Mer, ²J J Goswami, ³P P Rathod
¹PG Student, ²Associate Professor, ³Associate Professor
 Department of Mechanical Engineering,
 Government Engineering College, Bhuj (Gujarat), India

Abstract- Alarming situation of world fossil fuel and environment degradation has been stimulating the researchers and engineers to find new sources of fuel, which must be renewable, economically available and environment friendly. In this regard biodiesel has one of the most substantial alternative renewable fuels for diesel engine. Biodiesel has made from different feedstock depending on the availability. This study is related to effect of fatty acid composition on combustion characteristics, properties and emission of biodiesel. The main advantage of biodiesel is that it potentially reduces the key pollutants like CO, HC, PM and smoke opacity but on other hand it has increased NO_x and BSFC. The results of the study show that biodiesel with high saturate fatty acid has shorter delay period, low NO_x, high CN, high CV and higher oxidation stability, which has favourable aspect but on other hand it has high viscosity and high cold flow properties which is unfavourable. But biodiesel with high unsaturated fatty acid has low viscosity, low cold flow properties, longer delay, high NO_x, low CN, low CV and lower oxidation stability.

Keyword- biodiesel; chemical structure; fatty acid; properties; emission

I. INTRODUCTION

The socio-economic growth of the society, the energy requirement has increased globally this leads to diminishing resources of petroleum day by day, as well as increasingly stringent regulations, pose a challenge to science and technology. Diesel engines are being extensively utilized in transportation, industries and agriculture worldwide due to their high economic advantage and durability. They have appealing features including robustness, high torque, and lower fuel consumption under certain conditions. To provide an effective way to fight against the problem of petroleum base fuel crisis and the influence on environment stimulating the researchers and engineers to find new renewable fuel that meet the stringent emission norms.

Vegetable oil has one of the most preferable alternative fuels that replace the conventional petroleum diesel fuel. The development of vegetable is not new, Rudolf diesel tested peanut oil as fuel for engine for the first time in august 10, 1893[1]. Also during World War II, vegetable oils were used as fuel in emergency situations [2]. In principle, any vegetable or seed oil which essentially comprises hydrophobic substances primarily of the fatty esters of glycerol, so-called triglycerides of long chain saturated and unsaturated fatty acid can be used in diesel engines. This fuel is biodegradable, non-toxic and has performance and emission profile comparable to diesel.

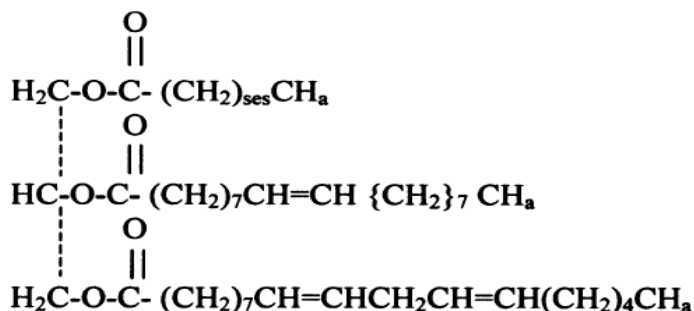
The fuel properties of vegetable oils as shown in table 3 indicate that the kinematics viscosity of vegetable oils varies in the range of 30–40 cSt at 38 °C. The high viscosity of these oils is due to their large molecular mass in the range of 600–900, which is about 10 times higher than that of diesel fuel. The flash point of vegetable oils is very high (above 200 °C). The volumetric heating values are in the range of 39–40 MJ/kg, as compared to diesel fuels (about 45 MJ/kg). The presence of chemically bound oxygen in vegetable oils lowers their heating values by about 10%. The cetane numbers are in the range of 32–40. It has been found that the neat vegetable oils can be used as diesel fuels in conventional diesel engines, but this leads to a number of problems. The injection, atomization and combustion characteristics of vegetable oils in diesel engines are significantly different from those of diesel [3]. To reduce these problems and to decrease viscosity, different methods have been adopted; namely, blending, micro emulsion, transesterification, preheating and pyrolysis (thermal cracking). From these, transesterification is the most common method [4]. Transesterification is primarily used to convert vegetable oil in to fatty acid alkyl esters (FAAE), which is known as biodiesel [3, 5]. Biodiesel conform the ASTM (American Society for Testing and Materials) specification for use in diesel engine [6]

II. BIODIESEL PRODUCTION BY TRANSESTERIFICATION PROCESS

In general, biodiesel feedstock can be divided into four categories [4, 7].

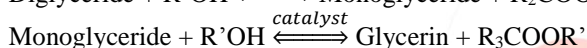
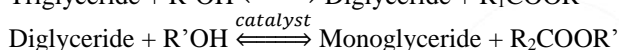
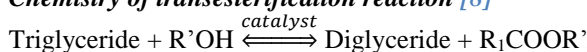
1. Edible vegetable oil: Sunflower, Rapeseed, Rice bran, Soybean, Coconut, Corn, Palm, Olive, Pistachia Palestine, Sesame seed, Peanut, Opium Poppy, Safflower oil etc.
2. Non-edible vegetable oil: Jatropha, Karanja or Pongamia, Neem, Jojoba, Cottonseed, Linseed, Mahua, Deccan hemp, Kusum, Orange, Rubber seed, Sea Mango, Algae and Halophytes etc.
3. Waste or recycled oil

4. Animal fats: Tallow, yellow grease, chicken fat and by-products from fish oil etc. Vegetable oils, also known as triglycerides have the chemical structure given below [3].



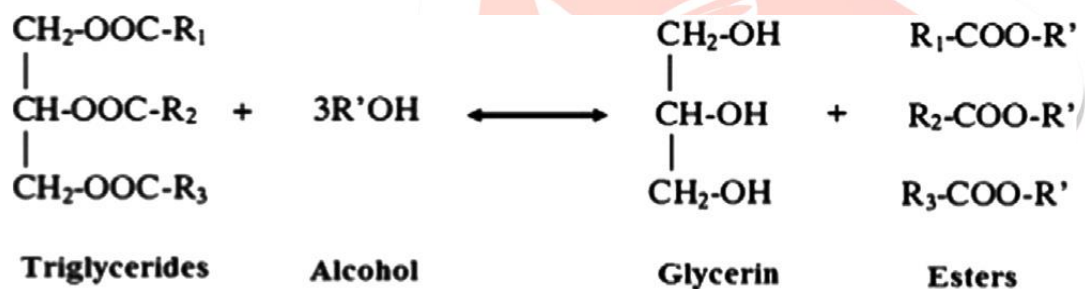
Triglycerides are esters of three molecules of fatty acids and one of glycerol and contain substantial amounts of oxygen in their structure. The fatty acids vary in their carbon chain length and in the number of double bonds. The most advanced and promising technology of biodiesel production is transesterification of oils (triglycerides) with alcohol in the presence of catalyst which gives biodiesel (fatty acid alkyl esters, FFAE) as main product and glycerine as by product.

Chemistry of transesterification reaction [8]



Where R_1 , R_2 and R_3 are long-chain hydrocarbons (fatty acid) which may be the same or different with $\text{R}' = -\text{CH}_3/\text{C}_2\text{H}_5$. The first step is the conversion of triglycerides to diglycerides, followed by the conversion of diglycerides to monoglycerides, and of monoglycerides to glycerol, yielding one methyl ester molecule per mole of glyceride at each step.

Over all chemical reaction [8]



As seen above, the transesterification is an equilibrium reaction in which excess alcohol is required to drive the reaction close to completion. Fortunately, the equilibrium constant favours the formation of methyl esters such that only a 5:1 molar ratio of methanol: triglyceride is sufficient for 95–98% yield of ester [3]. Catalyst used may be acidic (H_2SO_4) or basic (KHO , NaOH) depending upon the free fatty acid (FFA) present in the row oil. When FFA content of feedstock is more than 1%, transesterification with base catalyst will lead to **soap formation**. Hence, a suitable production process has been developing for handling higher FFA oils. A few researchers tried a two stage process, i.e. esterification (pre-treatment) with acid catalyst followed by transesterification with base catalyst [9-11].

III. FATTY ACID COMPOSITION IN BIODIESELS

Fatty acid composition is an important property for any biodiesel feed stock. The transesterification reaction of row oil produces biodiesel fuel corresponding to the fatty acid profile of its parent oil and hence it determines the properties produce biodiesel. The fatty acid composition and distribution of some oils are generally aliphatic compounds with a carboxyl group at the end of a straight chain. The carbon chain lengths of fatty acid of different biodiesels are from C8 to C22. The most common fatty acids with their chemical structure as shown in table: 1, from them some fatty acid chin contain carbon double bond in their structure. On the basis of the double bond, fatty acid alkyl ester can be classified as **saturated (free of double bond)**, **monounsaturated (single double bond)** and **polyunsaturated (double bond ≥ 2)** [7, 12].

Table: 1 Chemical structure of common fatty acids [3].

Name of fatty acid	Chemical name of fatty acids	Structure (CXX:Y)	Formula
Lauric	Dodecanoic	C12:0	$\text{C}_{12}\text{H}_{24}\text{O}_2$
Myristic	Tetradecanoic	C14:0	$\text{C}_{14}\text{H}_{28}\text{O}_2$
Palmitic	Hexadecanoic	C16:0	$\text{C}_{16}\text{H}_{32}\text{O}_2$
Stearic	Octadecanoic	C18:0	$\text{C}_{18}\text{H}_{36}\text{O}_2$
Arachidic	Eicosanoic	C20:0	$\text{C}_{20}\text{H}_{40}\text{O}_2$

Oleic	cis-9-Octadecenoic	C18:1	C ₁₈ H ₃₄ O ₂
Linoleic	cis-9,cis-12-Octadecadienoic	C18:2	C ₁₈ H ₃₂ O ₂
Linolenic	cis-9,cis-12,cis-15-Octadecatrienoic	C18:3	C ₁₈ H ₃₀ O ₂

Where CXX:Y = XX indicates number of carbons, and Y number of double bonds in the fatty acid chain.

IV. EFFECT OF FATTY ACID COMPOSITION ON IGNITION QUALITY, PROPERTIES AND EMISSION:

The fuel properties of biodiesel are strongly influenced by the properties of the individual fatty acid methyl esters in biodiesel. The type of fatty acid, length of chain and alcohol moiety present can have considerable influence on fuel ignition quality, Cetane number, calorific value, viscosity, density, Iodine value, Cold flow properties, lubricity, emission and oxidative stability. These properties are critical for the operation of a fuel in a diesel engine.

Table: 2 Fatty acid compositions of vegetable oils [7].

Oils	<C12:0	C14:0	C14:1	C15:0	C16:0	C16:1	C17:0	C18:0	C18:1	C18:2	C18:3
Coconut oil	65.0	18.5	-	-	7.5	-	-	3.0	5.0	1.0	-
Palm	0.1	1.0	-	-	42.8	-	-	4.5	40.5	10.2	0.2
Beef tallow	-	3.1	1.3	0.5	23.8	4.7	1.1	12.7	47.2	2.6	0.8
Cottonseed	-	-	-	-	28	-	-	11	13	58	-
Peanut	-	-	-	-	11	-	-	2	48	32	1
Soybean	-	-	-	-	13.9	-	-	2.1	23.2	56.2	4.3
Sunflower	-	-	-	-	6.4	-	-	2.9	17.7	72.9	-
Safflower	-	-	-	-	7.3	-	-	1.9	13.6	77.2	-
Rapeseed	-	-	-	-	3.5	-	-	0.9	64.1	22.3	8.2
Jatropha	-	0.2	-	-	15.1	0.9	-	7.1	44.7	31.4	0.2
Linseed	-	0.04	-	-	6.21	-	-	5.63	20.17	14.93	51.12
Madhuca	-	0.1	-	-	19.93	-	-	25.96	37.21	14.74	0.28
Karanja	-	-	-	-	11.65	-	-	7.5	51.59	16.64	-
Rubberseed	-	-	-	-	10.2	-	-	8.7	24.6	39.6	16.3
Mahua	-	-	-	-	24.2	-	-	25.8	37.2	12.8	-
Sesame	-	-	-	-	13.1	-	-	3.9	52.8	30.2	-

Ignition quality:

Ignition quality of fuel is very important index for economical and reliable operation of diesel engine. Ignition quality is mainly depending on the fuel quality (cetane number). Differences in molecular structure of fuel influence the physical and chemical processes occurring during the atomisation, vaporisation and combustion (delay period) of the fuel after it is injected into the combustion chamber.

Alessandro Schonborn et al [13] reported that the chain length and degree of unsaturation of pure individual fatty acid methyl ester (FAME) strongly influenced the ignition delay periods of the injected molecules. A longer fatty acid chain length and saturated fatty acid resulted in a shorter ignition delay. Also the molecules with longer FA chain and saturate FAME have lower heat release rate and pressure rise rate during uncontrolled combustion stage of CI engine than shorter chained molecules.

Oxidation stability:

Oxidation stability is one of the major issues affecting the use of biodiesel because of its content of polyunsaturated methyl esters. Stability of biodiesel is inferior compared to petro-diesel and therefore doping of biodiesel in petro-diesel will affect the stability of fuel significantly [14]. Stability of fatty compounds is influenced by factors such as presence of air, heat, traces of metal, peroxides, light, or structural features of the compounds themselves, mainly the presence of double bonds (G Knothe, 2005 [15]). Auto-oxidation of biodiesel occurs due to prolong exposure to air during storage. The oxidation stability decreased with the increase of the contents of polyunsaturated methyl esters.

The autoxidation of unsaturated fatty compounds proceeds with different rates depending on the number and position of double bonds. The positions allylic to double bonds are especially susceptible to oxidation. The bis-allylic positions in common polyunsaturated fatty acids such as linoleic acid (double bonds at C-9 and C-12, giving one bis-allylic position at C-11) and linolenic acid (double bonds at C-9, C-12, and C-15, giving two bis-allylic positions at C-11 and C-14), are even more prone to autoxidation than allylic positions (G Knothe, 2005 [15]; Maria Jesus Ramos[16]).

Rakesh Sarin et al [17] reported that fatty acid like oleic (C18:1), linoleic (C18:2) and linolenic (C18:3) acids are present having double bond 1, 2 and 3 respectively and the trend of increasing oxidation stability was linolenic < linoleic < oleic. These esters undergo auto-oxidation with different rates depending upon the number and position of the double bonds and results in formation of a series of by-products, like acids, esters, aldehydes, ketones, lactones etc, which may lead to deposit formation, storage stability problem and gum formation.

Fatty acid like palmitic and Stearic having absence of double bond has high oxidation stability and it's known as a saturated biodiesel. From the table 2, palm ME and coconut oil ME have better oxidation stability than other FAME.

Table: 3 physicochemical properties of fuels [7].

Properties	Density at 15 °C (kg/m ³)	Viscosity (mm ² /s) at 40 °C	Iodine value	Cetane number	Calorific value (MJ/Kg)	Flash point (°C)	Cloud point (°C)	Pour point (°C)	C (wt%)	O ₂ (wt%)
Cotton seed oil	876	34	-	38	39.47	234	1.7	-15	-	-
Cotton seed ME	850	6.0	105	52	41.68	200	-2	-4	77	10.5
Jatropha oil	910	38	105	-	39.58	235	9±1	4±1	76.11	11.1
Jatropha ME	884	4.12	100	57	39.6	162	-4	-8	76.5	11.3
Karanja ME	885	4.45	-	48	36.12	187	-2	-6	-	-
Linseed oil	894.5	26	184	34.5	39.30	241	1.7	-15	-	-
Linseed oil ME	890	4.3	184	48	40.75	161	-	-18	78.14	11.7
Coconut oil	920.6	28.05	6-11	-	38.68	228	-	-	-	-
Coconut oil ME	875	4.07	30	59	38.1	178	25	22	72	16
Palm oil	860	45	59	49	40.14	193	7.2	16	-	-
Palm oil ME	864.4	4.9	51	52	39.83	171	19	18	75.9	11.9
Olive oil	925	32	-	39	37	-	-	-	-	-
Olive oil ME	888	4.70	-	61	32.7	110	-2	-3	-	-
Castor oil	960	26.82	-	-	36.20	317	-	-	-	-
Castor oil ME	913	10.5	-	-	46.22	149	-	-	72.1	-
Sunflower oil	910	62.1	126.3	36.7	39.6	232	-6.7	-12.2	77.15	10.8
Sunflower ME	892	5.78	133	46.6	36.66	157.6	0	-6	76.7	11.6
Peanut oil	888	22.72	123.2	-	39.9	198	0	-6	70	-
Peanut ME	848.5	4.42	67.45	53.59	40.1	166	0.0	-8	62.1	-
Soybean ME	884.5	3.97	133.2	50.9	-	139	-	0	77.2	10.8
Rapeseed ME	882.8	4.34	97.4	52.9	-	107	-3.9	-8	-	-
Rubber seed ME	-	4.98	97.4	-	37.78	164	5	-8	-	-
Diesel	830	2.8	11	48	46.22	47	-12	-17	86.4	-

Cetane Number (CN):

Cetane number (CN) is widely used as diesel fuel quality parameter related to the ignition delay time and combustion quality. High cetane numbers help ensure good cold start properties and minimize the formation of white smoke. Cetane number is measured by matching against the blends two reference fuels namely n-cetane and α -methyl-naphthalene. The cetane number of biodiesel derived from different feeds stock shown in table 3, ranges from 48 to 65, which is higher than diesel. The variation in reported cetane number arises mainly due to chemical structure, oil processing technology and climate condition of the area where oil is collected [21]. It is well known that biodiesel cetane number depends on the feedstock used for its production. The longer the fatty acid carbon chains and the more saturated the molecules, the higher the cetane number reported by authors (Maria Jesus Ramos et al [16]; G Knothe, 2005 [15]; Pedro Benjumea et al [18]).

Knothe et al.1998, [19] have shown that the reason for lower CN of especially for more unsaturated esters compounds is due to the formation of low-CN compounds during -Pre-combustion phase were **straight-chain and branched alkanes, alkenes, and cyclic hydrocarbons, as well as aldehydes, ketones, esters, substituted benzenes, and other species, such as furans.** Some of the compounds formed during precombustion have low cetane numbers (CN)

One long straight chain is enough to impart a high cetane number although the other moiety is branched. Alcohol utilised in producing biodiesel also affect the cetane number. Branched esters derived from alcohols such as iso-propanol have cetane numbers competitive with methyl or other straight chain alkyl esters [20, 21]. Canakci et al. [22] have shown that saturated compounds like myristic acid (C14:0); palmitic acid (C16:0); stearic acid (C18:0) have higher cetane number. Biodiesel prepared from more saturated oil such as those prepared from tallow, used frying oil, palm oil, coconut oil etc. has higher cetane number.

Calorific value (CV):

The heat of combustion or calorific value of a fuel is an important measurable parameter as it shows the amount of heat liberated by the fuel within the engine that enables the engines to do the work. From table 3, Calorific value of biodiesel rang is 32-42 MJ/kg, which is considerably lower than petroleum diesel of 46 MJ/kg. It is mainly due to the biodiesel contain about 10-12% (w/w) O₂. G Knothe, 2005 [15] reported that the Calorific value increases with the chain length of fatty acid. However biodiesel from saturated fatty acid has higher CV than highly unsaturated fatty acid [7].

Viscosity:

Viscosity is very important properties of biodiesel for satisfactory operation in CI Engine. Vegetable oils have viscosity generally 10 times higher than diesel and it has not as per ASTM standard for CI engine fuel. Higher viscosity generate operational problem in CI Engine like poor atomization, excess penetration and poor mixing with air that leads to incomplete combustion. Viscosity

has reduced by pre-heating the oil and by transesterification of vegetable oil. Biodiesel produce by transesterification has viscosity from 4 to 6mm²/s, which is as per ASTM limits. Biodiesel viscosity also depends on the fatty acid composition.

Pratas et al. [23] and G Knothe, 2005 [15] show that the viscosity of all esters increases with the ester chain length (number of carbon atoms) and decreases with its level of unsaturation. This relation holds also for the alcohol moiety, as for equivalent fatty acid composition the ethyl esters exhibited a higher viscosity than the corresponding methyl ester. Viscosity is also affected by double bond configuration, cis double bond configuration giving a lower viscosity than trans. free fatty acids or compounds with hydroxyl groups possess significantly higher viscosity.

Cold flow properties:

Cold flow properties such as cloud points and pour points are the major problems associated such as wax settling and plugging of filters and fuel lines when weather is cold. The cold flow properties of biodiesel fuels depend on the feedstock of row oil and are a strong function of the level of saturated fatty acid. Biodiesels with significant amounts of saturated fatty compounds exhibits higher cloud point and pour point. Animal fats, palm and coconut oils are more highly saturated and thus have higher cloud point as shown in Table 3.

Maria Jesus Ramos et al. [16] reported that the Peanut biodiesel gave the worst CFPP (17 °C of CFPP). The Peanut biodiesel is rich in methyl esters of long carbon chain saturated fatty acids like behenic (C22:0) and lignoceric (C24:0) acid. The longer the carbon chains in the biodiesel, the worse the low-temperature properties.

In addition to the use of branched esters such as iso-propyl, iso-butyl and 2-butyl instead of the methyl esters is another approach for improving the low-temperature properties of biodiesel. [15].

Iodine number:

Iodine number is a measure of the degree of unsaturation of the fuel. It is expressed in grams of iodine which react with 100 g of the respective sample when formally adding iodine to the double bonds. Iodine value is limited to 120 g I₂/100 g in the European biodiesel standard UNE-EN 14214 [16]. Biodiesel with increase in unsaturation increases the number of double bonds which increases the iodine number. Soybean, sunflower and Grape seed oil were located between the limit imposed by the European Standard and the limit imposed by the Spanish law. On the other hand, palm oil, rich in esters of saturated fatty acids such as palmitic (C16:0) and stearic (C18:0) acids, was the oil with a lower iodine value.

Carbon monoxide (CO):

Main case of formation of CO is due to deficit of O₂ for complete oxidation of CO to CO₂. Reduced CO emissions were maintained, probably, thanks to the oxygen inherently present in the biodiesel, which makes it easier to be burnt at higher temperature in the cylinder [5, 24, 25]. Some other also reported that the CO of pure biodiesel and high blend ratio have higher than D100 due to the Poor atomisation and uneven distribution of small portions of fuel across the combustion chamber, along with a low gas temperature, may cause local oxygen deficiency and incomplete combustion [4, 25, 26]. CO exhaust emissions increase with increased chain length of fatty acid methyl esters. This effect is clearer when pure compounds are tested. Methyl esters with longer chain length have higher boiling and melting points, so they are less likely to be completely vaporised and burnt, thereby increasing CO emissions. [4].

Hydrocarbons (HC):

HC emission is mainly due to the incomplete combustion of fuel. The use of biodiesel generally results in lower HC emissions due to the higher cetane number of biodiesel and presence of O₂ causes a decrease in combustion delay that lead to complete combustion [1, 5, 7, 24]. HC exhaust emissions increase with increased chain length of fatty acid methyl esters. This effect is clearer when pure compounds are tested. This trend can be explained by the higher oxygen content in the shorter fatty acid molecules, which leads to a more complete and cleaner combustion. Moreover, methyl esters with longer chain length have higher boiling and melting points, so they are less likely to be completely vaporised and burnt, thereby increasing HC emissions [4].

Nitrogen oxide (NOx):

Formation of NOx depends on cylinder temperature, ignition delay and oxygen content in the fuel. NOx emissions were observed to increase for biodiesel. Biodiesels contain higher oxygen component compared to diesel fuel. So it is evident that there is higher oxygen content to react with the nitrogen component in the surrounding air, resulting in a larger amount of NOx formation [1, 5, 24].

Robertl. McCormick et al. [27] have found that the molecular structure of biodiesel can have a substantial impact on emissions. With the exception of pure methyl palmitate (C16:0), methyl laurate (C12:0), methyl and ethyl stearate (C18:0) all biodiesel fuels produced higher NOx than certification diesel (4.59±0.0125 g/bhp-h).

Alessandro Schonborn et al [13] reported that the longer fatty acid chain length and saturated fatty acid resulted to a shorter ignition delay. This leads to lower heat release rate and lower cylinder bulk-gas-averaged temperature, that cause of molecules with longer and saturated fatty acid chain lengths produced less NOx during their combustion than shorter chained and unsaturated molecules.

The biodiesel produced from saturated feed stock such as animal fat, palm ME and coconut ME may provide a better solution to reduce NOx emission. The most highly unsaturated fuels (canola, sunflower and soybean) produce the highest NOx emissions.

Smoke opacity:

Smoke of biodiesel is lower than petro-diesel. The reduction in smoke can be explained by the presence of less carbon with biodiesel based fuels as compared to diesel. In addition to that, biodiesel has more oxygen content contrary to diesel, which has no oxygen. The presence of oxygen in the biodiesel is in favour of carbon residual oxidation, which leads to reduction in smoke opacity [4, 7].

Pedro Benjumea et al. [18] reported that the Smoke Opacity slightly increased with the degree of unsaturation of the biodiesel fuels and result behind that the tendency of soot formation as premixed combustion phasing increases.

Particulate Matter (PM):

PM (particulate matter) is composed mainly of three components: DS (dry soot), sulphate and SOF (soluble organic fraction) [28]. PM emissions were generally reduced with the use of biodiesel as compare to diesel; due to the oxygen contained in the biodiesel molecules, the low levels of sulphur content and higher cetane number. Diesel contains sulphur which results in sulphates that are absorbed on soot particles and increase the PM emitted from diesel engines. As biodiesel is free from sulphur, and it has an advantage over diesel [29].

Alessandro Schonborn et al. [13] reported that the increase fatty acid chain length and degree of unsaturation fatty acid resulted to high PM emission. Robertl. McCormick et al. [27] shows that the highest PM emissions were observed for pure methyl linoleate (C18:2), which was the only biodiesel with PM emissions exceeding those of certification diesel (0.261 ± 0.014 g/bhp-h.).

V. CONCLUSION:

From above discussion Physicochemical properties of biodiesel derived from different feedstock mainly depend on type of fatty acid ester present in biodiesel composition. Biodiesel contain saturate fatty acid have some advantage likes good ignition quality good oxidation stability, high CN, high CV, low iodine number, low NO_x, low PM and low smoke opacity but also have some drawbacks like high cold flow properties and high viscosity. On the other end biodiesel contain unsaturated fatty acid (linolenic, linoleic, oleic) have low cold flow properties and low viscosity, but have poor oxidation stability, low CN, low CV, high iodine number, high NO_x, high PM and smoke opacity. Now to take advantage from both fatty acids simultaneously, combine both type of fatty acid biodiesel to form hybrid biodiesel, which is our next research scope.

VI. REFERENCE:

- [1] S Prabhakar, K Annamalai and Isaac Joshua Ramesh Lalvani, "Experimental study of using hybrid vegetable oil blends in diesel engine", Journal of Scientific & Industrial Research, 2012, 71, 612-615
- [2] Agarwal AK, Rajamanoharan K. Experimental investigations of performance and emissions of Karanja oil and its blends in a single cylinder agricultural diesel engine. Applied Energy 2009, 86, 106–12.
- [3] B.K. Barnwal, M.P. Sharma, "Prospects of biodiesel production from vegetable oils in India", Renewable and Sustainable Energy Reviews, 2004, 09, 363–378.
- [4] Wan Nor Maawa Wan Ghazali, Rizalman Mamat, H.H.Masjuki, GholamhassanNajafi, "Effects of biodiesel from different feedstocks on engine performance and emissions: A review", Renewable and Sustainable Energy Reviews, 2015, 51, 585–602.
- [5] T. Venkateswara Rao, G. Prabhakar Rao, and K. Hema Chandra Reddy, "Experimental Investigation of Pongamia, Jatropha and Neem Methyl Esters as Biodiesel on C.I. Engine", Jordan Journal of Mechanical and Industrial Engineering, 2008, 02, 117-122.
- [6] Schumacher LG, Gerpen JV, Adams B. Biodiesel fuels. ENC Energy 2004, 1, 151–62.
- [7] Niraj Kumar, Varun, Sant Ram Chauhan, "Performance and emission characteristics of biodiesel from different origins: A review", Renewable and Sustainable Energy Reviews, 2013, 21, 633–658
- [8] Abbaszaadeh A, Ghobadian B, Omidkhah MR, Najafi G. Current biodiesel production technologies: a comparative review. Energy Convers Manag 2012, 63(0), 138–48.
- [9] Prakash C. Jena, Hifjur Raheman, G.V. Prasanna Kumar, Rajendra Machavaram, "Biodiesel production from mixture of mahua and simarouba oils with high free fatty acids", biomass and bioenergy, 2010, 34, 1108-1116.
- [10] Raheman H, Phadatare AG. Diesel engine emission and performance from blends of karanja methyl ester and diesel. Biomass and Bioenergy 2004, 27, 393–7.
- [11] Ghardge SV, Raheman H, Process optimization for biodiesel production from mahua (Madhuca indica) oil using response surface methodology. Bio resourceTechnology 2006, 97, 379–84.
- [12] Atabani AE, Silitonga AS, Ong HC, et al. Non-edible vegetable oils: a critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. Renew Sustain Energy Rev, 2013, 18(0), 211–45.
- [13] Alessandro Schönborn, Nicos Ladommatos, John Williams, Robert Allan, John Rogerson, "The influence of molecular structure of fatty acid monoalkyl esters on diesel combustion" Combustion and Flame, 2009,156, 1396–1412.
- [14] Dunn RO, Knothe G. Oxidative stability of biodiesel in blends with jet fuel by analysis of oil stability index. J Am Oil Chem Soc, 2003, 80, 1047–8.
- [15] Knothe G, Steidley KR. Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components. Fuel 2005, 84, 1059–65.
- [16] María Jesús Ramos, Carmen María Fernández, Abraham Casas, Lourdes Rodríguez, Ángel Pérez, "Influence of fatty acid composition of raw materials on biodiesel properties", Bioresource Technology, 2009,100, 261–268.

- [17] Rakesh Sarin, Meeta Sharma, S. Sinharay, R.K. Malhotra, "Jatropha–Palm biodiesel blends: An optimum mix for Asia", *Fuel*, 2007, 86, 1365–1371.
- [18] Pedro Benjumea, John R. Agudelo, Andres F. Agudelo, "Effect of the Degree of Unsaturation of Biodiesel Fuels on Engine Performance, Combustion Characteristics, and Emissions", *Energy Fuels*, 2011, 25, 77–85.
- [19] Knothe G, Bagby MO, Ryan TW. Precombustion of fatty acids and esters of biodiesel. A possible explanation for differing cetane numbers. *Journal of the American Oil Chemists Society* 1998, 75(8), 1007–13.
- [20] Correa SM, Arbilla G. Carbonyl emissions in diesel and biodiesel exhaust. *Atmospheric Environment* 2008, 42, 769–75.
- [21] Pryde EH. Vegetable oils as diesel fuels: overview. *Journal of the American Oil Chemists Society* 1983, 60(8), 1557–8.
- [22] Canakci M, Gerpen JHV. Biodiesel production from oils and fats with high free fatty acids. *Transactions of the American Society of Agricultural Engineers* 2001, 44(6), 1429–36.
- [23] Pratas MJ, et al. Densities and viscosities of fatty acid methyl and ethyl esters. *Journal of Chemical and Engineering Data* 2010, 55(9), 3983–90.
- [24] Atul Dhar, Avinash Kumar Agarwal "Performance, emissions and combustion characteristics of Karanja biodiesel in a transportation engine", *Fuel*, 2014, 119, 70–80.
- [25] K. Srithar, K. Arun Balasubramanian, V. Pavendan and B. Ashok Kumar, "Experimental investigations on mixing of two biodiesels blended with diesel as alternative fuel for diesel engines", *Journal of King Saud University*, 2014
- [26] Ramadhas AS, Jayaraj S, Muraleedharan C. Use of vegetable oils as I.C. engine fuels—a review. *Renewable Energy* 2004, 29, 727–42
- [27] Robert I. McCormick, Michael s. Graboski, Teresa I. Alleman, Andrew m. Herring, "Impact of Biodiesel Source Material and Chemical Structure on Emissions of Criteria Pollutants from a Heavy-Duty Engine", *Environ. Sci. Technol.* 2001, 35, 1742-1747.
- [28] Chen H, Shuai S, Wang J. Study on combustion characteristics and PM emission of diesel engines using ester-ethanol-diesel blended fuels. *Proceedings of the Combustion Institute* 2007, 31, 2981–9.
- [29] Kalligeros S, et al. An investigation of using biodiesel/marine diesel blends on the performance of a stationary diesel engine. *Biomass and Bioenergy* 2003, 24, 141–9.

