Scope of biodiesel from oils of woody plants: a review

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Abstract

Non-edible oils obtained from chosen non-conventional woody plants are considered as potential raw materials for biodiesel production. These plants mostly grow in wastelands. Structural characteristics of these oils as raw material are very much in tune with the properties of biodiesel such as long-chain hydrocarbon, having an adequate level of unsaturation with branched chain. Four primary methods are being followed to make biodiesel from vegetable oil. They are direct use through blending, microemulsion, thermal cracking (pyrolysis) and transesterification. Non-edible oil would eliminate the issue of food vs fuel. The biodiesel manufactured from oils of woody plants may partially reduce the demand for liquid-fuel energy and addresses the environmental consequences of using fossil fuels. Oil from a total of 17 species of woody plants (Angiosperms) belonging to 14 families are considered in this paper. The habit, habitat and geographical distribution of each species are also presented. The physico-chemical properties of their oil, with special reference to the fatty-acid profile that ultimately decides the characteristics of the biodiesel prepared from them, are reviewed.

Graphical Abstract

Keywords: woody plant oils; biodiesel; transesterification; biodiesel properties
Introduction

Depleting resources of fossil fuels and increasing environmental degradation have stimulated the search for renewable energy sources that are capable of offsetting the fast-increasing energy demand [1, 2]. Biodiesel prepared from vegetable oils is renewable and known to minimize the environmental impact [3–5]. Fatty-acid alkyl esters (FAAE) that form the biodiesel are produced from virgin or used edible and non-edible oils and animal fats. Vegetable oil (triglycerides), as the raw material of biodiesel, is often blended with a desired portion of conventional diesel for use in diesel engines. No major structural alterations need to be made in the architecture of the engine so as to accept this blend [6]. Among the various methods being tried, such as the blending of vegetable oils with diesel, microemulsification, pyrolysis and transesterification [7], transesterification is the settled option for converting vegetable oils (triglycerides) into biodiesel. In the transesterification (alcoholysis) process, the vegetable oil or animal fat is allowed to react with a primary alcohol (methanol or ethanol) in the presence of a catalyst of chemical or biological origin [2, 8].

The quality of the biodiesel thus prepared is mostly influenced by the physical and chemical nature of the feedstock, production method, refining process employed and post-production storage conditions. The quality of the biodiesel is regulated by the standard ASTM D 6751 and EN 14214 in several countries. Other standards, namely DIN 51 606 (Germany), ON (Austria) and CSN (the Czech Republic), are also in practice. Basic properties of the biodiesel are expressed by cetane number (CN), heating (calorific) value (MJ kg⁻¹), density (kg m⁻³), viscosity (mm² s⁻¹), cloud and pour points (°C), flash point (°C), acid value (mg KOH g⁻¹), ash content (%), water content and sediment, copper corrosion, distillation range, carbon residue, sulphur content, glycerine residue (% v/v), phosphorus (mg kg⁻¹) and oxidation stability [9]. The oxygen present in the ester molecule actively promotes combustion and leads to low emission levels. The low sulphur content, high CN, good lubricity and low emission profile are the attractive properties of biodiesel [10, 11]. Emission from biodiesel is free from sulphur and contains carbon dioxide and low concentrations of carbon monoxide and particulate matter.

1 Biodiesel feedstock

The high cost of biodiesel is one of the major hurdles in its popularization or adoption. Biodiesel costs ~US$0.51 per litre, against diesel, which is ~US$0.35 per litre [12]. Since the cost of the biodiesel is being enhanced by the cost of the edible oils as raw material, the market value can be reduced if woody plant oils (non-edible oils) are exclusively used [13]. There is rich scope for getting oils from woody plants, since these plants are liberally available in nature without any agri-management and also there is a large extent of degraded derelict forest that supports such species.

Examples of such woody plants are Hevea brasiliensis (rubber tree) [13], Azadirachta indica (neem), Madhuca indica (mahua), Pongamia pinnata (pongam), Jatropha curcas, Ceiba pentandra (silk cotton tree) [14], Calophyllum inophyllum (punnnai) [15], Sterculia foetida (java olive oil tree), Lesquerella fendleri (deccan hemp), Nicotiana tabacum, Attalea speciosa (babassu), Simmondsia chinensis (jojoba), Cerbera odollam (sea mango), Scheicheira trigua (kusum), Putranjiva roxburghii (lucky bean tree), Thevetia peruviana (yellow oleaneder) [16], Vernicia fordii (tong), Schisandra wilsoniana (sojak) [17], Croton megalocarbus, Eucalyptus salmonophloia (salmon) [18], Salvadoria persica (piliu), Syringa [19], Shoreo busta (sal), Terminalia beleriaoxb (bahera), Camellia sp., Magnolia champaca (champak), Simaroubula glauca (paradise), Garcinia indica (kokum), Balanites aegyptiaca (hingan), Guizotia abyssinica, Syagrus romanzzoffiana (cocos palm), Idesia polycarpa var. vestita, Sapindus mukorossi (soapnut), Melia azedarach (syringe berry tree), Copaifera sp. (copaiba), Euphorbia trigona (miluk bush), Dipteryx odorata (cumaru), Carapa guianensis (andiroba), Caryocar brasiliensi (pigiui), Prunus sibirica (Siberian apricot), Zanthoxylum bungeanum, Xanthoceras sorbifolia [20], Pistacia chinensis, Vernicia fordii (tung oil), Corylus avellana (hazelnut oil), Sapium sebiferum (Chinese tallow oil), Camptotheca acuminata and Hodgsonia macrocarpa [11, 14]. These plants are well suited to arid, semi-arid land conditions with a modest fertility and moisture [14]. They are perennial and predominantly distributed in the subtropics [17]. Oil characteristics to suit the biodiesel manufacture are not well documented in many of the above species. In this paper, only 17 species whose oil is well studied as a potential raw material for biodiesel are presented. Characteristics of the woody plants, including the oil content and the fatty-acid composition of the oil from the seeds, are described below and presented in Table 1.

1.1 Jatropha curcas

Jatropha curcas is one of the most promising, drought-resistant shrubs, originally in existence in Central America, but also found in Southeast Asia, India and Africa [14, 16, 21] and also in regions having an annual rainfall of 250–1200 mm [63]. Its oil has a long-chain (16–18) hydrocarbon. The oil content of the seed ranges from 30% to 50% by weight and it is around 45–60% in kernel [22]. The oil is a rich source of palmitic acid (14.2%), stearic acid (7.0%), oleic acid (44.7%) and linoleic acid (32.8%) [14].

1.2 Pongamia pinnata

Pongamia pinnata is a tree of Indian origin. Hitherto, only 6% of the 200 million tonnes of its seed were being utilized for various applications and the rest is wasted, as it did not find any tangible commercial use [64]. This tree is distributed in India, Australia, Fiji and in certain regions of Eastern Asia [23]. It grows in humid and subtropical places.
| Botanical name                  | Common name               | Country of occurrence                  | Oil content (%) | Fatty-acid profile                                                                 | References |
|-------------------------------|---------------------------|----------------------------------------|-----------------|-----------------------------------------------------------------------------------|------------|
| Jatropha curcas               | Kattamanakku, jatropha    | Central America, South East Asia, India, Africa | 30–60           | Palmitic acid (14.2%), stearic acid (7.0%), oleic acid (44.7%) and linoleic acid (32.8%) | [14, 21, 22] |
| Pongamia pinnata              | Pungai, pongam, karanja   | India, Australia, Fiji, Eastern Asia   | 30–40           | Palmitic acid (3.7–7.9%), stearic acid (2.4–4.8), oleic acid (44.5–71.3%), linoleic acid (10.8–18.3%), eicosenic acid (9.5–12.4%) | [23–25] |
| Azadirachta indica            | Neem, vepam, margosa, ku lian | Asia, Africa, the Middle East, Australia, Central and South America | 30              | Oleic acid (25–58%), palmitic acid (16–34%), stearic acid (6–24%), linoleic acid (6–17%) | [26, 27] |
| Madhuca indica                | Iluppai, mahua            | Asian continent, Australian continent  | 20–50           | Palmitic acid (17.8%), and stearic acid (14.0%), oleic acid (46.3%), linoleic acid (17.9%) | [24, 28, 29] |
| Hevea brasiliensis            | Rubber tree               | India, Indonesia, Malaysia, Liberia, Sri Lanka, Sarawak, Thailand | 40–50           | Palmitic acid (10.2%), stearic acid (8.7%), oleic acid (24.6%), linoleic acid (39.6%), linolenic acid (16.3%) | [4, 14, 30] |
| Calophyllum inophyllum        | Honne, penaga laut, alexandrian laurel, kamani, polanga, tamanu, pinnai | India, Sri Lanka, East Africa, Australia, Southeast Asia, South Pacific | 40–75           | Palmitic acid (12.01%), stearic acid (12.9%), oleic acid (34.09%), linoleic acid (38.26%) and linolenic acid (0.3%) | [31–33] |
| Sapium sebiferum              | Stillingia oil, Chinese vegetable tallow | China, Japan, India, Southern coastal area of USA | 40–70           | Palmitic (76%) and oleic acid (23%) | [34] |
| Prunus sibirica               | Siberian apricot          | China, Eastern Siberia, Mongolia       | 44.73–57.83     | Oleic acid (65.23%), linoleic acid (28.92%), palmitic acid (3.79%), stearic acid (1.01%) | [35, 36] |
| Ricinus communis              | Castor                     | India, China, Central Africa, Brazil, Australia, USA | 45–50           | Ricoleic acid (89.5%), linoleic acid (3–6%), oleic acid (2–4%), palmitic and stearic acid (1–5%) | [24, 37–39] |
| Thevetia peruviana            | Yellow oleander           | America, Mexico, Brazil, West Indies, Asia, Africa | 67              | Palmitic acid (22.10%), stearic acid (7.62%), oleic acid (37.93%), linoleic acid (26.33%), arachidic acid (1.51%) | [40–42] |
| Sapindus mukorossi            | Soap nut                  | Asia, America, Europe                  | 23              | Palmitic acid (4.67%), stearic acid (1.45%), oleic acid (52.64%), linoleic acid (4.73%), a or \(\lambda\) linoleic acid (1.94%), arachidic acid (7.02%), eicosenic acid (23.85%), behenic acid (1.45%), enucic acid (1.09%) | [43–45] |
| Simmondsia chinensis          | Jojoba                     | Mojave, Sonoran deserts of Mexico, California, Arizona | 50–60           | Palmitic (7.38–9.70%), lauric acid, myristic acid, pentadecanoic acid (<0.1%), eicosenic acid (52.36–64.56%), docosanoic acid (6.86–9.95%), oleic acid (16.31–27.36%), linoleic acid (0.37–0.95%), linolenic acid (0.87–2.5%) | [24, 46, 47] |
| Zanthoxylum bungeanum         | Chinese spice oil          | China                                   | 27–31           | Palmitic acid (10.61%), palmitoleic acid (5.19%), stearic acid (1.43%), oleic acid (32.10%), linoleic acid (25.60%), linolenic acid (24.10%) | [48–51] |
| Mesua ferrea                  | Nageshwar (Nahar)          | India, Bangladesh, Sri Lanka, Indonesia, Cambodia | 70–75           | Stearic acid (9.5%), palmitic acid (15.9%), oleic acid (52.3%), linoleic acid (22.3%), myristic acid (2.13%), arachid acid (2.92%) | [52–55] |
| Cerbera odollam               | Sea mango oil             | South India, Vietnam, Cambodia, China, Sri Lanka, Myanmar, Madagascar, Malaysia | 54              | Palmitic acid (24.86%), palmitoleic acid (0.75%), stearic acid (5.79%), oleic acid (52.82%), linoleic acid (13.65%), other (2.13%) | [55–57] |
| Pistacia chinensis            | Kakra shingi              | East Asia, central and southern China, and the Philippines | Above 40        | Oleic acid (47.32%), linoleic acid (31.58%), palmitic acid (17.50%), linolenic acid (1.68%), stearic acid (0.92%) | [58–60] |
| Moringa oleifera             | Moringa, drumstick tree, horseradish tree, benzoil tree | India, Africa, Arabia, Southeast Asia, The Pacific, Caribbean Islands, South America, Philippines, Cambodia, Central and North America | 38–40           | Palmitic acid (6.5%), palmitoleic acid (2.0%), stearic acid (6.0%), oleic acid (72.2%), linoleic acid (1.0), arachidic acid (4.0), gadoleic acid (2.0) | [61, 62] |
with an annual rainfall ranging between 500 and 2500 mm [24]. It is also grown in degraded, waste or fallow lands and is tolerant of fluctuating soil salinity [25]. Each tree can yield 900–9000 kg of seeds per hectare per year. Thus, this tree has the inherent capacity to meet the large-scale manufacture of biodiesel [65]. Its oil has palmitic acid (3.7–7.9%), stearic acid (2.4–8.9%), oleic acid (44.5–71.3%) and linoleic acid (10.8–18.3%). In addition, it contains a little amount of eicosenoic acid (9.5–12.4%) [23, 24].

1.3 Azadirachta indica

Neem (Azadirachta indica) is a tree of the mahogany family, Meliaceae. This is widely distributed in Asia, Africa, the Middle East, Australia, and Central and South America [66]. Neem kernels contain 30–50% oil. This oil is used as an insecticide, lubricant, constituents in soap manufacturing and in medicine for various kinds of ailments [26]. This plant can grow in almost all types of soils, including clay, saline, alkaline, dry, stony, shallow and even in high-calcareous soil. Neem oil comprises phospholipids such as phosphatidylcholine (3.9%) phosphatidylethanolamine (39.4%), cardiolipin (10.3%) and phosphatidylinositol (36.4%). It also contains rich quantity of oleic acid (25–58%), palmitic acid (16–34%), stearic acid (6–24%) and linoleic acid (6–17%). The fatty-acid composition is known to vary in accordance with the genetic makeup of the tree [27].

1.4 Madhuca indica

Madhuca indica (mahua) is a deciduous tree found abundantly in Asian and Australian continents, and gives an annual yield of 181 000 metric tonnes of oil in India [67]. This tree grows along the roadside and canal banks and in social forestry programmes especially in tribal areas. The kernel contains about 20–50% of oil [68]. Mahua oil is rarely used for human consumption through blending 5% of the same with other edible oils [28]. This oil is reported to contain palmitic acid (17.8%), stearic acid (14.0%) and unsaturated fatty acids such as oleic acid (46.3%) and linoleic acid (17.9%) [69].

1.5 Hevea brasiliensis

Hevea brasiliensis, commonly called a rubber tree, belongs to the family Euphorbiaceae. It is distributed in India, Indonesia, Malaysia, Liberia, Sri Lanka, Sarawak and Thailand [11, 14]. China planted these trees initially in an area of 87 500 ha in various provinces and slowly increased to 95 000 ha during the year 2010 [29]. Similarly, Malaysia planted this tree in 1 million ha and obtained a seed yield of 120 000 tonnes per year; the oil obtained from it is used for biodiesel production [70]. Rubber seed kernel contains 40–50% of pale-yellow oil [4, 30]. The oil has both saturated and unsaturated fatty acids, such as palmitic acid (10.2%), stearic acid (8.7%), oleic acid (24.6%), linoleic acid (39.6%) and linolenic acid (16.3%) [4].

1.6 Calophyllum inophyllum

Calophyllum inophyllum of the family Clusiaceae (mango-steen) is grown in the coastal areas of India, Sri Lanka, East Africa, Australia, Southeast Asia and the South Pacific, where the annual rainfall ranges from 1000 to 5000 mm [31, 32]. It prefers a low altitude ranging from 0 to 200 m and sandy, well-drained soils. This tree yields around 70 000 metric tonnes of seed in India. Its kernels have 40–75% oil whose unsaturated fatty acids form around 71% [31, 71]. A mature tree produces 1–10 kg of oil per year, depending upon the richness of the tree and the efficiency of extraction process [72]. The oil contains palmitic acid (12.01%), stearic acid (12.95%), oleic acid (34.09%), linoleic acid (38.26%) and linolenic acid (0.3%) [33].

1.7 Sapium sebiferum

Sapium sebiferum belongs to the family Sterculiaceae. This tree is a native of China and it has spread to Japan and India and established well in the Southern coastal areas of the USA [19, 37]. This tree has a lifespan of around 40 years but comes to economic yield in 3–4 years [19]. The seeds contain 40–70% oil [19, 34, 73]. The oil is a rich source of unsaturated (palmitic 76% and oleic acid 23%) fatty acids [34].

1.8 Prunus sibirica

Prunus sibirica is a member of the family Rosaceae. It is a deciduous shrub indigenous to the temperate, continental, mountainous regions of Northern and North Eastern China, Eastern Siberia and Mongolia. The oil content of the kernel ranges from 44.73% to 57.83% [35, 36]. This tree is grown in an area of 1.7 million ha in China yielding 192 500 tonnes of oil a year [74]. This oil is currently being used in the manufacture of lubricants, cosmetics and surfactants, and also in the management of cardiovascular diseases, especially to counter the increasing cholesterol level. It is also recommended to be used as a raw material in biodiesel production. This oil has oleic acid (65.23%), linoleic acid (28.92%), palmitic acid (3.79%) and stearic acid (1.01%) [36].

1.9 Ricinus communis

Ricinus communis (castor) belongs to the family Euphorbiaceae and is distributed in India, China, Central Africa, Brazil, Australia and the USA [37, 75]. India produces around 60% of the total castor oil of the world (0.73 million metric tonnes a year) [75]. This plant needs less management and grows well in semi-arid regions. The oil content of the seed is 45–50% [38]. Castor seeds and oils are used in textiles, printing and lubricants, as well as in the production of resins or polymers and also in traditional medicine. The major fatty acid present is ricinoleic acid (89.5%) [75]. Other fatty acids are linoleic acid (3–6%), oleic acid (2–4%)...
and saturated fatty acids such as palmitic and stearic acid (1–5%) [39].

1.10 Thevetia peruviana
Thevetia peruviana, also called yellow oleander or milk bush, is an evergreen ornamental plant. It belongs to the family Apocynaceae and is widely distributed in America, Mexico, Brazil, the West Indies, Asia and Africa [40]. The kernels contain 67% oil [41, 42]. Each plant produces 400–800 fruits per year, depending on the age and rainfall. It yields a maximum of 52.5 tonnes per hectare per year and the oil yield is around 1750 litres per hectare. The fatty acids present are palmitic acid (22.10%), stearic acid (7.62%), oleic acid (37.93%), linoleic acid (26.33%) and arachidic acid (1.51%) [41].

1.11 Sapindus mukorossi
Sapindus mukorossi, also called soapnut, contains saponins in the pericarp that are mainly used as a detergent for washing delicate fabrics and hair, and also in the cleaning of ornaments. The saponin also is used in industries for the production of toothpaste, shampoos, soaps, insecticides, germicides, etc. [75, 76]. This tree grows at an altitude ranging from 200 to 1500 m in tropical and subtropical areas of Asia, America and Europe [43, 44]. The seeds contain 23% oil, of which 92% is triglycerides [45]. The oil has palmitic acid (4.67%), stearic acid (1.45%), oleic acid (52.64%), linoleic acid (4.73%), α- or λ-linoleic acid (1.94%), arachidic acid (7.02%), eicosanoic acid (23.85%), behenic acid (1.45%) and erucic acid (1.09%) [77].

1.12 Simmondsia chinensis
Simmondsia chinensis is a shrub belonging to the family Simmondsiaceae and is a native of the Mojave and Sonoran deserts of Mexico, California and Arizona [46, 75]. It is a dioecious woody evergreen shrub with flat green leaves and has a lifespan of 100–200 years [78]. The seeds contain 50–60% oil [46]. Each plant can produce 270–300 kg of oil after 4 years of planting and the oil yield increases as a function of its age [79]. The oil contains saturated and unsaturated fatty acids such as palmitic acid (7.38–9.70%), lauric acid, myristic acid, pentadecanoic acid in small quantities and eicosanoic acid (52.36–64.56%), docosanoic acid (6.86–9.95%), oleic acid (16.31–27.36%), linoleic acid (0.37–0.95%) and linolenic acid (0.87–2.50%) [47].

1.13 Zanthoxylum bungeanum
Zanthoxylum bungeanum is a woody plant growing to a maximum height of 7 m and is widely distributed in China [48]. Around 1 million metric tonnes of its seed are produced in China and the seed contains 27–31% oil [49]. A single tree yields 2–3 kg of seeds and the total oil yield is about 160 million kg per year in China [50]. The oil contains palmitic acid (10.61%), palmitoleic acid (5.19%), stearic acid (1.43%), oleic acid (32.10%), linoleic acid (25.60%) and linolenic acid (24.10%) [49].

1.14 Mesua ferrea
Mesua ferrea is distributed widely in India, Bangladesh, Sri Lanka, Indonesia and Cambodia [52]. It grows to a maximum height of 30 m and a width of 15–20 m in its crown spread. The fruit is enclosed in a capsule and its size ranges from 1 to 3 cm [53]. The seeds contain rich quantity of oil (~75%). The oil has stearic acid (9.5%), palmitic acid (15.9%), oleic acid (52.3%), linoleic acid (22.3%), myristic acid (2.13%) and arachidic acid (2.92%) [54].

1.15 Cerbera odollam
Cerbera odollam belongs to the family Apocynaceae and is widely distributed in South India and along the riverbanks in Southern and Central Vietnam, Cambodia, China, Sri Lanka, Myanmar, Madagascar and Malaysia [55, 56]. This tree can grow to a maximum height of 15 m, with dark-green and freshly lanceolate leaves. The seeds contain oil up to 54% [55]. The oil has palmitic acid (24.86%), palmitoleic acid (0.75%), stearic acid (5.79), oleic acid (52.82%), linoleic acid (13.65%) and others (2.13%) [56].

1.16 Pistacia chinensis
Pistacia chinensis belongs to the family Anacardiaceae. This plant is a native of the sub-Himalayan regions of North West India, Africa, Arabia, Southeast Asia, the Pacific and Caribbean Islands and South America, the Philippines, Cambodia, and Central and North America [61]. It requires a rainfall ranging from 250 to 2000 mm, depending on soil conditions. The fruit looks like a stick and contains 6–10 seeds. The matured seeds yield 38–40% of oil [58, 59]. The oil contains oleic acid 47.32%, linoleic acid 31.58%, linolenic acid 1.69%, palmitic acid 17.50% and stearic acid 0.92% [59].

1.17 Moringa oleifera
The tree Moringa oleifera is a native of the sub-Himalayan regions of North West India, Africa, Arabia, Southeast Asia, the Pacific and Caribbean Islands and South America, the Philippines, Cambodia, and Central and North America. It requires a rainfall ranging from 250 to 2000 mm, depending on soil conditions. The fruit looks like a stick and contains 6–10 seeds. The matured seeds yield 38–40% of colourless and odourless oil [62]. It has 70% oleic acid and a smaller quantity of palmitic acid (6.5%), palmitoleic acid (2.0%), stearic acid (6.0%), linoleic acid (1.0%), arachidic acid (4.0%) and gadoleic acid (2.0%) [80]. This oil is considered good for biodiesel, although the quantum of it may not be sufficient to reach a commercial proposition.

2 Methods of biodiesel production
The vegetable oils can be used as a fuel without any amendment in diesel engines but such use is not recommended due to the prohibitive viscosity, low volatility and rich carbon
Vegetable oils have a high molecular weight and complex chemical structure, which naturally enhance the viscosity. High viscosity impedes pumping, combustion and atomization in the injector systems of the diesel engine. It also causes gumming, injector deposits, ring sticking and incompatibility with conventional lubrication oils in the long run. These problems are addressed mainly by dilution and blending, microemulsion, pyrolysis (thermal cracking) and transesterification (Fig. 1). Table 2 compares the performance of various methods employed for biodiesel production from the oil of woody plants as reported in the literature.

2.1 Direct use and blending of vegetable oils
The vegetable oil is often blended with conventional diesel at an appropriate ratio and used directly in diesel engines so as to reduce the viscosity. The blending does not involve any chemical process. The oil of *Jatropha curcas* and conventional diesel, if mixed at a 1:1 ratio, can be used in a compression ignition engine without any major modification. Rubber seed oil is blended with diesel up to 50–80% for feeding in IC engines. In such blends, satisfactory brake thermal efficiency and specific fuel consumption are ensured. Blending of jojoba oil having high viscosity (25.48 cSt) with gas oil is shown to be an effective method to reduce engine problems. Reasonable viscosity of the jojoba oil is reached at a mixing ratio of 3:2. However, continued use of neat vegetable oil or its blend is impractical due to high viscosity, unfavourable fatty-acid profile, free fatty-acid (FFA) level, gum formation on oxidation, polymerization during storage and combustion, carbon deposits and continued thickening of lubrication oil. Many authors opined that the blending does not meet the required conditions for long-term use.

2.2 Microemulsion
Microemulsion is a transparent, isotropic, clear or translucent, thermodynamically stable colloidal dispersion of oil, water and surfactant that often exists as an amphiphilic molecule (co-surfactant) in which the diameter of the particle in the dispersed phase ranges from 100 to 1000 Å. Microemulsion is prepared from vegetable oils with an ester using a dispersant, or alcohol and a surfactant with or without diesel fuel to overcome the problem of the high viscosity. Methanol is often used in the emulsification due to its economic advantage over ethanol. The physiochemical properties of emulsified vegetable oils stand closer to the quality of conventional diesel.

2.3 Pyrolysis (thermal cracking)
In pyrolysis, or thermal cracking, the aliphatic long-chain compounds are cracked into aliphatic short-chain compounds such as alkanes, alkadienes, aromatics, carboxylic acids and hydrogen by simple heating or heating in the presence of catalysts. The pyrolytic process is arduous to explain on account of a variety of reaction paths and reaction products. Pyrolysis produces different products that are high in CN and low in viscosity, with acceptable levels of sulphur, water, sediments and copper corrosion. Nevertheless, other properties such as ash contents, carbon residues and pour points are unacceptable in routine use. Catalytic cracking is another form of thermal process in which the reaction is carried out in the presence of a catalyst at a low reaction temperature. The catalyst selection plays a significant role in this method. The catalyst normally provides acid sites to enhance the cracking.

2.4 Transesterification
The transesterification process is simple and has been widely accepted. It is a chemical reaction between triglycerides and a primary alcohol (methanol or ethanol) in the presence of a catalyst. The process consists of three consecutive reversible reactions in which triglycerides are...
converted to diglycerides and then to monoglycerides followed by the separation of the resulting glycerol. In each step, an ester molecule is formed [14, 102]. In such a reaction, methanol is a much-preferred alcohol both due to its economically favourable proposition and advantageous physical and chemical properties (polar and short-chain alcohol) [7]. Stoichiometrically, three moles of methanol are required for each mole of triglyceride but, in general, a higher molar ratio is required to drive the reaction forward. The transesterification reaction is the best choice to reduce the viscosity and the glycerol formed as a by-product has a commercial value [101]. The transesterification process has many advantages such as low processing cost, acceptable fuel standards, feedstock flexibility and compatibility with the engine architecture [7].

Transesterification of the oil obtained from woody plants may be carried out using chemical and biological catalysts. The chemical process involves homogeneous catalysts such as alkalis or acids, heterogeneous agents, heterogeneous nanocatalysts or supercritical fluids (SCFs) [103]. An alkali catalyst has proved to be effective [104]. The biological process is carried out using free and immobilized enzymes [2]. Enzymatic transesterification has several benefits over chemical-based transesterification, since it needs low energy followed by easy separation of the biodiesel from the glycerol. Further, the transesterification reaction may be made on any oil having high FFA with suitable process modification [105–107]. In spite of its advantages, there will be high production costs arising due to the expensive biocatalysts especially in enzymatic transesterification [81].

2.5 Electro-catalytic process and SCFs

The reaction was carried out at room temperature using chitosan gels as catalysts. The electro-catalytic process had a biodiesel recovery of high conversion of 90.3 percent in chitosan xerogel and 93.1 percent in chitosan xerogel [103].

SCF transesterification helps to overcome any negative impacts of catalyst-based transesterification. SCF has a shorter reaction time than the traditional catalytic reaction and the conversion rate is relatively high. Although the absence of a catalyst is a major advantage, operational safety as a consequence of the high temperature and pressure needs to be ensured [38, 108, 109]. This method overcomes the existing problems of homogeneous and heterogeneous catalytic processes. It is environmentally friendly due to the absence of catalysts [107, 110]. The nature of the solvent, reaction temperature and pressure are the major parameters involved in SCF technology. The formation of a single phase between the reagents and the triglycerides in this method is quite advantageous. The conditions of SCFs favour the reaction kinetics of the transesterification by bringing the reagents in close proximity, which enhances the production. In SCFs, both the pressure and the temperature are maintained above their critical values (Fig. 2) [111, 112].

Generally, methanol is employed in this method due to its dielectric constant. The dielectric constant of methanol reduces from 34 to 5 under isobaric heating from 25°C to 260°C at 20 MPa [113]. Biodiesel production from Jatropha curcas was reported to be made straight from powdered seeds (0.5–2.0 mm) at a high reaction temperature (200–300°C) and low reaction duration (45–80 min) with great success. Optimum oil-extraction efficiency and fatty-acid methyl ester (FAME) yield are achieved at a reaction temperature of 300°C and at a reaction pressure of 240 MPa [114].

3 Properties of biodiesel from the oils of woody plants

The properties of biodiesel primarily depend on the fatty-acid composition of the feedstocks [115], which in turn has a bearing on the engine performance and emission characteristics. The physico-chemical properties of biodiesel developed from the oils of various woody plants are shown in Table 3. This table provides the properties of oils from 17 species, which are shown to deviate from the standards, thus requiring any species-specific amendments when the oils are converted into biodiesel, such as an alteration in lubricity, as indicated in Section 3.9.

3.1 Kinematic viscosity

The viscosity of a liquid is a measure of its resistance to flow due to internal friction. Kinematic viscosity is a significant property of fuel, which influences the flow rate and atomization characteristics. The high viscosity of fuel causes hindrance to the injection process resulting in poor fuel atomization. It also influences cold-engine start-up and ignition delay [125, 126]. The viscosity of biodiesel is close to that of conventional diesel. The temperature dependence of viscosity is a phenomenon by which liquid viscosity tends to decrease as its temperature increases. Viscosity also reduces as the proportion of diesel in the blend increases [24]. The short-chain hydrocarbon in liquid fuel has low viscosity. In fatty acids, if they contain cis double bonds, the viscosity is low, while the presence of trans double bonds has a lower effect on the viscosity as compared to saturated compounds with an equal number of carbons. The viscosity of branched esters is then identical to their straight-chain counterparts. The viscosity of methyl ricinoleate increases significantly due to its OH functional group. Generally, the effect of oxygenated moieties on kinematic viscosity is in the order COOH > C-OH > COOCH<sub>3</sub> ≈ C=O > C–O–C > no oxygen; at shorter chain lengths, there is a reversal of COOH vs OH. The viscosity of the hydrocarbons in biodiesel (fatty-acid alkyl esters) is governed by the chain length [127].
| Source                        | Catalyst                                                  | Production method (%) | Reaction conditions                                                                 | Biodiesel yield (%) | Recycle | Reference |
|-------------------------------|-----------------------------------------------------------|-----------------------|-------------------------------------------------------------------------------------|---------------------|---------|-----------|
| Zanthoxylum bungeanum seed oil| SnCl4.5H2O                                                 | Acid esterification   | Methanol-to-oil ratio 25:12:1, catalyst 2.72%, temperature 95°C, time 2.95 h        | 96                  | NA      | [82]      |
| Sludge palm oil               | Toluene-4-sulfonic monohydrate acid (PTSA) and KOH         | Acid and alkaline transesterification | Acid esterification: catalyst 0.75% (w/w), oil-to-methanol molar ratio 1:10, temperature 60°C, stirring rate 400 r.p.m., time 1 h. Alkaline transesterification: acid esterified oil, catalyst 1 wt% KOH, oil-to-methanol molar ratio 10:1, temperature 60°C, stirring rate 460 r.p.m., time 1 h. | 96                  | NA      | [83]      |
| Pongamia pinnata oil          | KOH                                                        | Direct alkaline transesterification | Catalyst 1%, oil-to-methanol molar ratio 1:6, temperature 65°C, stirring rate 360 r.p.m., time 3 h. Acid esterification: oil 11, catalyst 10 ml, methanol 100 ml, temperature 50°C, time 2 h. Alkaline transesterification: catalyst 14.5 g, methanol 300 ml, temperature 60°C, time 1 h. | 97-98               | NA      | [84]      |
| Hevea brasiliensis oil        | H2SO4 and NaOH                                             | Acid and alkaline transesterification | Acid esterification: oil 11, catalyst 0.8 ml, methanol 100 ml, temperature 50°C, time 20 min. Alkaline transesterification: acid esterified oil 1 l, catalyst 10 gm, methanol 200 ml, temperature 60°C, time 1 h. | 85                  | NA      | [13]      |
| Azadirachta indica oil        | H2SO4 and NaOH                                             | Acid and alkaline transesterification | Acid esterification: oil 11, catalyst 0.8 ml, methanol 100 ml, temperature 50°C, time 20 min. Alkaline transesterification: acid esterified oil 1 l, catalyst 10 gm, methanol 200 ml, temperature 60°C, time 1 h. | 85                  | NA      | [85]      |
| Cotton seed oil               | CaO–MgO/Al2O3                                              | Direct alkaline transesterification | Catalyst 12.5 wt%, molar ratio of ethanol to cottonseed oil 8.5, temperature 95°C, stirring rate 750 cycle/min, time 3 h | 92.45%              | 4       | [86]      |
| Madhuca indica oil            | Heteropoly acid-coated ZnO                                 | Direct alkaline transesterification | Oil 50 ml, catalyst 2 g, methanol 50 ml, 55 ± 5°C, time 5 h                           | 98%                 | NA      | [87]      |
| Cerbera odollam (sea mango)   oil| Sulphated zirconia alumina                                 | Direct alkaline transesterification | Catalyst 6 wt%, oil-to-methanol molar ratio 1:8, time 180 min, temperature 180°C | 83.8                | NA      | [88]      |
| Croton megalocarpus oil       | SO4<sup>2−</sup>/SnO<sub>2</sub>-SiO<sub>2</sub> (sulphated tin oxide with silica) | Direct alkaline transesterification | Catalyst 3 wt%, temperature 180°C, oil-to-methanol molar ratio 1:15, stirring rate 360 r.p.m., time 2 h. Acid esterification: catalyst 1.43% (w/v) ml, methanol (0.28 v/v), temperature 60°C, time 88 min. Alkaline transesterification: acid esterified oil 1 l, catalyst 3.5 + acid value % (w/v), methanol 0.16 v/v, temperature 60°C, time 24 min | 95%                 | NA      | [89]      |
| Jatropha curcas oil           | H2SO4 and NaOH                                             | Acid and alkaline transesterification | Acid esterification: catalyst 2% Li loading 5 wt%, oil-to-methanol molar ratio 1:10, reaction temperature 65°C, time 4 h | 94%                 | NA      | [91]      |
| Mesua ferrea oil              | Li-CaO                                                     | Direct alkaline transesterification | Catalyst 2% Li loading 5 wt%, oil-to-methanol molar ratio 1:10, reaction temperature 65°C, time 4 h | 94%                 | NA      | [91]      |
| Sapium sebiferum (Linn.) Roxb (Chinese tallow) oil | Surfactant (non-ionic dioleyl glutamate ribitol amide)-coated lipase | Direct alkaline transesterification | Catalyst 18.5%, oil-to-methanol ratio 1:3, temperature 49°C, water content 15.6%, time 9.2 h | 93.86               | NA      | [92]      |
| Euphorbia lathyris L. (EL), Sapium sebiferum L. (SS) and Jatropha curcas L. (JC) | H2SO4 and KOH | Acid esterification and alkaline transesterification | Acid esterification: catalyst (0.8 wt% (EL), 0.4 wt% (SS), 0.4 wt% (JC)), oil-to-methanol molar ratio (1:10 (EL), 1.8 (SS), 1.8 (JC)), temperature 60°C, time 45 min (EL), 30 min (SS and JC). Alkaline transesterification: catalyst (0.8 wt% (EL), 1.0 wt% (SS), 1.0 wt% (JC)), oil-to-methanol molar ratio 1:6, temperature 60°C, time 30 min | 86.2 (EL), 88.3 (SS), 86.2 (JC) | NA      | [93]      |
3.2 Density

The density is another important factor that brings in changes to the fuel-injection rate. Since fuel-injection pumps work on a volume basis and not on a mass basis, the mass of the fuel injected indirectly depends on its density. As a consequence, the air:fuel ratio and energy released within the combustion chamber are influenced by the fuel density [128]. Biodiesel is denser and less compressible than diesel [37]. Density is one of the most crucial parameters in deciding the functional efficiency. The biodiesel (FAME) density is influenced by the composition of the unsaturated hydrocarbon molecules. Higher unsaturated molecules lead to an increase in density [129]. Biodiesel has high molecular weight, which is one of the factors that contribute to the increase in density [130]. Table 3 indicates that biodiesels from *Sapium sebiferum* (900 kg m\(^{-3}\)) and *Ricinus communis* (923.7 kg m\(^{-3}\)) have a higher density than that of biodiesels prepared from other woody plant oils. The astounding molecular weight is the sole reason for the high density.

3.3 CN

CN is a dimensionless measure of a fuel’s auto-ignition quality, especially on the knocking tendency. The CN of any fuel is related to the chemical structure in terms of the chain length, degree of unsaturation, the position of the double bond and cis or trans structures [131]. The fatty-acid profile does not change during the processing of oil under proper conditions [132]. CN is reported to increase along the chain length of hydrocarbon [133]. A higher CN value of the fuel has a favourable ignition quality. Biodiesel contains long-chain hydrocarbon molecules (with virtually no branching or with aromatic compounds) and consequently its ignition delay time is shorter than that of conventional
Table 3: Physico-chemical properties of biodiesel derived from woody plant oils as compared to conventional diesel fuel, ASTM D6751 and EN14214 standards

| Source of biodiesel | Physical and chemical properties | Kinematic viscosity @ 40°C (cSt) | Pour point °C | Flash point °C | Copper strip corrosion for 3 h at 100°C | Total sulphur % by mass | Ash % by mass | Carbon residue % by mass | Sediment % by mass | Water content % by mass | Acid value (mgKOH g⁻¹) | Cetane number |
|-------------------|----------------------------------|-----------------------------------|---------------|---------------|----------------------------------------|-------------------------|----------------|--------------------------|----------------------|--------------------------|---------------------|----------------|
| Jatropha curcas [90, 93] | 980 | 4.3 | 2 | 135 | 1 a | NA | 0.012 | 0.20 | NA | 0.025 | 0.40 | 55.4 |
| Pongamia pinnata [3, 64, 95] | 980 | 4.33 | 5 | 174 | 1 a | 0.01 | 0.001 | 0.002 | 0.005 | 0.005 | 0.23 | 57.6 |
| Azadirachta indica [26, 85] | 898 | 5.81 | 8 | 175 | 1 a | 0.03 | 0.00 | 0.08 | 0.00 | 0.00 | 0.22 | 56.78 |
| Madhuca indica [68, 117] | 880 | 3.98 | 6 | 208 | NA | NA | NA | 0.1 | 0.20 | NA | 0.04 | 0.41 | 65 |
| Hevea brasiliensis [13, 149] | 895 | 6.18 | 6 | 165 | 1 a | 0.015 | 0.05 | 0.17 | NA | 0.00 | 0.42 | 53 |
| Calophyllum inophyllum l [22] | 877.6 | 3.45 | 2.0 | 165.5 | 1 a | 6.23 | 0.001 | 0.03 | NA | 0.015 | 0.34 | 59.5 |
| Sapium sebiferum [19] | 900 | 4.81 | 137 | NA | 2.61 | 0.037 | 0.26 | NA | NA | 0.007 | 50 |
| Prunus sibirica [36] | 878.2 | 3.431 | NA | 173 | 1 a | 4.7 | NA | NA | NA | 0.027 | 0.25 | 48.8 |
| Ricinus communis [37, 151] | 923.7 | 14.5 | NA | 273.1 | 1 a | 0.034 | NA | 0.110 | <0.05 | <0.05 | 0.996 | 50 |
| Thevetia peruviana [40, 119] | 870 | 4.1 | –8 | 174 | NA | NA | 0.003 | 0.06 | NA | NA | 0.62 | 72 |
| Sapindus mukorossi [118, 120] | 878 | 4.88 | –4 | 177 | NA | 0.03 | 0.12 | NA | 0.086 | 0.12 | 58 |
| Simmondsia chinensis [37, 46] | 863.5 | 6.67 | –16 | 61–75 | 1 a | 0.01 | 0.037 | 0.26 | 0.03 | 0.3 | 1.37 | 69 |
| Zanthoxylum bungeanum [50] | 882.6 | 4.0 | –6 | >174 | 1 a | NA | NA | NA | NA | NA | NA | 0.3 | 47 |
| Mesua ferrea [121, 122, 152] | 897 | 4.1 | –1.2 | 142 | 1 a | 0.01 | 0.003 | 0.250 | NA | NA | 1.8 | 54.6 |
| Cerbera odoratum [123] | 869.7 | 4.86 | 6.0 | 159.5 | NA | NA | NA | NA | NA | 0.17 | NA |
| Pistacia chinensis L [124] | 887 | 5.24 | –2.0 | 166 | NA | NA | 0.013 | NA | 0.35 | NA | 0.22 | 56.3 |
| Moringa oleifera [153] | 859.6 | 5.05 | 19 | 150.5 | 1 a | 0.0124 | 0.01 | NA | NA | NA | 0.051 | 49.7 |
| Conventional diesel [123, 125, 128, 129] | 840.0 | 2.95 | –2 | 70.5 | 1 | 0.0014 | 0.08 | 0.821 | 0.003 | 0.003 | 0.003 | 0.051 | 49.7 |

NA, not available.
diesel [134]. Tallow and palm biodiesels have higher CN due to the rich saturated fatty-acid composition when compared to that of soybean and rapeseed oil. The cetane number is calculated by comparing the ignition delay of the test fuel to that of a mixture of hexadecane (100 CN) and heptamethylnonane (15 CN). The cetane number of the test fuel is the percentage by volume of n-cetane in a blend of n-cetane (100 CN) with heptamethylnonane (15 CN) when tested in the same engine under the same test procedures [135]. CN has a relationship with NOx emissions as well as with particulate-matter emissions. The effect of CN and NOx emissions indicates the chain length and saturation levels of hydrocarbon molecules. Saturated methyl esters release a lower amount of NOx emissions than unsaturated methyl esters, but particulate matter seemed to be less affected. Hydrocarbons and CO emissions in the exhaust decrease with an increase in the chain length of methyl esters (i.e. higher CN fuels) [136].

3.4 Flash point

The flash point is inversely proportional to the fuel volatility. The biodiesel specification for the flash point is intended to protect the engine against contamination by highly volatile impurities, mainly due to residual methanol. Even a small amount of residual methanol in biodiesel will give a wrong value for the flash point [128]. High viscosity and low volatility of a fuel provide poor cold-engine start-up, misfire and ignition delay. The high flash point may cause carbon deposits in the combustion chamber [132]. Biodiesel has a flash point greater than conventional diesel since biodiesel contains large hydrocarbon molecules. The vegetable oil from which biodiesel is produced has a higher flash point than the resultant biodiesel. Rubber seed oil has a flash point of 198°C and, in the corresponding biodiesel, it is 165°C. The flash points of the biodiesel from *Jatropha curcas* (191°C), *Pongamia pinnata* (150°C), *Glycine max* (153°C), *Brassica juncea* (162°C) and *Hevea brasiliensis* (165°C) are generally a function of the fatty-acid composition and reaction conditions of the transesterification process [86].

3.5 Water and sediment

Water and sediment contamination in biodiesel is due to housekeeping problems. Water in biodiesel may remain as a dissolved form or in suspended droplets. Biodiesel retains a trace amount of wash-water, though it is normally considered to be insoluble in biodiesel. Sediment is normally formed due to suspended dust and dirt particles or it may be formed as insoluble compounds during oxidation when it is stored for a long time. Water content in fuel causes corrosion of the engine. The most direct form of corrosion is rust. The water may become acidic with the length of the storage period and may corrode the fuel-storage tanks. Water contamination may also lead to microbial growth. Yeast, fungi and bacteria may develop at the interface between the fuel and the water at the bottom of the storage tank. These organisms form sludge and slime, which ultimately may create filter plugging. Some organisms convert the trace of sulphur into sulphuric acid, which may ultimately corrode metal tanks [81, 136]. Water and sediment can be assessed by centrifuging the biodiesel [90].

3.6 Acid value

The acid value or neutralization number is a reference of the FFA contained in a fresh sample. FFA occurs as saturated or unsaturated monocarboxylic acids, which are constituents of fats, oils or greases but are not associated with glycerol. The fatty-acid level is based on the carbon-chain length and on the number of unsaturated bonds (double bonds). A high amount of FFA is reflected by the high acid value. The high acid value is one of the causes of corrosion of the engine components [81, 135]. The acid value reduces (0.69 mg KOH g⁻¹) due to the purification of raw biodiesel (1.44 mg KOH g⁻¹). This reveals that purification is an integral part of the biodiesel-production process [74].

3.7 Ash content

The ash content signifies the level of inorganic contaminants such as abrasive solids, catalyst residues and the concentration of soluble metal soaps present in a fuel. The ignited biodiesel, when treated with sulphuric acid, gives the level of sulphated ash in the biodiesel [81].

3.8 Carbon residue

The carbon residue of a fuel denotes the carbon-deposition property of a fuel after combustion. Carbon residue in biodiesel assumes significance, as it offers a high correlation among FFAs, unsaturated fatty acids, soaps, glycerides, polymers and inorganic impurities. Table 3 indicates that the carbon residues of biodiesel from woody plant oils are low when compared to conventional diesel.

3.9 Lubricity

Lubricity is an important parameter responsible for increasing the lifespan of the engine. Fuel lubrication is necessary for the engine to reduce the friction among the moving parts [137]. Neat biodiesel offers greater lubricity than conventional diesel. However, adding free fatty acids or alkyl esters or other selected oxygenated compounds to the fuel at a pre-calculated concentration helps to improve the lubricity [138]. Biodiesel is an oxygen-rich fuel and the oxygen moieties in it offer lubricity in the order COOH > CHO > OH > COOCH₃ > C=O > C–O–C. The fatty acids in the biodiesel contain polar-imparting oxygen atoms, which offer better lubricity to the fuel. Besides,
hydroxylated FAME significantly improves the lubrication when compared to that of the non-hydroxylated FAME [139]. Biodiesel from Jatropha curcus, Pongamia glabra, Madhuca indica and Salvadorla oleoides, when blended with conventional diesel, improves the lubricity and causes a reduction (45%) in the wear and tear of engine parts due to long usage as per wear scar diameter (WSD) specifications being followed [140]. The lubrication effects of certain minor constituents as additives to ultra-low sulphur diesel are being studied. The minor constituents are FFAs, glycerol, antioxidants and phospholipids. Crude soy biodiesel, with all of its major and minor constituents, decreases the WSD by 55%, whereas distilled biodiesel, which is composed of pure FAMEs, decreased the WSD by only 29%. This reveals that certain of the minor constituents indicated above have significant effects on increasing the lubricity. FFA and asolecin phospholipids have conspicuous roles in enhancing the lubricity [141].

3.10 Oxidative stability

Oxidative stability indicates the resistance of fuel to oxidation during extended storage [134]. Biodiesel is a degradable fuel due to a number of reasons: thermal oxidation at elevated temperature and hydrolysis in the presence of moisture and microbial degradation due to bacteria or fungi. The oxidation process of biodiesel is influenced by the fatty-acid structure, presence of certain metals, elevated temperature, extraneous materials, peroxides, light or pressure and antioxidants, as well as the extent of the exposed surface area between the biodiesel and air [136]. These factors act as a catalyst in the process of oxidation, which leads to the removal of hydrogen from the backbone of the biodiesel structure. High levels of unsaturated fatty acids and the presence of double bonds in the molecule make the biodiesel prone to oxidation due to its high reactivity with O2 [137].

Oxidation of biodiesel normally does not require any catalyst, since it is spontaneous. The oxidation stability of biodiesel is greatly influenced by the storage conditions [142]. Moreover, biodiesel has the inherent quality of absorbing atmospheric moisture, which in turn activates the degradation process. However, such a course of action is rather minimal. The most ideal condition for biodiesel storage is the absence of light at room temperature <40°C [143]. Biodiesel, when stored in a container or fed into the engine, is likely to come into contact with metallic materials such as copper, zinc, lead, tin and bronze, which also may increase the rate of degradation through metal-catalysed oxidation. However, their effects are lower in comparison to highly unsaturated fatty acids [144]. The oxidative stability of biodiesel on exposure to iron, nickel, manganese, cobalt and copper was investigated. The results indicate that copper has a stronger catalytic effect on the oxidation than other metals [145].

3.11 Cold-flow properties

The cold-flow properties of biodiesel are indicated by the cloud point (CP), pour point (PP), cold filter plugging point (CFPP) and low-temperature filterability test. Two significant parameters to be kept under control for low-temperature applications of fuel are the CP and the PP. The CP indicates a temperature limit below which the wax or bio-wax in biodiesel solidifies, thereby forming a cloudy appearance. Solidified or crystallized waxes thicken the oil and clog the fuel filters and injectors in the engines [146]. PP refers to a temperature at which the wax in the solution turns into a gel. Biodiesel has a higher CP and PP compared to conventional diesel [129]. The poor cold-flow properties (CP and PP) are the critical impediments to the liberal usage of biodiesel. The fatty-acid composition of biodiesel grossly influences the cold-flow properties. The freezing point of biodiesel increases with an increase in the number of carbon atoms in the carbon chain and decreases with increasing unsaturated hydrocarbon molecules [133, 134]. Table 3 indicates the PP levels of different biodiesels.

Ethyl levulinate (ethyl 4-oxopentanoate) (EL) was used as a bio-based novel cold-flow improver for use in the biodiesel of cottonseed oil methyl esters (CSME). Various amounts of EL were blended with CSME for improving the cold-flow properties. Reductions of 4–5°C in CP, 3–4°C in PP and 3°C in CFPP were observed in the blend at 20% (v/v) EL. The kinematic viscosity and flash point decreased with the increase in the content of EL. The acid value and oxidative stability did not change upon addition of EL [147]. Petroleum diesel, kerosene and ethanol were tried to improve the cold-flow properties of biodiesel. B20 of palm biodiesel with diesel and kerosene has improved the CP by 57.62% and 86.87% and PP by 68.52% and 109%, respectively. Ethanol is a good cold-flow improver for palm biodiesel at 20% addition, which has improved the CP and PP by 65.23% and 79.18%, respectively [146]. The impact of different solvents in stabilizing the biodiesel-polymer solution such as the bio-solvent of expanded polystyrene and co-solvents of cyclohexane, xylene, toluene, tetrahydrofuran, benzene, methyl ethyl ketone, acetone, pyridine, dimethylformamide, methanol and ethanol was explored. Benzene, toluene, xylene and acetone gave the best stabilizing effect. However, cyclohexane, xylene and toluene are harmful to human health and the environment. Acetone was found to offer the best stabilizing effect. Besides, acetone addition largely improved the deteriorating impact of polymer dissolution on the CP value of the fuel. Acetone also improves the flash point relatively and thus enhances fuel safety [148]. In general, the quantity of blending agents required are very high in volume and hence such attempts are economically not feasible.

4 Critical analysis

Most of the 17 plant species discussed in this paper are reported to occur in derelict shrub jungles and are not
and India are actively focusing on the production of alternate materials by 2020 [157, 158]. The Government of Indonesia has implemented several policies for the development of alternate energy in the transportation sector. Biofuels are to account for 5% of Indonesia's total energy mix in 2025. It is expected that ethanol will replace 15% of the gasoline consumed and biodiesel will replace 20% of the diesel consumed in 2025. Indonesia is currently the world's largest palm-oil producer and the second largest exporter. It accounts for 44.5% of the world's production of palm oil. Therefore, Indonesia's policy primarily focuses on the use of palm oil to make biodiesel and secondarily on jatropha-derived oil [158, 159]. The Government of Thailand actively implements policies to push forward increased production and usage of biodiesel. The scheme of 5% blending (B5) was also introduced in Bangkok [160]. Biodiesel production in South Africa is expected to increase to 35PJ in 2025 at a growth rate of 30% per year from 2010 [160]. The settled general opinion the world over is to make use of biodiesel as a blending material for diesel at a maximum rate of 10%. In this context, it is strongly felt that the oleaginous seeds of those woody plants listed above, if extracted in full for oil and making use of such oils as raw material for biodiesel, may easily manage to bridge the 10% gap in the resource.

5 Conclusion
Fossil fuels have been on use as a primary source of fuel in transportation, agriculture and power generation in the commercial, domestic and industrial sectors for more than a century. As fossil fuels are dwindling fast, biodiesel has become the best alternative fuel for internal combustion engines in many countries. They are being derived from both edible and non-edible vegetable oils. However, the use of edible oils in the production of biodiesel is not actively recommended in view of their direct use in human consumption. Biodiesel is not a complete replacement for conventional fuel, but it can be a partial substitute for fossil fuel. Agricultural land has shrunk over the years due to the extension of urban areas consequent to the increase in the human population. At the same time, more agricultural land is needed for the production of food. These issues create a spiralling impact on the production of biodiesel. Therefore, non-edible oils, especially from woody plants, genetically engineered plants and microalgae, may secure the sustainability of biodiesel production in the future.

Energy policies of the governmental agencies that are being revised from time to time shall be comprehensive and shall address the complexities in energy production, distribution and consumption, taking into account the second-generation biodiesel with special reference to the scope of biodiesel from derelict perennial trees that has hitherto not been taken seriously. These oil resources, which certainly act as fringe sources, are material to be concentrated so as to complement the existing raw materials for non-conventional first-generation fuel resources especially for biodiesel and bioethanol [158]. The Government of Indonesia has implemented several policies for the development of alternate energy in the transportation sector. Biofuels are to account for 5% of Indonesia's total energy mix in 2025. It is expected that ethanol will replace 15% of the gasoline consumed and biodiesel will replace 20% of the diesel consumed in 2025. Indonesia is currently the world's largest palm-oil producer and the second largest exporter. It accounts for 44.5% of the world's production of palm oil. Therefore, Indonesia's policy primarily focuses on the use of palm oil to make biodiesel and secondarily on jatropha-derived oil [158, 159].
biodiesel, though such resources have limited significance with reference to their volumetric contribution. There is a need to collect, secure and process the oil seeds from woody perennial biomass that is otherwise being wasted unintentionally and did go unaccounted for with respect to biodiesel. Technological improvements are needed to extract the oil from the seeds, as most of them are well encapsulated in hard shells, and the resultant oil has a disproportionate level of FFA, which imposes cumbrous additional procedures in the production methodology.

Currently, energy insecurity and climate changes are the twin crises emerging in the world. The global temperature is gradually increasing every year. If it increases further by 2°C, nearly 1 million species are feared to vanish and hundreds of millions of people will be negatively impacted irrevocably. A large amount (4.1 billion metric tonnes) of carbon dioxide may be released into the atmosphere in the next 15 years. To overcome such issues, it is high time the world should wake up from slumber. The approach expected to proceed with such issues, it is high time the world should wake up from slumber. The approach expected to proceed with thereby expected to proceed with a need to collect, secure and process the oil seeds from woody perennial biomass that is otherwise being wasted unintentionally and did go unaccounted for with respect to biodiesel. Technological improvements are needed to extract the oil from the seeds, as most of them are well encapsulated in hard shells, and the resultant oil has a disproportionate level of FFA, which imposes cumbrous additional procedures in the production methodology.

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**Conflict of Interest**

None declared.

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