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Article

A review of global current scenario of biodiesel adoption and combustion in vehicular diesel engines

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Review article

A review of global current scenario of biodiesel adoption and combustion in vehicular diesel engines

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ABSTRACT

Delving into the current chronicles of research findings, explorations of biodiesel production and utilization in diesel engines have been at the forefront of sustainable and creative energy discovery. Far beyond the problems of energy crises, renewable biodiesel offers unlimited solutions to the associated issues of depleting reserves and harmful emissions with fossil fuels. In overcoming the increasing energy demand owing to the growing worldwide population, the emergence of biodiesel and its global adoption in the transportation sector has brought along a reliable fuel supply that can be used in diesel engines without any modification. This study explores the comprehensive utilization of biodiesel as engine fuel and shows the prevalent global current adoption in automobiles engines. The production rates are documented globally and promoting policies that are being mandated in many countries of the world are discussed as well. The improved state of things in achieving effective power conversion from biodiesel combustion with minimal emission impact on the environment has been documented. Worldwide technological adoption has been captured according to production rate, usage and legislation favouring the economic feasibility of diesel engines that are suitable for biodiesel with little or no modification. With the progress made so far by many researchers to establish biodiesel as a viable engine fuel, coupled with the ability to eradicate environmental issues like global warming and sustainability, it is evident that biodiesel is designed to make a future energy investment and significant addition to the domestic and industrial automobile economy.

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Nomenclature

Symbols

CoCl ₂	Cobalt (II) chloride
CuCl ₂	Copper (II) chloride
CuO	Copper (II) oxide
CuSO ₄	Copper (II) sulphate
FeCl ₃	Iron (III) chloride
H ₂ SO ₄	Sulphuric acid
CO	Carbon monoxide
CO ₂	Carbon dioxide
NO _x	Nitrogen oxides

Abbreviations

ANN	Artificial neural network
ASEAN	Association of Southeast Asian Network
ASTM	American society for testing and materials
BHA	Butylated hydroxyl anisole
BHT	Butylated hydroxyl toluene
BP	Brake power
BSFC	Brake specific fuel consumption
BTE	Brake thermal efficiency
BtL	Biomass-to-liquid
CCD	Central composite design
CI	Compression ignition
CN	Cetane number
CRD	Common rail diesel
DI	Direct ignition
DPA	Diphenylamine
EN	European union standard
EU	European union
FAEE	Fatty acid ethyl ester
FAME	Fatty acids methyl esters
FFA	Free fatty acid
GA	Genetic algorithm
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
HHV	Higher heating value
HVOs	Hydrotreated vegetable oils
IC	Internal combustion
LHV	Lower heating value
MEFA	Methyl ester fatty acid
nPAH	Nitrated PAH's
PAH	Polycyclic Aromatic Hydrocarbons
PG	Propyl-gallate
PHEV	Plug-in hybrid electric vehicle
PL	Pyrogallol
PM	Particulate matter
RSM	Response surface methodology
SBD	Shea butter biodiesel
SDS	Sustainable Development Scenario

TBHQ	Tert-butylhydroxyquinone
THC	Total hydrocarbons
VOCs	Volatile organic compounds

1. Introduction

The idea of using biofuels in diesel engines emanated when the first diesel engine was displayed by its mastermind, Rudolf Diesel, at the world fair in Paris in 1900. Peanut oil was used as the fuel and he assumed that oil from locally grown crops could be used to operate his engines (Chalkley, 1917). Basically, fossil diesel has been effectively utilized in all sectors such as agriculture, transportation and industrially because of its adaptability, availability, reliability, as well as high energy efficiency (Mofijur et al., 2013). The diesel engine runs on the diesel, burnt by the heat of compression of air in the cylinder because of its desirable properties such as ignition quality, viscosity, volatility, specific gravity and lubricity. At the same time, depletion of resources has always been a concern with regard to fossil fuels, especially farmers who have always sought alternative fuel for their agricultural production (Demirbas, 2008).

In consideration of global total energy consumption and GHG emissions, transportation occupies 3rd place (after the industry and the building sectors) owing to the heavy dependence of vehicular engines on fossil fuels such as gasoline and diesel. This level of utilization is expected to rise by 60% by 2030 mainly because of industrialization, population increase and better standards of living (Bhuiya et al., 2016). All the technologies needed for transition to 100% renewables are already available, one of the major advantage biomass and biofuels have always had above the volume of energy they produce is their renewability. Biofuels are significant because of their sustainability while fossil fuels are a limited resource. Biofuels have the capacity to power different types of diesel engine cars regardless of the atmospheric conditions. Improving the production of liquid biofuels, such as biodiesel, would therefore lead to much availability of a cleaner, cheaper source of energy in contrast to fossil fuels.

Different seed oils have been used in several countries as feedstocks for production of biodiesel according to their availability. Soybean oil is often used in United States, Brazil and Argentina, while rapeseed oil is common to a good number of European countries, while palm and coconut oils are used in Malaysia and Indonesia for biodiesel production (Ghadge and Raheman, 2005). In Southeast Asia and India, *Jatropha curcas* (Kumar Tiwari et al., 2007; Martínez et al., 2014), *Pongamia pinnata* (Martínez et al., 2014; Srivastava and Verma, 2008), and *Mahua indica* (Ghadge and Raheman, 2005) are utilized as significant sources of fuel. Some variety of bio-lipids can also be used for biodiesel production. Pure vegetable oil feedstocks such as rapeseed and soybean oils are commonly used, though other crops such as palm oil, sunflower, mustard, hemp, and even microalgae are promising. Used vegetable oil, animal fats including lard, tallow and yellow grease, and non-edible oils such as jatropha, neem oil, castor oil, and tall oil are some of the feedstocks being used as well (Demirbas, 2008). The oils of the seed plants like *Cynara cardunculus* L. and *Brassica carinata* (Martínez et al., 2014), residual cooking oil (Nguyen et al., 2017), microbial and insect oils (Živković et al., 2017), castor, tobacco seed, neem, rice bran and rubber seed oils

have also been identified as other raw materials showing signs of success for production of biodiesel (Negm et al., 2017).

Several current studies focusing on utilization of non-edible oils have promoted vast discovery of non-edible oil feedstocks for production of biodiesel locally and industrially (Banković-Ilić et al., 2012). Rapeseed, soybean and palm oils remain the commonest feedstocks while mustard seed, peanut, sunflower and cotton seeds are new oil plants that are being used currently (Banković-Ilić et al., 2012; Demirbas et al., 2016). Biodiesel production from non-edible oil seeds has been substantially explored over the last few years. Examples of non-edible oil seeds which have been extensively used for biodiesel production include *Jatropha curcas*, *Pongamia pinnata*, *Madhuca indica*, *Ricinus communis*, *Azadirachta indica*, *Hevea brasiliensis*, *Nicotiana tabacum*, rice bran, *Thevetia peruviana*, *Hura crepitans*, jojoba, *Ailanthus altissima*, etc. Oyelade et al. (2017), Ogunkunle et al. (2017), Gimbun et al. (2012), Heroor and Bharadwaj (2013), Zarei et al. (2014), Oniya et al. (2017b), Sánchez et al. (2015), Avhad et al. (2016) and Hoseini et al. (2018). There is currently increase in extraction of oils from inedible oil seeds that are used in producing biodiesel which have the expected fuel properties for engine applications with no modification to the engine (Sánchez et al., 2015; Avhad et al., 2016; Hoseini et al., 2018). There is currently increase in extraction of oils from oil seeds that are used in producing biodiesel which have the expected fuel properties for engine applications with no modification to the engine. In this light, the authors recently carried out robust optimized studies on biodiesel production from *Parinari polyandra* oil (Ogunkunle and Ahmed, 2019b) and made an attempt to test its engine application and performance (Ogunkunle and Ahmed, 2019a), all of which are new contributions that have not been addressed before.

From established reports, the continuous combustion of fossil fuels in engines have brought about release of GHG that are contributing to increase in global warming (Lim and Teong, 2010a). However, biofuels possess a number of benefits, among which is the reduction of GHG in our atmosphere. The exhausts from combustion of diesel in IC engines portray a serious threat to our existence by contributing to global warming. Biodiesel is one of the renewable sources of energy for meeting increasing energy demand for transportation and reducing GHG emissions remarkably. The present review provides a comprehensive account on sustainable production and utilization of biodiesel synthesized from inedible and waste edible oils as engine fuel that will be useful for researches, engineers, fuel suppliers and end users, manufacturers and investors who are into biodiesel production and manufacturing of diesel engines.

Considering the research literature on the different applications of biodiesel in engines, there is no available work which has explored the current state of the art of global biodiesel production and utilization in transportation sector and the expected outgrowth for it to pass the SDS goals by the year 2030. Also, to the best knowledge of the authors, the commercialization of non-edible oils in countries with high biodiesel production rate has not yet been established nor addressed before. With the recent records of increase in diesel vehicle sales in the United states and consistent rise in diesel car markets in Europe for the past decade, this review is intended to serve as a paradigm pointer to an imminent corresponding increase in global biodiesel policies adoption and complete switch to diesel engines in respect to improved performances of engines running on renewable and environmental friendly biodiesel fuel. The expected challenges and prospects of promoting on biodiesel as a future fuel in the transportation sector were also identified for further studies. The chosen literatures were peer reviewed scientific researches that provided significant contributions to the study area. Elsevier's reference manager software Mendeley was used for capturing, citing and listing the references of the article that were selected.

2. Review of biodiesel production technologies

It is generally accepted that viscosity is the main difficulty that hampers the direct use of vegetable oils in traditional diesel engines (Demirbas, 2009; Singh and Singh, 2010). Consequently, there are established techniques and processes that have been used to produce biodiesel from various non-edible feedstocks to reduce viscosity. These methods include pyrolysis, micro-emulsification, dilution, and transesterification. Of all these methods, transesterification remains the viable process that has been adopted so far for the reduction of viscosity. The flowchart shown in Fig. 1 describes the routes to produce biodiesel from non-edible oil seeds and their final products (Atabani et al., 2013; Van Gerpen, 2005; Atabani et al., 2012; Balat and Balat, 2010). Transesterification was found to be the most common method used in biodiesel production. More emphasis is given to this under this section.

2.1. Pyrolysis

Pyrolysis refers to anaerobic thermal disintegration of organic materials in the presence of a catalyst. The fragmented matters can be animal fats, vegetable oils, natural triglycerides or FAME. Common products of pyrolysis of triglycerides are alkanes, alkenes, alkanes, aromatics and carboxylic acids (Bhuiya et al., 2016; Balat and Demirbas, 2009). The liquid components of the disintegrated fats are similar to diesel fuels. The pyrolysis products have CN, viscosity, flash point, and pour point properties lower than diesel fuel but similar heating values (Demirbas, 2009; Singh and Singh, 2010; Mahanta and Shrivastava, 2004).

2.2. Micro-emulsification

Micro-emulsification, which is also known as co-solvent blending, is the thermodynamic equilibrium dispersion of microstructures with average diameter, d , less than 0.25 of the wavelength of visible light. Much agitation is needed for the mixture to remain in a single state. A microemulsion can be made by using a co-solvent to dissolve immiscible substances such as vegetable oils and an ester, or vegetable oils and alcohols, such as methanol, ethanol, butanol, hexanol, with the addition of a surfactant and a cetane improver. Addition of diesel fuel is optional depending on the type of engine. Micro-emulsification is a stable technique for reducing high viscosity of triglycerides (Demirbas, 2009; Balat and Balat, 2010).

2.3. Dilution

Dilution involves the addition of diesel fuel to triglycerides to make it thinner (reduce the viscosity) for better engine performance. No chemical process is needed for this method (Demirbas, 2008; Balat, 2011). It is established that complete replacement of some vegetable oils for diesel fuel is not realistic experimentally due to variation in the viscosity and pour points. Consequently, mixing 20%–25% blends of vegetable oil with diesel has been examined to produce quality performance results for diesel engines (Bhuiya et al., 2016; Ogunkunle and Ahmed, 2019a; Singh and Singh, 2010; Kousoulidou et al., 2012a; Nabi et al., 2017; Dhar and Agarwal, 2014). The details of diluting fossil diesel with varieties of non-edible seed oil such as turpentine, *Putranjiva roxburghii*, cotton seed, linseed, rubber seed, *Jatropha curcas* and *Pongamia pinnata* oil are reported in some literatures (Ramadhas et al., 2005a). Diluted fuels such as, preheated palm oil and palm oil/diesel oil blends, palm oil/waste cooking oil mixtures, were prepared and successfully applied as fuels in an IC engine (Ndayishimiye and Tazerout, 2011).

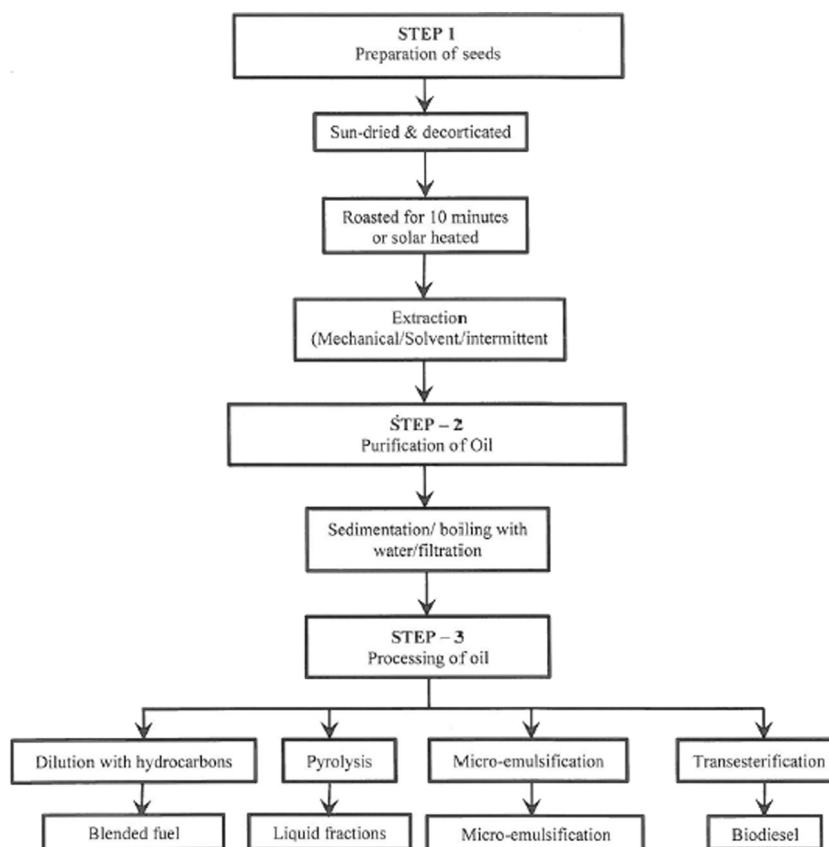


Fig. 1. Process flowchart of non-edible crop seeds to biodiesel.

Source: Atabani et al. (2013), Balat and Balat (2010) and Salvi and Panwar (2012).

2.4. Transesterification

Transesterification has been extensively used in reducing the viscosity of vegetable oil and influencing their conversion to biodiesel. It is a process by which alkyl esters are produced from chemical reactions between alcohol and vegetable oils in the presence of catalyst. The most affordable and available alcohols in this reaction include methanol and ethanol (Bhuiya et al., 2016; Leung et al., 2010). The type of alcohol used does not entirely determine the biodiesel yield, the selection is determined by cost and performance. Transesterification is a reversible reaction involving a sequence of three reaction stages in which the triglyceride in oil is converted into diglyceride, and diglyceride is converted into monoglyceride (methyl or ethyl ester) (Van Gerpen, 2005). Three moles of alcohol are required in this reaction for each mole of triglyceride. But usually, more molar ratio is often employed to shift the reaction forward for maximum biodiesel production. Three ester molecules are produced in the overall chemical reactions; one ester molecule from each step (Fig. 2). Glycerol, which has commercial value, is derived as a by-product of this reaction (Fig. 3) (Sharma and Singh, 2008).

The catalysts that are commonly used are acid and alkali catalysts depending on the nature of the oil used for biodiesel production. Transesterification catalysis involving the use of enzymes are currently being explored for higher biodiesel production. As a result of the differences in the saturation of oil, the acid value of any chosen feedstock has to be reduced to less than 2.0 mg KOH/g for a one-way alkaline transesterification (Canakci and Van Gerpen, 2013).

Other authors however recommend it to be below 4.0 mg KOH/g (Sharma and Singh, 2008), but the reaction will be slowed

down as a lot of water is produced along with ester (Canakci, 2007). To overcome this, many other studies have employed two-step transesterification processes to produce biodiesel from saturated oils with fatty acid values greater than 2.0 mg/KOH/g. The first step involves acid esterification reaction between the oil and an acid to reduce the fatty acid content. The catalyst commonly used during acid esterification of neat oil is H_2SO_4 (Veljković et al., 2006). This is then followed by transesterification reaction where the purified/neat oil is reacted with alcohol in the presence of a catalyst. Generally, alkaline transesterification would favour biodiesel production as it appears to take place about 4000 times faster than acid transesterification (Fukuda et al., 2001). The alkaline catalysts used at industrial level include homogeneous catalysts such as NaOH and KOH. The use of homogeneous catalysts has been successful at industrial level for biodiesel production. However, the biodiesel and glycerin have to be purified by washing the products with hot distilled water to remove the basic catalyst (Bhuiya et al., 2016). A reasonable number of researchers have used non-synthetic heterogeneous solid catalysts which have relative advantages of reusability and reduction of overhead cost of washing the products (Ogunkunle et al., 2017; Betiku and Ajala, 2014; Gohain et al., 2017; Betiku et al., 2016; Xie et al., 2006; Anr et al., 2016; Hossain et al., 2019; Roschat et al., 2017; Moradi et al., 2015; Farooq et al., 2013; Vicente et al., 2017). Methanol was also found to have high reaction potential and preferred over other alcohols due to its relatively low cost (Ramadhas et al., 2005b).

In order to meet up with high transportation demands for biodiesel fuel, both local and industrial production of biodiesel must be improved for high biodiesel yields. Optimization techniques have proved to be efficient tools in producing quality and

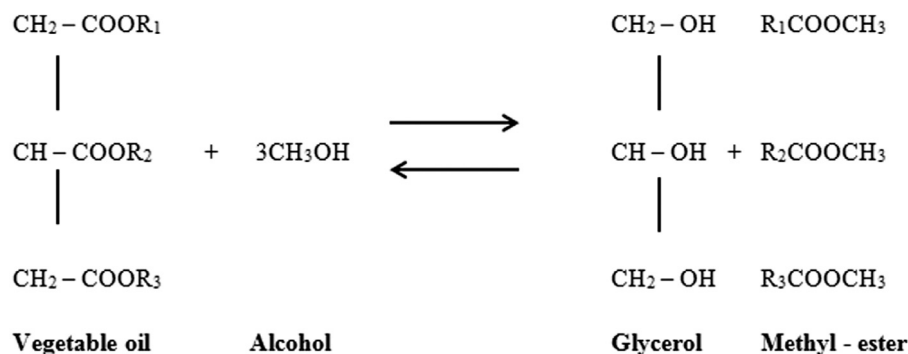


Fig. 2. Reaction mechanism for transesterification.

Source: Demirbas (2009) and Singh and Singh (2010).

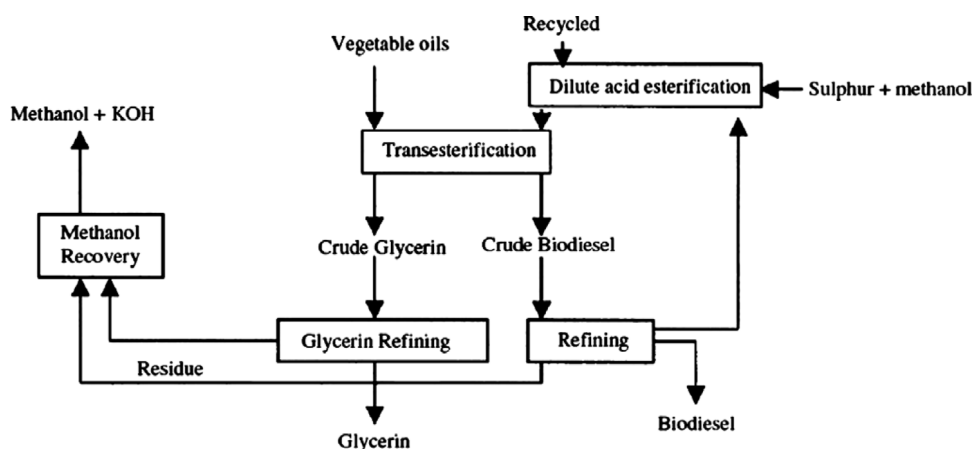


Fig. 3. Basic schemes for biodiesel production.

Source: Marchetti et al. (2007).

high esters yield. It is of great significance to study the effect of applied reaction parameters on biodiesel yield because they influence directly the efficiency of biodiesel production. Statistical procedures, such as RSM (Ogunkunle and Ahmed, 2019b,a; Da Silva et al., 2006), Factorial design (De Lima Da Silva et al., 2009), Box–Behnken factorial design (Ogunkunle et al., 2017; Liao and Chung, 2011), Taguchi technique (Yusup and Khan, 2010), D-Optimal design (Oyelade et al., 2017), GA coupled with ANN (Jena et al., 2010; Betiku et al., 2015; Mohammad Fauzi and Saidina Amin, 2013; Dharma et al., 2017a) are commonly used optimization methods for biodiesel production.

The different findings on optimized yields of biodiesel production from selected inedible seed oils with high biodiesel potentials are outlined Table 1. Several biodiesel optimization layouts were achieved through the use of traditional and heuristic algorithm-based support vector machines to recognize the perfect sets of reaction conditions and obtain regression models with greater precision for optimizing biodiesel production from waste cooking oil (Bobadilla et al., 2018). Many of these procedures for biodiesel optimization were achieved using standardized software features to achieve best utilization and performance of resources. Quadratic models were commonly used, and the ANOVA results showed that some of these reaction parameters, especially temperature, alcohol to oil molar ratio, and catalyst concentration had significant impact on biodiesel production at 95% probability level. The application of RSM to optimize biodiesel production has generated wider applications than other heuristics models (GA, ANN, ANFIS, SA, etc.). The most commonly used optimization models are RSM, ANN and GA. Analysis of Scopus indexed

publications on the subject area shows that 530, 89, and 30 documents have been published on the application of RSM, ANN, and GA respectively in the last 30 years. For the Web of Science based journals, a total number of 530, 97, and 62 have been published on the application of RSM, ANN, and GA respectively. Though there have been quite some arguments on the use of these optimized models for better prediction, it appears RSM is still scaling high as the most commonly used model over the years. A better explanation found for this is the cost effectiveness and reliable optimization methodology which requires reduced number of experimental runs for evaluating multiple applied parameters in any process control (Lee et al., 2000; Porretta et al., 1995; Yeniyay, 2014). The application of RSM can be a useful utility in improvement of industrial biodiesel production. Sarve et al. (2015) reported that ANN had better prediction capability than RSM in predicting the FAEE content from crude *Madhuca indica* oil transesterification. Betiku et al. (2014) also demonstrated that ANN established a reliable model than RSM in the prediction of biodiesel production from *Azadirachta indica* seed oil. To verify the statistical predictions for the biodiesel yields, verifications experiments were carried out and a similar agreement was found between the experimental and predicted values.

3. Current research scenario of biodiesel combustion as vehicular fuel

Biodiesel has become an important vehicular fuel owing to its excellent and similar properties as diesel engine fuel (Behzadi and Farid, 2009; Chongkhong et al., 2009; Bhatti et al.,

Table 1
Optimized biodiesel yields from different inedible oil feedstocks.

Oil feedstocks	Maximum Biodiesel yields	Model	Independent variables	References
<i>Vitellaria paradoxa</i>	99.65%	ANN coupled with GA and RSM	Catalyst amount, oil/methanol molar ratio, temperature, time	Betiku et al. (2015)
<i>Jatropha curcas</i> , <i>Pongamia pinnata</i> and <i>Calophyllum inophyllum</i>	93%, 91%, and 85%	NM	Mode of reaction condition, molar ratio of alcohol to oil, type of alcohol, type and amount of catalysts, time, temperature and purity of reactants	Sahoo and Das (2009)
<i>Jatropha curcas</i>	>99%	RSM	Methanol quantity, acid concentration, reaction time	Kumar Tiwari et al. (2007)
WCO	96.03%	NM	Temperature, time, methano-to-oil mole ratio	Hossain et al. (2019)
<i>Hura crepitans</i>	93.97%	D-Optimal	Temperature, time, catalyst concentration, catalyst type	Oyelade et al. (2017)
<i>Thevetia peruviana</i>	81%	RSM	Temperature, time, alcohol-to-oil ratio	Ogunkunle et al. (2017)
<i>Parinari polyandra</i>	95.62%	RSM	Temperature, time, catalyst amount	Ogunkunle and Ahmed (2019b)
Jojoba	83.5%	RSM	Temperature, catalyst concentration	Bouaid et al. (2007)
<i>Pongamia pinnata</i>	98%	NM	Catalyst concentration, methano/oil molar ratio, temperature, mixing intensity	Meher et al. (2006)
Oleic acid	82.1%	RSM, ANN-GA	Methanol to oleic acid molar ratio, catalyst loading, temperature, time	Mohammad Fauzi and Saidina Amin (2013)
Castor oil	94.19%	Factorial Design	Temperature, catalyst concentration, ethanol:castor oil molar ratio	De Lima Da Silva et al. (2009)
Castor oil	99.81%	RSM	Temperature, methanol/oil molar ratio, catalyst concentration	Kiliç et al. (2013)
Mahua oil	92.7%	RSM	Catalyst concentration, methanol amount, temperature, time	Muthukumar et al. (2017)
WCO	98%	GA	Molar ratio, catalyst, time, speed, temperature, humidity, impurity	Bobadilla et al. (2018)
<i>Pongamia glabra</i>	95%	NM	Methanol to oil molar ratio, catalyst concentration, temperature, time	Patil and Deng (2009)
Shea butter	92.16%	RSM	Temperature, agitation, methanol:oil mole ratio, catalyst loading	Ajala et al. (2017)
Black soldier fly larvae	96.18%	RSM	Temperature, methanol:fat molar ratio, enzyme loading, time	Nguyen et al. (2017)
Sterculia oil	90.2%	RSM coupled with ANN	Temperature, catalyst concentration, oil to methanol ratio, agitation speed	Kavitha and Murugavelh (2019)
<i>Jatropha curcas</i> - <i>Ceiba pentandra</i>	93.47%	ANN-GA	Methanol-to-oil ratio, agitation speed, catalyst concentration	Dharma et al. (2017a)
<i>Brucea javanica</i>	94.34%	RSM	Methanol to oil ratio, catalyst concentration, temperature	Hasni et al. (2017)
Loofah	88%	RSM-ANN	Time, temperature, amount of alcohol, amount of KOH	Oniya et al. (2017a)
<i>Simarouba glauca</i>	62%	RSM-ANN	Oil:alcohol ratio, temperature, time	Sivamani et al. (2018)
<i>Bauhinia monandra</i>	93.33%	RSM	Catalyst loading, methanol/oil molar ratio, time	Betiku et al. (2016)
<i>Sesamum indicum</i>	96.62%	RSM and ANN	Time, catalyst amount, temperature, methanol to oil molar ratio	Adepoju and Okunola (2015)
Cantaloupe	94.5%	NM	Methanol to oil molar ratio, temperature, catalyst loading	Akhtar et al. (2017)

2008). Many researchers have tested biodiesel combustion in automobile diesel engines using different ratio of biodiesel with diesel blends. According to some reports, fuel blends above 20% generated maintenance problems and even occasionally damaged the engine (Shahid and Jamal, 2008; Basha et al., 2009; Agarwal et al., 2008). Biodiesel of lower blends, B2 and B5, in diesel fuel have been used successfully in existing diesel engines as well as new designs coming off the assembly line. Biodiesel is used in the marine industry as a shipping fuel because of its non-toxicity and essential absence of sulphur and aromatics.

While some studies have shown the possibility of using more than 20% of vegetable oils as addition to diesel fuel, the acceptable submissions are that chemically refined vegetable oil can be used to operate CI engines for prolonged period without any engine modification (Ogunkunle and Ahmed, 2019a; Basha et al., 2009;

Datta and Mandal, 2016; Bae and Kim, 2017). In 2005, Chrysler introduced into the American market the Jeep Liberty CRD vehicles which can run on 5% biodiesel blends. This was a symbolic pointer for partial acceptance of biodiesel as a sustainable diesel fuel extender. Warranty coverage was increased to 20% biodiesel blends in 2017 with the expectation that biofuel quality in the US will be improved (Tickell and Murphy, 2006). The Volkswagen Group stated categorically that many of its cars are suitable with EN 14214 standardized B5 made from rapeseed oil. Mercedes Benz does not permit biodiesel fuel blends which exceeds 5% biodiesel as a result of production defects in their engine designs. The application of different fuel blends in their cars other than specified will revoke any warranty. It was also gathered that the Mercedes-Benz Limited Warranty does not cover any damages incurred by the use of restricted fuels (Tickell and Murphy,

2006). However, extensive research in the use of biodiesel–diesel blends in CI engines have proved that seed oil-derived biodiesels have benefits relative to improved combustion performance and emissions reduction. In 2004, the city of Halifax, Nova Scotia revolutionized its transportation network by allowing the city rapid buses to run wholly on a fish-oil based biodiesel. There were few initial mechanical issues which were overcome when the entire fleet had been successfully converted after several years of refining.

Ejaz and Younis (Shahid and Jamal, 2008) in their study identified biodiesel as vehicular fuel which can be used to replace diesel fuel. The authors also concluded that its renewability and similar fuel properties to fossil diesel make it a potential useful fuel to replace fossil diesel in the nearest future. Biodiesel produced from plant sources can be modified by blending with other fuels such as diesel, biodiesel and biodiesel blends in order to complement the saturation level of fuel and attain better combustion (No, 2011). Among several oil sources, it can be concluded that jatropha oil, depending on variety, is a leading candidate for the commercialization of non-edible vegetable oils for biodiesel production as an alternative diesel fuel in IC engines. For instance, the seed oil of jatropha was used as an alternative to diesel fuel during the Second World War in Madagascar, Cape Verde and Benin (Gübitz et al., 1999). Mofijur et al. (2013) concluded that B10 and B20 blends of jatropha biodiesel can be used in a diesel engine without any modification. The results indicate that viscosities of B10 and B20 are similar to that of diesel. It was observed that BSFC increases as the biodiesel volume increases.

Ogunkunle and Ahmed (2019a) created fuel blends between the range of B5 and B20 from *Parinari polyandra* biodiesel and used them to run a 5Hp diesel engine. The biodiesel blends had properties which were within the ASTM standards for engine fuel. The study showed that the flammability index of biodiesel blends is better because of its higher CN and oxygenated characteristics. The test results of two Euro 3 passenger cars diesel engines, fuelled with saturated and unsaturated biodiesel fuel blends, showed that a maximum 30% blend with fossil diesel can only be permitted due to cold-flow inhibition (Kousoulidou et al., 2012b). The results indicate that higher blending ratio majorly affect the exhaust emissions, alongside the fuel unsaturation level and engine technology. It was concluded that the composition level of saturated and unsaturated biodiesel should be carefully monitored in biofuel markets in order to achieve maximum environmental and operational benefits.

The biofuel potential of different palm oil-based products was evaluated in IC engines and the results showed that a high proportion of palm oil in diesel fuel decreases the heating value of the blend, but the brake thermal efficiency increases for the palm oil/diesel blends (Ndayishimiye and Tazerout, 2011). The treatments applied include preheating palm oil and preparation of palm oil/diesel oil blends, mixtures of palm oil with waste cooking oil, which are all converted into esters by transesterification process. The methyl ester was found useful as an engine fuel without engine modification. Biodiesel produced from different inedible oil seeds have been utilized in blended forms between the range of B5 and B20 with significant similarities to that of fossil fuel combustion in IC diesel engines (Mofijur et al., 2013; Ramadhas et al., 2005b; Kousoulidou et al., 2012b; Puhan et al., 2005; Geng et al., 2017; Suarez-Bertoa et al., 2019; Panwar et al., 2010; Porte et al., 2010; Goga et al., 2019; Fontaras et al., 2014; Can et al., 2017). The biodiesel has better lubricating properties which reduces thermal loss, the HV of blended biodiesel were relatively high for better combustion.

Exploration of recent literature studies show that lower blends of biodiesel increase the BTE and moderates the fuel consumption of CI engines. The exhaust gas temperature increases with

increasing volume of biodiesel in fuel blends. The results established that the use of biodiesel in CI engines is viable and sustainable. Amidst the use of biodiesel as an engine fuel, there lie the problems of low-temperature flow property, thermal and oxidation stability facing the suppliers and end users of biodiesel blends.

The addition of additives to biodiesel has shown to improve its combustion by inhibiting oxidation and thermal degradation of B100 and biodiesel blends. Fuel additives are now gaining interest to meet market demands for viable fuels containing biodiesel blends. Fuel additives can increase fuel economy and reduce emissions either directly or indirectly. Their use allows the operation of the engine to be maintained at ideal conditions over its entire lifespan. For example, oxygenated additives, metal based additives, antioxidants, CN improvers, smoothness and cold flow are used to meet certain automotive specifications and quality (Rashedul et al., 2014). Some research findings show that the most effective method of reducing emissions and improving engine performance is by adding nano additives and using emulsified fuels (Khond and Kriplani, 2016). Common additives used by researchers include di-ethyl ether, methyl oleate, synthetic Mg additives, orange oil, kerosene, methanol, ethanol, etc. Some of these, and many other ones that are used to improve the cold flow properties of biodiesel, engine performance and emission properties were discussed by Ali et al. (2013).

Latest researches show the inclusion of Nano-sized particles in diesel–biodiesel fuel emulsion. The results obtained reveal an enhancement in the thermophysical properties, the heat transfer rate, and stabilization of the fuel mixtures. There are notable reductions in the exhaust emissions and increases in the engine performance parameters depending on the amount of nanofluid additives (Soudagar et al., 2018a). Metal-based additives that are commonly used include CuCl_2 , FeCl_3 , CuO -nano-structured, CoCl_2 and CuSO_4 . They have catalytic effect and are added in diesel and biodiesel based on the necessary requirements. The application is done in nano form and finely dispersed into the fuel using an ultrasonicator (Kannan et al., 2011). The use of these additives also reduces the exhaust emissions (Yang et al., 1998). The commonly used oxygenates are alcohols (methanol, ethanol, propanol and butanol), ether and ester. The fuel-efficient groups in acetoacetic esters include dicarboxylic acid esters and dimethyl carbonate esters (Rashedul et al., 2014). The addition of oxygenates will minimize the ignition temperature of biodiesel, stabilize the fuel combustion potential, and also reduce the smoke emissions (Ribeiro et al., 2007). Certain additives, such as nitrites, peroxides nitrates, aldehydes and tetra-azoles, are meant to improve the CN. Alkyl nitrates are commercially used with evidences of good outcomes. Alkyl nitrates have been tested as the most essential additives in commercial improvement of CN. The type which has been used for years is 2-Ethylhexyl, and has become general additive for improving CN (Stein et al., 2010). Examples of antioxidant additives include BHA, BHT, PL, DPA, TBHQ and PG. The successful ones from literature include TBHQ, PL and PG. (Karavalakis et al., 2011; Schober and Mittelbach, 2004).

Nano-additives that were synthesized from different sources such as ferrous material, polymeric materials, ceramics, non-organic materials, metal oxides such as aluminium, carbon, titanium, iron, and CNTs have been mixed with diesel–biodiesel blends and their effects studied in many literatures (Khond and Kriplani, 2016; Ali et al., 2013; Soudagar et al., 2018a; Vijay Kumar et al., 2018a). The fuel additives are reported to have the capability to increase the oxygen level in the engine, reduce the exhaust emissions, improve the fluid flow properties, reduce the ignition delay for better combustion and increase the viscosity index (Ribeiro et al., 2007). The conclusion of Vijay Kumar et al.

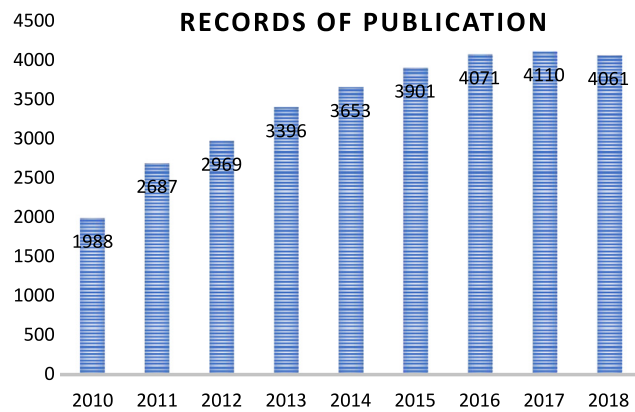


Fig. 4. Research publication records on biofuel production and application from 2010 to 2018.

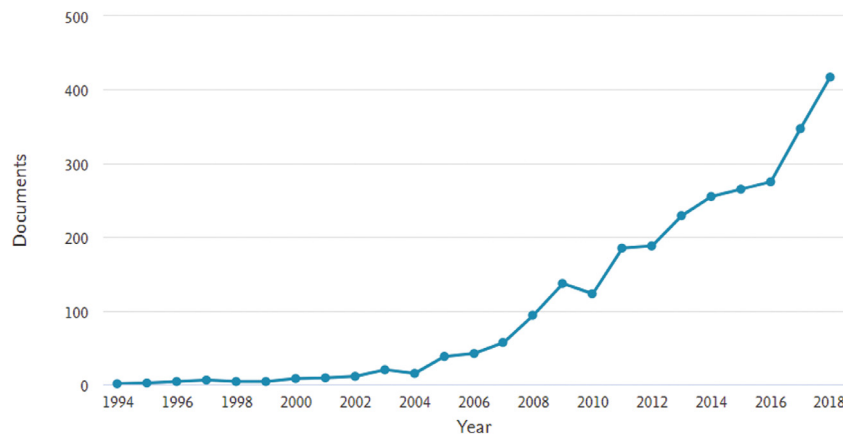


Fig. 5. Publication trend by year on application of biodiesel in vehicular diesel engines.

(2018b) reveals that the improvement of combustion performance and reduction of emission characteristics of biodiesel can be achieved through the use of additives to the 2nd generation of biodiesel.

4. Recent trends in scientific publications for engine performance using biodiesel as fuel

In search of a renewable alternative fuel that can suitably replace fossil fuels and the environmental impacts consideration of emissions from petrochemical products, researchers have directed their interests to biomass-derived fuels. This appears to be the logical solution to the environmental concerns, energy security challenges and socioeconomic issues facing the conventional petrol–diesel. According to the records of Web of Science, publications records (Fig. 4) focusing on development of biofuels and their applications in several areas have increased from 1988 in 2010 to 4061 in 2018, with records to show the spatial distribution all around the globe.

Scopus analysis for scientific contributions on the application of biodiesel as vehicular engine fuel suggests how research interest in this area has increased over the years. It is evident that the utilization of biodiesel fuel in diesel engines is gaining successful application as the publications by year showed increasing trend as reflected in Fig. 5. One (1) publication was recorded on the use of biodiesel in diesel engine in 1994 while the number has increased over the years gradually to 418 documents from different parts of the world in 2018. The documents by country analysis recovered a total of 2736 peer-reviewed documents related to performance of biodiesel combustion in vehicular diesel engines

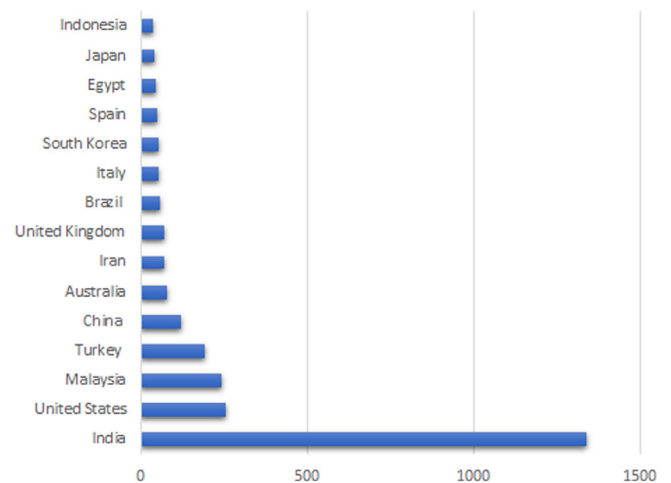


Fig. 6. Publications by country on application of biodiesel in vehicular diesel engines.

between 1994 and 2018, with India leading 1339 publications. The distribution of journal publications counts for fifteen leading countries where biodiesel fuel technology is being used as fuel in diesel engines is shown in Fig. 6. Venezuela, Paraguay, Qatar, Rwanda, Slovakia, Sudan, Tunisia and Trinidad and Tobago are some of the countries with the lowest research interests, having just one publication each on this subject area.

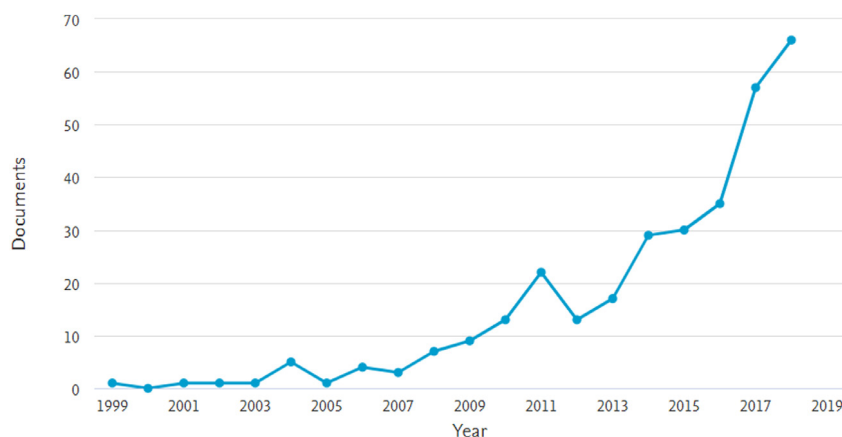


Fig. 7. Publication trend of documents by year for application of fuel additives in biodiesel combustion technology.

It is worth noting that there has been an increasing number of publications on the use of fuel additives to improve the combustion efficiency of biodiesel in vehicular diesel engines. Of the total publications recorded in this study area, about 12% focused on application of fuel additives to improve the engine performance and reduce the GHG emissions from the engine exhausts. The application trend (Fig. 7) varied from the first publication in 1999 to 66 scopus indexed documents in 2018.

The increasing trend observed between these years shows that application of fuel additives is gaining popularity in the transportation sector for improvement of engine performance and reducing harmful emissions. However, this technology, most especially the usage of Nano additives, need more research capacity and concerted efforts to make it an adoptable technology.

5. Advantages of using biodiesel

The benefits of using biodiesel in IC engines are profound and are marked for its wider applications based on the following highlights:

- Diesel engines have proved to be more efficient than petrol engines in term of energy conversion and power output (Goga et al., 2019; Ghobadian et al., 2009; Eguchi et al., 2015; Qi et al., 2009; Reza Miri et al., 2017).
- The efficiency of engine shelf-life can now be prolonged while reducing the costs of procurement of early replacement.
- Biodiesel are clean burning fuels. The combustion of biodiesel in IC engines reduce the release and impact of GHG. Literature studies suggest that the combustion of biodiesel reduces GHG by 40%–65% (Hanaki and Portugal-Pereira, 2018; US EPA, 2018). Compared to the last 20 years, GHG of major cities with high automobiles usage in the world will be reduced by more than 20% (International Energy Agency, 2019).
- Better thermal efficiency from friction reduction as a result of smoother lubricating quality of biodiesel–diesel blends (Ogunkunle and Ahmed, 2019a; Enweremadu et al., 2011; Adailah and Alqadah, 2012).
- The raw materials for biodiesel production are organic and easy to source. More biodiesel products can be made available from different plant oil materials and waste oil (da Silva et al., 2018).
- Biodiesel is renewable and does not give rise to global warming due to its closed carbon cycle. Amount of the carbon taken by plants are returned back to the atmosphere. Biodiesel is carbon neutral because it contributes zero emissions to global warming.

- Biodiesel is non-toxic and also safe to transport from one point to another owing to its relative high flash point.
- Provision of foreign exchange earners. The availability and abundance of feedstock oil seeds in specific areas have created job opportunities for local farmers in creating more plantations of the feedstocks and increasing the production for foreign exchange.

6. Impact of biodiesel combustion on engine performance and emissions

Current research investigations have presented that biodiesel can help in enhancing the performance and reducing harmful exhausts in a diesel engine (Goga et al., 2019). The study of the impact of biodiesel on engine power and torque show that there is no major difference in engine power when pure biodiesel or diesel fuel is used to run the engine. (Ogunkunle and Ahmed, 2019a; Ghobadian et al., 2009; Qi et al., 2009; Lapuerta et al., 2008; Keskin et al., 2008; Oğuz et al., 2007). Amazing increases in power or torque of an engine from pure biodiesel were reported by some researchers (Song and Zhang, 2008; Al-Widyan et al., 2002). For instance, it was found that the difference in maximum and minimum engine power and torque at full load between petrol–diesel and some plant oil biodiesels were only 1.49% and –0.64%, 1.39% and –1.25%, respectively (Lin et al., 2009). This was caused by higher BSFC, higher oxygen content and higher combustion rate of biodiesel. Qi et al. (2009) reported that soybean oil biodiesel demonstrated similar combustion properties to that of diesel, and that the power outputs were almost identical. There was also significant reduction in CO, THC, NOx and smoke under full load conditions.

Song and Zhang (2008) reported an increase in the engine BP and torque as tobacco oil biodiesel content increased in the fuel blends. The improved power produced by the engine while running on pure biodiesel could reach 70% relative to diesel fuel (Al-Widyan et al., 2002). Ghobadian et al. (2009) studied the performance and exhaust emission analysis of a diesel engine using WCO biodiesel and diesel blends at different engine speeds. The results show that the combustion of WCO biodiesel blends produced better engine performance and cleaner emissions. Also, the combustion of lower blends (B5) of castor oil biodiesel in a diesel engine increased the break thermal efficiency and reduced the fuel consumption. The exhaust gas temperature also increased with increasing biodiesel concentration (Panwar et al., 2010). Additionally, the combustion of canola biodiesel blends under different load conditions revealed that heat release rate decreased gradually with the reduction of premixed combustion fractions and caused increase in the combustion proportions when canola

Table 2

Summary of current findings on emissions from diesel engines fuelled with biodiesel blends.

Feedstock	Fuel blends	Engine condition	Emissions reduction compared to petrol diesel (%)				Author
			CO ₂	CO	HC	NOx	
Jatropha	B100	1500 and 2000 rpm	–	–20 to –25	–17 to –23	–0.3 to –4.5	Huang et al. (2010)
Soybean	B100	250 bar at 2400 rpm	–	–33	–	20	Çelikten et al. (2010)
Soybean	B5, B20, B50, B85	9.6–35.7 kW	–0.89 to 1.48	28 to 48	–9 to 18	–	Valente et al. (2010)
Soybean	B10, B20, B30, B40	Full load, 1400–2100 rpm	–	–27	–27	–5	Qi et al. (2009)
<i>E. sativa</i>	B10	5.88 kW at 2600 rpm	160	–30	–	108	Chakrabarti et al. (2011)
Waste oil	B20, B40, B80, B100	1500 rpm, 0–5 kW	–	–31	–57	18.33	Nantha Gopal et al. (2014)
Waste oil	B5, B10	0.12–0.48 MPa, 2200 rpm	3.3 to 5	–11.8 to –51	–2 to –29	6.4 to 8.7	Can (2014)
Waste oil	B10, B30, B50	Full load, 1000–2000 rpm	8.7 to 38.5	–3.3 to –26.3	–	4.7 to 19.0	Chuah et al. (2015)
Waste oil	B5	Full load, 1000–2500 rpm	–	–8.5	–28	–24	Khalife et al. (2017)
Jatropha	B10, B20, B30, B50	Full load, 1500–2400 rpm	13.08	–16.3	–7.4	27.25	Ong et al. (2014)
Jatropha	B10, B20, B40, B50	1900 rpm	–40 for B50	150 for B50	–	99.05 for B50	Dharma et al. (2017b)
Jatropha	B5, B10, B20, B30	20% to full load	20 for B20	–19.6 for B20	–22.6 for B20	23 for B20	Chauhan et al. (2010)
Waste oil	B25, B50, B75	0–25 kW	8.5 for B50	20.1 for B50	23.5 for B50	4.8 for B50	Valente et al. (2012)
<i>Chlorella protothecoides</i>	B20, B50, B100	1700 to 2900 rpm	–0.7 to –4.2	–12.3 to –28	–	–2.4 to –7.4	Al-lwayzy and Yusaf (2017)
<i>Chlorella protothecoides</i>	B100	1500 rpm, Varied load	–	–31	–27	–13	Satputaley et al. (2017)
<i>Chlorella vulgaris</i>	B2	2200 rpm, 50% load	–	–0.34	–50.2	2	Kennedy Mwangi et al. (2015)
<i>Chlorella vulgaris</i>	B10, B20		–3.4 to –5.4	–41.8 to –47.4	–44.3 to –51.1	1.9 to 5.1	Tayari et al. (2020)

biodiesel ratio was increased (Can et al., 2017). There were higher NOx emissions, reduced smoke, CO, THC and higher CO₂ emissions for all loads. The oxygenated nature of biodiesel influences its complete combustion in engines, and thus lower CO and HC emissions are often released from biodiesel combustion in engines (Hoekman et al., 2012; Rajasekar et al., 2010).

The BSFC of IC engine increases with increase in biodiesel volume in fuel blends (Saravanan et al., 2007; Kegl, 2011; Armas et al., 2010). A higher biodiesel consumption by the engine is based on the difference in the energy content per gallon compared to diesel fuel. Demirbas (Demirbas, 2008) reported that biodiesels have relatively LHVs. The values, which range from 39 to 41 MJ/kg, are slightly lower when compared those of gasoline (46 MJ/kg), petrol–diesel (43 MJ/kg), or petroleum (42 MJ/kg), but greater than coal (32–37 MJ/kg). As engine delivers fuel on volumetric basis, more biodiesel is supplied for combustion to compensate the LHV (Qi et al., 2009). The exhaust gas temperature increases just as biodiesel volumes increases in the fuel blends (Ogunkunle and Ahmed, 2019a; Vijay Kumar et al., 2018a). This has majorly been the reason for the increased NOx emissions from biodiesel combustion. High gas temperature reacts with atmospheric air which in turns forms oxides of Nitrogen from the combustion of atmospheric Nitrogen. The BTE of diesel engines is lower when run on biodiesel than diesel fuel. The low calorific value, high volatility and poor spray properties of biodiesel are found to be responsible for the increased BTE efficiency Bhaskar (Chauhan et al., 2013; Bhaskar et al., 2014).

Summarily, it was found that blending of biodiesel with diesel increases both the cetane number and oxygenated chemical compounds of the fuel which improves the overall combustion and reduces the gaseous emissions which increase global warming level and are also hazardous to health (Mani and Ernestas Šutinys, 2016). A summary of current researches which report reductions in the gaseous emissions compared to petrol–diesel is presented in Table 2. The United States Environmental Protection Agency (USEPA) 2018 reports (USEPA, 2018) identified CO, PM, NOx and VOCs as the major transportation pollutants that contribute to smog formation and poor air quality. All these are emitted basically from combustion of fossil fuels and they have negative impacts on the health of US citizens. The good fortune is that biodiesel combustion reduces CO, unburned HC and PM even from older engines. High-level reduction of GHG emissions continue to happen as biodiesel fuel remains the best carbon footprint of any US produced fuel. The emissions reduction percentage indexes from the use of biodiesel fuels wholly or partly in diesel engines in the US in 2018 are recorded in Table 3. These values are based on how the fuel blends are used in the vehicle (tank-to-wheel). These are important reasons why perceptive customers are shifting toward using biodiesel.

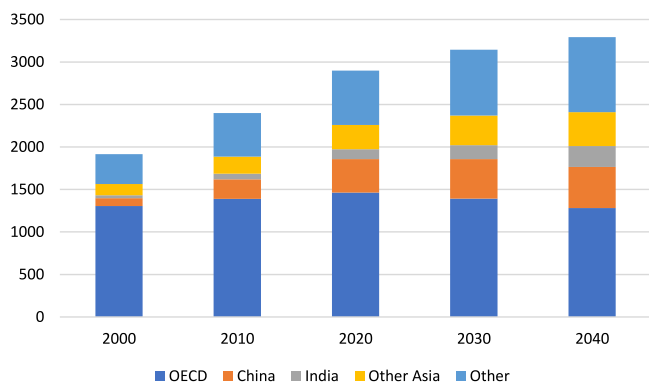
As stated in Section 3, the performances of biodiesel can be improved in IC engines with the use of different fuel additives (Soudagar et al., 2018a; Kannan et al., 2011; Ribeiro et al., 2007; Vijay Kumar et al., 2018a; Sivalakshmi and Balusamy, 2014). The addition of these fuel improvers in biodiesel is inherent for improving the fuel properties, engine performance and

Table 3

2018 emissions reduction in biodiesel in US.

Source: National Biodiesel Board (US EPA, 2018).

Emissions type	B100	B20
Regulated emissions		
Unburned THC	−67%	−20%
CO	−48%	−12%
PM	−47%	−12%
NOx	+10%	+2% to −2%
Non-regulated emissions		
Sulfates	−100%	−20% ^a
PAH	−80%	−13%
nPAH	−90%	−50% ^c
Ozone potential of speciated HC	−50%	−10%

**Fig. 8.** Global transportation demand by fuel.

emission control (Rashedul et al., 2014). Extensive use of this can be found in several literatures (Khond and Kriplani, 2016; Ali et al., 2013; Ribeiro et al., 2007; Vijay Kumar et al., 2018a; Soudagar et al., 2018b; Berghthorson and Thomson, 2015).

7. Global status of biodiesel adoption as vehicular fuel

Many countries have introduced biodiesel production and commercial feasibility into their energy industries (Lobo et al., 2009). An early consideration of alternative fuels for future possibility previously took place during the 1980s (Heywood, 1981). These efforts were made to find alternative solutions to energy security and sustainability, as well as seek advantages of alternative fuels to improving engine efficiency and reducing harmful emissions. According to 2017 reports of The Outlook for Energy, a worldwide view of demand and supply for energy through 2040 shows that the demand for both diesel and gasoline will keep increasing, with the former taking the lead. However, as the demand for energy in the transportation sector keeps increasing in the shortest period, the ratio of biofuel blending to the total quantity of fuel is also expected to increase and eventually lead to substantial reduction of the net GHG emissions on a long-term viewpoint (ExxonMobil, 2017; IEA-International Energy Agency, 2014). From a practical perspective, the vast use of biodiesel in diesel engines would guarantee the dual possibility of ensuring the world has access to cheap and reliable energy supplies while reducing emissions to solve the problem of climate change. Biofuels represent around 3% of the total global transportation fuels by 2012 (IEA, 2012). The global energy demand in the transportation sector is expected to rise steadily at an average rate of 1.3% per annum as shown in Fig. 8 adapted from 2018 BP sustainability report.

A thorough review of the 2018 reports of World Energy Issues Monitor shows that there has been apparent constant advancement of the global energy sector towards a more transformed

global energy blend penetration and shifting toward renewable energy technologies. World biofuels production has increased by an average of 11.4% in the last ten years. In 2017, an increase of 3.5% was recorded. Global ethanol production grew at a similar rate of 3.3% contributing over 60% to total biofuels growth (World Bioenergy Association, 2017). The biodiesel production increased by 4% in 2018, driven mainly by growth in Argentina, Brazil and Spain (British Petroleum, 2018). Major supplying countries of biodiesel are notably Indonesia, India, China, Norway, Hong Kong, with Argentina taking the lead in production and supply of rapeseed biodiesel to the EU countries (Eurostat, 2018). According to 2018 Biodiesel Market Report, the biodiesel market is expected to grow remarkably in the period between 2018 and 2023 (REN21, 2018).

Governmental support, favourable policy and public support are capable of playing an important role in the development of biodiesel industry in any country of the world (Azad et al., 2016; Hochman et al., 2008). Important tools needed by the government include investment in research and development, price subsidies and renewable energy policy to promote biodiesel production and adoption by users (Lin et al., 2011; Chu and Majumdar, 2012; Qiu et al., 2012). Research and development have become a major driving force in the biodiesel industries by improving the technology of processing and production of biodiesel from individual feedstock (Lim and Teong, 2010b). The growth in the global biodiesel market can be associated to the enterprising implementation of biofuel policies in various nations including US, Argentina, Brazil, and Indonesia. For instance, the U.S. Renewable Fuel Standard (RFS) requires increased volumes of renewable fuels each year, with the current plan estimating companies to blend a total of 19.24 billion of renewable fuels in the country's fuel supply by 2019. The regulations regarding the formulation of fuel in these regions are expected to increase the share of biodiesel, thereby increasing the demand. So far, the Economic Impact Analysis has shown that biodiesel usage has supported a total of 64,000 jobs in US and generated \$11.42 Billion (USEPA, 2018).

7.1. Biodiesel adoption policies by continent

7.1.1. North America

In North America, Diesel and Gasoline powertrains are envisaged to continue their influence on the commercial vehicle sector in the EIA forecasts through 2025. Diesel, HEV diesel and PHEV diesel powertrains together are estimated to make up nearly 62% of U.S. commercial vehicle registrations by 2025 (Doa, 2008). The critical question that has arisen from this is: can those diesel engines be operated in a cleaner and more sustainable way without sacrificing the performance of the engines? The good news is yes; it can be done. Biodiesel blends, which are readily available in the marketplace of America, Asia and Europe, can be used in old and modern diesel engines without modification (Silva et al., 2016b,a). The Canadian government has used production subsidies to promote excessive growth in biodiesel production. There is a mandate on fuel blends to support the policy reduction of GHG emissions. Half of the domestic biodiesel production comes canola oil (Naylor and Higgins, 2017). The Canadian and US market share base case of commercial vehicle registration are shown in Fig. 9 and Table 4 respectively.

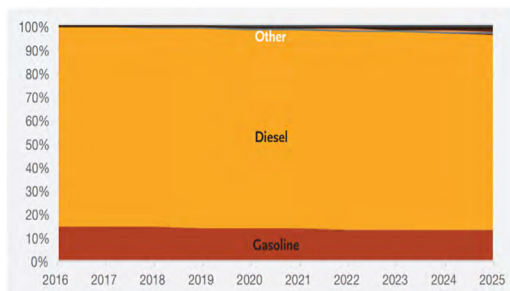
According to the US National Biodiesel Board, 2.1 billion gallons of biodiesel was used by 3.8 million US consumers in 2015 which led to reduction of carbon emissions by a round figure of 18 million metric tons (about 78% less lifecycle greenhouse gas than petroleum diesel). Biodiesel has continued to succeed as America's first and only EPA-recommended biofuel, demonstrating its ability to attain large scale production. About 14.9 million acres

Table 4

US market share base case of commercial vehicle registration.

Source: EIA (2008).

	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Gasoline	35.10%	35.19%	35.29%	35.36%	35.41%	35.45%	35.46%	35.46%	35.45%	35.42%
Diesel	63.61%	63.34%	63.06%	63.78%	63.50%	63.21%	63.93%	63.64%	63.35%	63.07%
HEV Gasoline	0.06%	0.06%	0.07%	0.08%	0.10%	0.11%	0.13%	0.15%	0.17%	0.19%
HEV Diesel	0.13%	0.15%	0.18%	0.22%	0.27%	0.33%	0.39%	0.46%	0.53%	0.61%
PHEV Gasoline	0.01%	0.01%	0.01%	0.02%	0.03%	0.03%	0.04%	0.06%	0.07%	0.08%
PEH Diesel	0.01%	0.01%	0.02%	0.03%	0.05%	0.07%	0.09%	0.12%	0.15%	0.18%
BEV	0.02%	0.03%	0.05%	0.07%	0.09%	0.11%	0.14%	0.16%	0.19%	0.23%
FCV	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.01%
CNG	0.56%	0.64%	0.73%	0.81%	0.90%	0.98%	1.07%	1.15%	1.23%	1.32%
LNG	0.20%	0.21%	0.22%	0.23%	0.23%	0.24%	0.24%	0.24%	0.25%	0.25%
PAGV	0.31%	0.34%	0.37%	0.40%	0.44%	0.47%	0.51%	0.56%	0.60%	0.65%

**Fig. 9.** Canada market share base case of commercial vehicle registration.
Source: EIA (2008).

of mature forests have been preserved while 466 million oil trees were planted. The USEPA has submitted that users are looking out for cleaner substitutes to petroleum products and they see biodiesel as a superior, cost-competitive alternative to petrol-diesel. As at 2014, domestic production of biodiesel was 1.47 billion gallons in 2014, while imports increased from 510 million gallons in 2014 to an estimated 670 million gallons in 2015, a pointer to biodiesel's rising popularity in the US. These numbers also prove that the biodiesel usage standard is absolutely working by introducing notable volumes of improved biofuel to the American people.

7.1.2. Latin America

Brazil is currently one of the world leading producers of bioethanol and biodiesel production (Silva et al., 2016b,a). Biodiesel production in Brazil has increased from 736 million litres to approximately 2.7 billion litres between 2005 and 2011 (Geraldcastanheira et al., 2014). The great extension of land and variety of climate and soil in Brazil favour cultivation and growth of different oilseeds that can be used for biodiesel production (Quadros et al., 2011). An adaptation (Fig. 10) of the major feedstocks used for biodiesel production in 2017 is taken from da Silva et al. (2018). An increase in biodiesel utilization was experienced in Brazil from January 2008 to November 2014 as blending level increased from 2% to 7% (Quadros et al., 2011; Oliveira et al., 2017). Until 2012, Soybean biodiesel has accounted for more than 85% of the total biodiesel output in Brazil. The increase in biodiesel is borne out of the policy to promote renewable energy and efficient use of biodiesel. This has seen Brazil emerged as the third largest producer of biodiesel after the US and Germany (Naylor and Higgins, 2017). There are indications that domestic demand will increase to 6 billion litres of B7 and 8.6 billion litres of B10 in the year 2023, as predicted by the Decennial Energy Extension Plan (De Oliveira and Coelho, 2017). The reality of biodiesel in the Brazil has guaranteed the country a leading place in connection to the rest of the world. The level

of biodiesel production and usage heighten the engagement of biofuels in the national energy market and portrays Brazil as a country that consider the variation of energy sources (da Silva et al., 2018). In 2017, it was legislated to add 8.0% biodiesel to the diesel fuel sold to the final consumer (Shimamoto and Tubino, 2016), and that content will be raised to 10% in March 2019 (Brasil, 2016).

Argentina is another country well known for biodiesel production, promotion and exportation, with the bulk of their production coming from soybean, sunflower, safflower, rapeseed, and peanut vegetable oils (Lamers et al., 2008). Much of the biodiesel produced in Argentina is being exported. Sixty percent of 2.78 billion litres produced in 2012 was exported (Rico and Sauer, 2015). Seventy percent of their production between 2008 and 2014 was also exported (Naylor and Higgins, 2017). The evolution of biodiesel industry in Peru has led to recognition of palm oil and jatropha as two major potential feedstocks for biodiesel production. Biodiesel fuel blends have increased from 2.0% in 2009 to 5.0% by 2011 as a result of increase in demand and usage of biofuel in diesel engines (Andres Quintero et al., 2012). Such development has continued to strengthen biodiesel production in the Amazon up till present time. In encouraging biodiesel production and its commercial potential, the Colombian government has legislated policies mandating the use of blends of diesel and biodiesel with appropriate tax exemptions and subsidies provisions. Colombia has the potential for high biodiesel production as they are currently the fourth largest producer of palm oil in the world. The blending mandate, which was set by the Colombian government in 2015, endorsed B10 for remote rural areas while the industry regulated at approximately B8 (Naylor and Higgins, 2017).

7.1.3. Europe

The Europe marketplace has a big possibility in countries like India, UK, and China, because of the growing diesel costs and huge quantity of diesel cars. With the growing existing feedstock efficiency, the marketplace will probably have a pattern shift within the forecast range. In the upcoming years, the possibility of biodiesel production from new feedstocks like algae has been predicted. The Europe region is a noteworthy biodiesel producer with France and Germany serving as the pinnacle producers (REN21, 2014). The policy framework for the development of a biofuels market in the European Union (EU) and the promotion of their use or other renewable fuels for transport is Directive 2003/30/EC (Jones et al., 2007). For instance, the progressive use of biofuels as an alternative transport fuel has become mandatory for the partial substitution of diesel with biodiesel and bioethanol derived from agricultural sources. Furthermore, gaseous and liquid biofuels and other renewable fuels should substitute refined fossil fuels wholly or partially (blends) in their respective varieties.

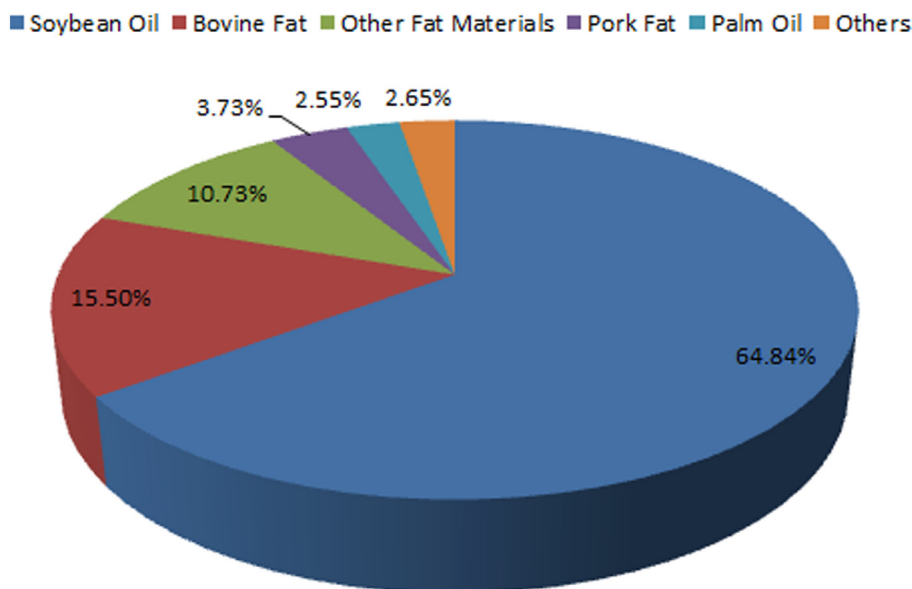


Fig. 10. Raw materials utilized for biodiesel production in Brazil in 2017.

The 28 member countries of the EU are increasingly covering its demand for energy with biodiesel imports, even though they remain as the world's biggest producer of biodiesel. Their production capacities have not been fully explored with their accomplishment of 3.9 billion gallons of biodiesel production including renewable diesel. However, more than 990 million gallons of biodiesel were imported from third world countries in 2018, a value three times more than a year earlier. The leading recipients of biodiesel imports remain the Netherlands, Spain and Belgium owing to the large storage magnitudes at their ports. Biodiesel products are transported to other EU countries from these places (Eurostat, 2018). The index of EU imports of biodiesel and their major importers are shown in Fig. 11.

The EU's plan to meet demand for low-carbon fuels has seen Targray, a leading international marketer of biodiesel, opened a trading desk in Geneva, Switzerland. This is part of the increasing plan to create sustainable value for customers in the EU countries. Also, biodiesel production and usage in diesel engines in Germany have continued to project higher. The recent report of Germany's biodiesel quality management association (AGQM) show that biodiesel imports to Germany increased more in 2018, reaching a quality mark of 1.2 million tons including HVOs. The Netherlands, which are Germany's main supplier, have supplied in excess of 620,000 tons of biodiesel/HVO in 2018, more than twice the previous year's amount.

7.1.4. Asia

The government of Thailand established a B7 mandate in 2012 which led to the formation of the Alternative and Renewable Energy Development Plan. Thailand has basically enlarged its biodiesel production sector mainly from palm oil, being the third largest producer after Indonesia and Malaysia (Naylor and Higgins, 2017). Indonesia is gaining freedom from total independence on fossil fuels through the production and use of palm biodiesel (Indrawan et al., 2017). Biodiesel production costs in Indonesia are the lowest compared to other countries because the fuels are being subsidized and this had led to rapid growth of the industry in Indonesia (Rico and Sauer, 2015). By 2025, the Indonesian Ministry of Energy and Mineral Resources (MEMR) seek to revolutionize domestic consumption of biodiesel by establishing a policy to substitute 15 and 20% of petrol–diesel fuels with bioethanol and biodiesel, respectively (Indrawan et al.,

2017). Malaysia as the second largest producer of palm oil after Indonesia has enough reasons and resources to promote biodiesel production on industrial scale. Currently, the country meets its B7 (7% biodiesel in fuel blend) biodiesel mandate (Naylor and Higgins, 2017) after the National Biofuel Policy introduced 5% biodiesel blend (B5) officially in 2009 (Ashnani et al., 2014). Taiwan has surfaced on the list of countries which have decided to increase biodiesel production with a projection of 150 million litres per year by 2020 (Huang and Wu, 2008). This was fostered by the consensus at the First National Energy Conference in 1998 to encourage the application of clean energy in Taiwan. Xu et al. (2016) reported on the Chinese capacity to develop a brilliant biodiesel industry that will add more potential to the global trend of biodiesel development. The major raw materials that are currently used for biodiesel production in China are rapeseed oil, cottonseed oil and jatropha oil, with the expectation of replacing them with waste vegetable oil and microalgae in the future.

The government has encouraged the use of biodiesel in Turkey by legislating that marketable diesel fuel should contain 1.0% MEFA from January 1, 2014. This figure has however increased to 2.0% in 2015 and 3.0% in 2016. Turkey, which have great production capacity for cotton and sunflower, produced 17,729 tons and 21,876 tons of biodiesel in 2012 and 2013 respectively (Eryilmaz et al., 2016). Biodiesel production has become an essential commodity in Iran as energy demand was expected to increase from 2003 to 2030 by an average of 2.6% yearly. Oilseed yields for possible biodiesel production in Iran were seen to be 3,678,540.43 tons from 2007 to 2008. Feedstocks such as canola, cotton and soybeans, are the promising sources of biodiesel in Iran while olive, sesame, safflower, sunflower, corn, almond and coconut remain potential sources of oil (Safieddin Ardebili et al., 2011).

7.1.5. Africa

Biodiesel production in Africa is emerging as a good prospect in the last ten years. The future of biodiesel production in Africa looks promising as it is one of the fastest growing continents in the world. Africa is endowed with a land mass of over 30 million km² which is equivalent to combined land masses of the United States of America, Brazil and Japan (Yang et al., 2014). Africa appears to have the capacity to become the single largest producer

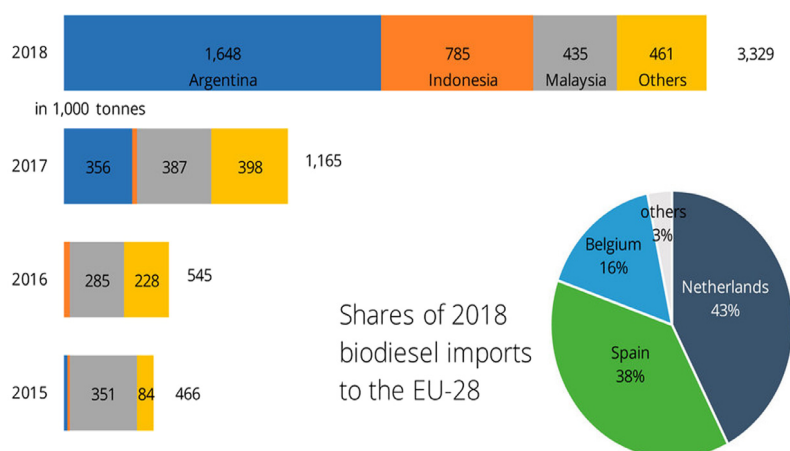


Fig. 11. EU biodiesel imports index and their major importers.
Source: Eurostat (2018).

of bioenergy crops for the global production of biodiesel (Wolde-Georgis and Glantz, 2010). Africa with the fastest growing population according to 2019 United Nations reports on global issues, biodiesel production and usage along with abundant fossil fuel reserves will offer Africa some prospect of energy sufficiency and environmental protection based on the comparative advantages. Estimated reports from the World Bank (2008) and Müller et al. (2008) show that biodiesel will constitute 60%–80% transport fuel in Africa by 2030. Scientific researchers have therefore shifted their attention to exploring several non-edible oil seeds, which are abundant in African rain forests, in order to overcome the food security problems associated with the use of edible oils. The authors have been able to work on some inedible oils seeds (Oyelade et al., 2017; Ogunkunle et al., 2017; Ogunkunle and Ahmed, 2019b; Oniya et al., 2017a), while exploring other promising ones for sustainable production of biodiesel.

African countries, such as Ghana, Zambia, Liberia, Tanzania, Ethiopia, Nigeria, Senegal, Kenya and South Africa, are emerging as commercial producers of biodiesel with large-scale investment projects. Africa is blessed with vast number of inedible oil plants which are widespread in many parts of the continent. The common feedstocks which present adequate properties for biodiesel production include jojoba, mahua, castor, and karanja (Yang et al., 2014). The most populous non-edible feedstock for biodiesel production in Africa is jatropha. There are searches for other relative seeds with high oil yields as jatropha cannot encourage biodiesel production for Africa's future energy security (Wood, 2005). Biodiesel production in Africa has led to the discovery of abundant oil seeds with good potential for biodiesel production. The biodiesel potentials of different non-edible feedstocks in selected African countries are recorded in Table 5. Several factors, among which are prices of crude oil, price instability, environmental impacts caused by fossil fuels, obligatory legislation from developed countries (UK, Germany, Japan, USA, etc.) on the use of biodiesel blends in the transport sector, creation of jobs, advances in research and technological, and the need to meet the increasing demand for fuel, contribute to the increasing production level of biodiesel in Africa (Wolde-Georgis and Glantz, 2010; Amigun et al., 2011; Prasad and Visagie, 2005).

7.1.6. Oceania

Beauty leaf oil and Castor oil have been identified as the two major on-edible oil prospects in production of biodiesel in Australia (Azad et al., 2016). The Australian Biofuel Research Institute (ABRI) was established in 2010 to centre on production of second and third generation of biodiesel (Australian Biofuel Research

Institute, 2015). This project is focused on capturing atmospheric carbon and also neutralize it when biodiesel is burned in engines. The Australian Government is solely responsible for funding ABRI through the Australian Renewable Energy Agency (ARENA). A sum of \$20 million AUD was set aside for funding renewable energy projects with \$5.0 million for supporting algal biodiesel production and research proposals from across Australia (Australian Biofuel Research Institute, 2015).

Collaborative research works were found between the institute and some universities in Australia (Azad et al., 2016). The Australian Government has recently revised her position on use of biodiesel in the transport sector as part of "Clean Energy Initiative" and progress into new renewable energy technologies (Programs, 2010). For instance, State governments in New South Wales and Queensland have enacted mandates for B4 (4% biodiesel in fuel blends) and E5 (5% ethanol in fuel blends) (REN21, 2017). Some considerable measures have been taken concerning generation of clean energy through Australian renewable energy policy. The main objective of the Australian clean energy council is to produce 20% of national grid supply from renewable resources by 2020. Reports from Puri et al. (2012) showed that the Australian government has been able to increase researches focused on production of biofuel by investing AUD \$5.1 billion over the coming decade (Programs, 2010).

7.2. Projected progress and use of biodiesel

From a global perspective, biodiesel is anticipated to form 70% of transport fuel to be demanded for by the year 2040 (Exxon-Mobil, 2017; Naylor and Higgins, 2017). The development of biodiesel industry in many countries has been largely influenced by their goal to mitigate climate change because biodiesel produced from biomass have the carbon-neutral potential (Zhou and Thomson, 2009). The size of biodiesel produced from 2002 to 2013 grew by a factor of 15% (De Oliveira and Coelho, 2017). There is a projected shift of biodiesel demand from 86.1 million barrels/day, to 110.6 million barrels/day by 2035 (EIA, 2008). Fig. 12 shows the highest 14 biodiesel producing countries in 2017 as adapted from Renewable Energy Network (REN21, 2017). Table 6 shows the top major countries with expected high biodiesel production by the year 2030 and the fraction of biodiesel blends expected to be used in vehicle engines. If the development trend achieved by established biodiesel producers can be followed by other developing countries, biodiesel production and adoption in vehicle engines will continue to increase in meeting up the sustainable goal of eradicating fossil fuel combustion.

Table 5

Biofuel potential of promising non-edible feedstocks in selected African countries.

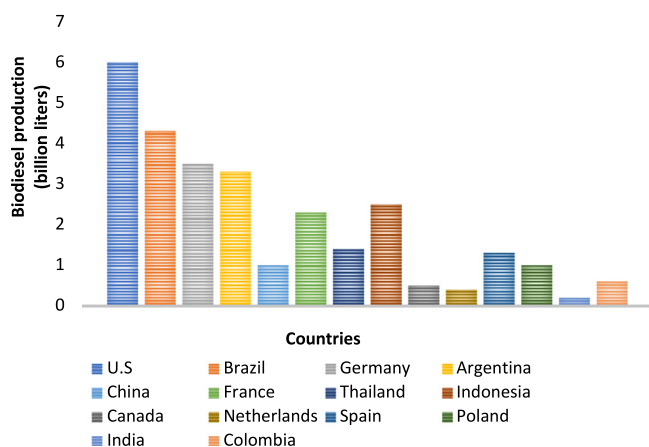
Source: Jumbe et al. (2009).

Country	Raw material	Biodiesel		Bioethanol	
		Megalitres (ML)	Mega Joules (MJ)	Megalitres (ML)	Mega Joules (MJ)
Benin	Jatropha	30	1.3×10^4	20	8.4×10^7
Burkina Faso	Sugarcane	–	–	20	8.4×10^7
Ivory Coast	Molasses	–	–	20	8.4×10^7
Ghana	Jatropha	50	2.1×10^4	–	–
Guinea Bissau	Cashew	–	–	10	4.2×10^7
Mali	Molasses	–	–	20	8.4×10^7
Malawi	Molasses	–	–	146	6.1×10^8
Kenya	Jatropha/Molasses	40	1.7×10^4	413	1.7×10^9
Ethiopia	Jatropha/Molasses	–	–	80	3.3×10^8
Niger	Jatropha	10	4.2×10^7	–	–
Nigeria	Jatropha/Molasses	–	–	70	2.9×10^8
Sudan	Molasses	–	–	408	1.7×10^9
Swaziland	Molasses	–	–	480	2.0×10^9
Senegal	Molasses	–	–	15	6.3×10^7
Tanzania	Jatropha/Molasses	–	–	254	1.1×10^9
Togo	Jatropha	10	4.2×10^7	–	–
Uganda	Molasses	–	–	119	5.0×10^8

Table 6

Top major countries with expected high biodiesel production.

Country	Growth index, %	Expected production (2030), billion litres	Projected use, billion litres	Blending ratio (2030), %
United States	6	8	6.9	15
Canada	8	5	5	10
EU	8	22	14	20
India	11	32.1	31.1	10–20
Brazil	6	5	5.6	25
Argentina	5	11	1.9	30
China	17	5	5	10
ASEAN	8	13	4.1	20

**Fig. 12.** Highest 14 biodiesel producing countries in 2017.

2008; Soukht Saraee et al., 2017; Raheman and Phadatar, 2004; Kataria et al., 2019). The fraction ratio can also be expected to increase based on evolving research studies demonstrating improved use of higher biodiesel blends without any major engine modification.

One of the strongest arguments for biodiesel usage, aside the environmental benefits and good engine performance, is the current production rate relative to its demand. Most of the current world biodiesel producers have increased at an average index of 15% compared to previous years. However, biodiesel consumption could experience a shortfall if higher blending rates is not encouraged in the transportation sector. Most biofuel consumption in many of these countries take place at low level of blending with fossil fuels. Higher blending ratio is expected to meet SDS demand in 2030. Another degree of constraint that could limit the replacement is the commercialization of biofuel. The industrial production of biodiesel in US and EU comes majorly from palm oil which is limited in supply because it is required for consumption in many countries. The commercialization of inedible seed oils needs to be established in order to explore seed oil-derived biodiesel and BtL synthetic fuels. The study has also shown that domestic production of biodiesel is still falling behind as well. The increasing population growth can also be a factor contributing to the production and demand for biodiesel fuel (Hoogeveen et al., 2009). As population increases, the demand for transportation increases, and there comes the need for provision of promising fuels. This must however be sustainable enough in order to meet up with increasing demand. With the current industrialization and commercialization of biodiesel production from limited feedstocks, the scenario will worsen if prompt attention is not shifted to commercialization of vast organic plant oil seeds which have large abundance in the natural forests. More research facts are nevertheless needed progressively to furnish the scientific world with important processing details and quality of biofuels synthesized from oil rich oil seeds.

8. Conclusions

This paper presents a review of current global production and adoption of biodiesel as a vehicle engine fuel based on research findings and essential descriptive statistics garnered from available literatures on the subject matter. It can be concluded that reliance on petroleum-based fuel in the future can no longer hold because the desire for energy security and concern for reducing GHG emissions have led to increased usage of biodiesel fuel. From the studies reviewed, the following conclusions can be made:

According to 2030 projections of Energy Outlook review, increase in energy consumption can only be brought by increased production of energy and industrialization in the developing world. A higher level of biodiesel blending with fossil diesel, B30, is expected to be promoted as alternative fuel in the transport sector by the year 2030. This can be supported by successful existing research studies on engine performance using higher blends of biodiesel–diesel fuel (Kousoulidou et al., 2012a; Dharma et al., 2017a; Fontaras et al., 2014; Dharma et al., 2017b; García-Martín et al., 2018; Hirkude and Padalkar, 2012; Roy et al., 2016; Vedaraman et al., 2011; Abed et al., 2018; Sureshkumar et al.,

1. The high demand for diesel fuel has necessitated the need for renewable biodiesel from cheap sources which can meet the demand without depleting in the near future. From a realistic point of view, the extensive use of renewable biodiesel can directly give rise to improvements in engine performances and emission characteristics.
2. The improved state of things in achieving an effective power conversion from biodiesel combustion with minimal emission impact on the environment has been documented in this work. This has been able to show the global utilization of biodiesel in diesel engines most especially in the transportation sector.
3. An increasing trend is foreseen in the use of biodiesel in diesel engines considering its relative advantages. The worldwide usage adoption was captured according to the rate of production, usage and legislation favouring the economic feasibility of biodiesel products that are compatible and fit for diesel engines without any modification. With the establishment of biodiesel production and major biofuels market all around the globe, the adoption of biodiesel wholly or in blends has been fostered through policies that promote its marketability and use.
4. New jobs are being created to meet up with labour force for expanding industry, and viable foreign exchange earnings keep increasing for importers and exporters of biodiesel fuel.
5. GHG emissions are being reduced using biodiesel in diesel engines, and more can be achieved through the projected increase in biodiesel production and its combustion as fuel.
6. With the advantages offered by biodiesel, its renewable availability and better engine performance characteristics, there is no doubt that manufacturers of diesel engines can go on making good transactions in the automobile market and more end users are expected to acquire these engines with reliability and satisfaction of using biodiesel as the running fuel. Overtime, switching to diesel engines can be expected to revolutionize the future of liquid fuel and power engines in automobile vehicles.

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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