Process Integration and Optimization for Sustainability (2023) 7:1081–1116
https://doi.org/10.1007/s41660-023-00343-w

REVIEW ARTICLE

# A Comprehensive Review on Rare Biodiesel Feedstock Availability, Fatty Acid Composition, Physical Properties, Production, Engine Performance and Emission

**Brihaspati Singh[1] · Anmesh Kumar Srivastava[1] · Om Prakash[1]**

Received: 10 December 2022 / Revised: 8 April 2023 / Accepted: 28 May 2023 / Published online: 23 June 2023

**Abstract**
The world is now experiencing the first real global energy crisis, the effects of which will be felt for many years to come. Fossil fuels have accounted for more than 80% of the world's energy requirements for decades. The cost of coal has reached record highs, while the price of oil reached at it's peak in the middle of 2022 at well over 100 US dollars per barrel before declining. Rising energy costs of fossil fuels are driving a significant wealth shift from consumers to producers. The primary causes of the growing level of carbon dioxide in the atmosphere are fossil fuels. Stated Policy Scenario predicts a 1% annual growth in primary energy demand through 2030, which will be mostly satisfied by greater usage of renewable energy sources. Biodiesel is gaining popularity as a means of supplying energy since it is a renewable fuel, non-toxic, biodegradable, and locally available using recycled or agricultural materials with a lesser environmental effect. Biodiesel refers to a non-petroleum-based diesel fuel consisting of short-chain esters, made by using numerous resources, which can be used (alone or blended with conventional diesel) in an unmodified diesel engine. The greenhouse gas emission for biodiesel is 74% lesser as compared to diesel fuel. With the widespread implementation of blending rules, the usage of biofuels rises to 5.5 million barrels of oil equivalent per day (mboe/day) in 2030 from 2.2 mboe/day in 2022. This study explores the numerous rare biodiesel feedstock, production, fatty acid content, physical properties and their effect on diesel engine output behaviour. These resources contain a large amount of free fatty acids and triglycerides which are usually used in the preparation of biodiesel. Since biodiesel has a higher oxygen content and a lower energy content than diesel fuel, it often offers better brake thermal efficiency, brake specific fuel consumption, $NO_x$ emission, and decreased HC, CO and smoke emissions at some blending ratio. The exhaust gas recirculation assembly in the engine reduces the $NO_x$ emission. The incorporation of non-additive in biodiesel blend acts as a catalyst during the combustion process and improves engine combustion by increasing the surface area of combustion. Biodiesel is clean energy and can be a promising future energy source for diesel engines.

**Keywords** Biodiesel · Feedstock · Properties · Fatty acid · Transesterification · Diesel engine · Performance · Emission

## Introduction

As the population grows, so does the need for energy. Energy has revolutionised human lifestyles over the past several centuries, and new sources of energy are being discovered to meet the demand. Basic sources of energy in the ancient times have included human muscles, plants, timber and crops, as well as decaying animal corpses. As the industrial revolution progressed, a plethora of energy resources became available for the generation of various forms of energy. In the current scenario, some energy sources include fossil fuels energy, hydro-energy, nuclear energy and renewable energy. During the industrialisation period, energy is mostly obtained from fossil fuels. The combustion of fossil fuels has a variety of adverse consequences, including abrupt climate change, global warming and the release of greenhouse gases. Every year, millions of species die as a result of air pollution, which is mostly caused by the burning of fossil fuels. As per the International Energy Agency, the world is now experiencing the first really global energy crisis, the effects of which will be felt for many years to come. The unprovoked Russian invasion of Ukraine in February

✉ Brihaspati Singh
brihaspatis.phd20.me@nitp.ac.in

[1] Department of Mechanical Engineering, National Institute of Technology Patna, Bihar 800005, India

had a profound effect on the global energy system, upsetting supply and demand trends and shattering long-standing trade alliances. The cost of coal has reached record highs, while the price of oil peaked in the middle of 2022 at well over 100 US dollars per barrel before declining. For decades, the proportion of fossil fuels in the world's energy mix has remained persistently high, at over 80%. In the Stated Policy Scenario, this percentage decreases to less than 75% by 2030 and to little around 60% by 2050. In the Stated Policy Scenario, the globe struggles with the energy price shocks of today, with some areas returning to earlier patterns and others seeing a quicker move to renewable energy and end-use electrification due to stronger decarbonisation policies. The Stated Policy Scenario predicts a 1% annual growth in primary energy demand through 2030, which will be mostly satisfied by greater usage of renewable energy sources. Under the Stated Policy Scenario, renewable energy sources continue to grow more quickly than any other source of energy. Wind and solar PV continue to dominate the expansion of renewable electricity, which is primarily supplemented by hydropower, biofuels and geothermal energy. In addition, because of the widespread implementation of blending rules, the usage of biofuels rises to 5.5 million barrels of oil equivalent per day (mboe/day) in 2030 from 2.2 mboe/day in 2022. The use of renewable energy sources helps reduce the amount of carbon. In the Stated Policy Scenario, worldwide energy-related $CO_2$ emissions peak in 2025 at 37 billion tonnes (Gt) year and then decline to 32 Gt by 2050. According to the Net Zero Emissions (NZE) by 2050 Scenario, $CO_2$ emissions will be nil in 2050 and will drop to 23 Gt in 2030, which is compatible with keeping global warming to less than 1.5 °C in 2100. As a potential replacement for diesel and a means of reducing the energy problem, biodiesel has a lot of potential in the upcoming decades. Biodiesel is a fuel with the designation B100 that complies with ASTM D6751 specifications and is made up of mono-alkyl esters of long-chain fatty acids obtained from vegetable oils or animal fats (International Energy Agency 2022). Biodiesel is created using a variety of plant oils (such as soybean, cottonseed, canola and corn oils), recycled cooking greases or oils (such as yellow grease), animal fats (such as beef tallow and swine lard), or recycled cooking greases and oils. Used cooking oils are mostly made of plants, although they may also include animal fats. Cooking oil waste may be recycled and is renewable. New feedstocks are being created, and they could soon be made available on the market, as biodiesel production and consumption rise. Numerous resources can be used to produce biodiesel, which has many benefits. Biodiesel has the following benefits: it is renewable that does not have any sulphur or polycyclic aromatic compounds in it; it can replace fossil diesel fuel; biodiesel can be used directly in existing diesel equipment with slight to no modification; it can lower greenhouse gas emissions; it is compatible with new technology diesel engines; it can reduce engine exhaust emissions, including air toxics; biodiesel is nontoxic and biodegradable; it is appropriate for sensitive environments; biodiesel can be made locally using recycled or agricultural materials. Greenhouse gas emissions are drastically reduced when biodiesel is used instead of petroleum. In comparison to fossil fuel diesel, B100 has been determined to produce 74% less greenhouse gas emissions across its whole life cycle (O'Connery 2010). Biodiesel helps to reduce the dependency on foreign energy sources (Mishra and Goswami 2018). Nowadays, biodiesel become an alternative and economical source of renewable energy. Sodium hydroxide (NaOH), potassium hydroxide (KOH), and other homogeneous and heterogeneous catalysts in presence of alcohol are used throughout the transesterification process to produce biodiesel (Atabani et al. 2013).

As far as biodiesel is concerned, more than 350 sources of fats and oils have the potential to be used to make biodiesel, although more than 95% of biodiesel is made from edible vegetable oils (Sierra-Cantor & Guerrero-Fajardo 2017). Brazil, USA, Malaysia, Argentina, Spain, Belgium and Germany are some of the biggest biodiesel producers and meet the 80% demand of biodiesel (Rezania et al. 2019). A significant replacement for diesel made from petroleum is microdiesel, which is produced by microorganisms utilising renewable resources as carbon sources (Bhatia et al. 2017). The biodiesel burns similarly to fossil fuels up to a certain biodiesel–diesel blending ratio and does not need any modifications to current engines (A. Saravanan et al. 2020). There have been reports of the production of biodiesel using a variety of food oils, including sunflower, maize, mustard palm, soybean, canola and coconut oils. Ahmad et al. (2022) have critically examined the catalytic transesterification reaction's use in the generation of biodiesel from coconut oil. Öztürk and Can (2022) have evaluated the performance and emission behaviour of direct-injection diesel engines running on canola oil biodiesel–diesel blends under various operating conditions. Rezania et al. (2022) have produced biodiesel from wild mustard seed oil using a heterogenous nanoparticle catalyst and found more than 90% biodiesel yield. Rama Krishna Reddy et al. (2022) have analysed the diesel engine's performance, combustion and emission characteristics while using corn-based biodiesel blends. Foroutan et al. (2022) have studied the biodiesel production from sunflower oil using the composite catalyst. Jayakumar et al. (2022) investigated the direct-injection diesel engine emission and performance behaviour fuelled with soybean biodiesel.

The utilisation of edible oil for biodiesel creates the problem of food security and hike in edible oil prices. The largest producers of biodiesel are the USA, Brazil, Indonesia, etc. Biodiesel produced from edible oil requires a large area of agriculture land that causes a dispute between food and fuels (Lustig 2009). Some important edible oil resources used for

**Table 1** Fatty acid composition of different biodiesel feedstock

| Fatty acid | Acid name | *Prosopis julifera* oil | Tamarind seed oil | Sea mango biodiesel | *Ailanthus altissima* seed oil | *Michelia champaca* seed oil | *Crambe abyssinica* oil | *Aegle marmelos* seed oil | *Cuphea* oil | *Melia azedarach* oil | Sal seed oil | Jojoba oil | *Garcinia indica* | Taramira seed oil | *Raphanus sativus* L. oil | Tannery waste fat |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C 8:0 | Caprylic acid | – | – | – | 0.31 | – | – | – | 0.3 | – | – | – | – | – | – | – |
| C10:0 | Capric acid | – | – | – | – | – | – | – | 64.7 | – | – | – | – | – | – | – |
| C12:0 | Lauric acid | 0.2 | 3.78 | – | – | – | – | – | 3.0 | – | – | – | – | – | – | – |
| C14:0 | Myristic acid | 0.1 | 1.59 | – | – | – | – | 4.3 | 4.5 | – | – | – | – | – | – | 4.18 |
| C16:0 | Palmitic acid | 10.6 | 12.67 | 30.3 | 2.01 | 15.8 | 2.18 | 38.8 | 7.0 | 9.1 ± 0.5 | 7.35 | – | 8.0 | 6.9 | 6.13 | 24.22 |
| C16:1 | Palmitoleic acid | – | – | – | 0.2 | 6.9 | – | – | – | 1.8 ± 0.01 | – | – | – | 0.2 | 0.05 | |
| C18:0 | Stearic acid | 5.2 | 15.93 | 3.8 | 0.88 | 2.5 | – | – | 0.9 | 3.9 ± 0.1 | 49.38 | – | 5.5 | 2.3 | 1.86 | 30.23 |
| C18:1 | Oleic acid | 34.7 | 47.48 | 48.1 | 25.53 | 22.3 | 16.49 | 12.6 | 12.2 | 61.5 ± 0.4 | 34.69 | 2.47 | 50.2 | 11.9 | 23.87 | 37.76 |
| C18:2 | Linoleic acid | 43.4 | 18.34 | 17.8 | 37.36 | 42.5 | 9.34 | 13.4 | 6.7 | 9.2 ± 0.2 | – | 0.38 | 26.0 | 16.3 | 13.46 | 2.78 |
| C18:3 | Linolenic acid | – | 0.63 | – | 0.17 | – | 4.80 | 18.4 | – | 0.8 ± 0.0 | – | – | – | 36.2 | 10.34 | 0.17 |
| C18:3 | Ricinoleic acid | – | – | – | – | – | – | 12.5 | – | – | – | – | – | – | – | – |
| C20:0 | Arachidice acid | 0.13 | – | – | 0.32 | – | – | – | – | – | 8.56 | – | – | – | 0.68 | 0.20 |
| C20:1 | Eicosenoic acid | – | – | – | – | – | 4.69 | – | – | – | – | 46.8 | – | 13.0 | 8.57 | – |
| C20:2 | Eicosadienoic acid | – | – | – | – | – | – | – | – | – | – | – | – | 1.2 | 1.64 | – |
| C22:0 | Behenic acid | 0.1 | – | – | – | – | – | – | – | – | – | – | – | 1.7 | – | – |
| C22:1 | Erucic acid | – | – | – | – | – | 62.50 | – | – | – | – | 39.8 | – | 10.3 | 31.76 | – |
| C23:0 | Tricosanoic acid | – | – | – | – | – | – | – | – | – | – | 2.09 | – | – | – | – |
| C24:0 | Lignoceric acid | – | – | – | – | – | – | – | – | – | – | 6.27 | – | – | – | – |
| C24:1 | Nervonic acid | – | – | – | – | – | – | – | – | – | – | 2.16 | – | – | – | – |
| – | Keto acid | – | – | – | – | 10 | – | – | – | – | – | – | 10.3 | – | – | – |
| | Other acids | – | – | – | 34.05 | – | – | – | – | – | – | – | – | – | – | – |
| Ref | | (Rajeshwaran et al. 2018) | (Raju et al. 2020) | (Kumar and Sharma 2011) | (Hoseini et al. 2018d) | (Hosamani et al. 2009) | (Uyaroğlu et al. 2018) | (Katagi et al. 2011) | (Knothe et al. 2009) | (Awais et al. 2020) | (Hasan et al. 2020b) | (El-Seesy et al. 2018) | (Hosamani et al. 2009) | (Flanders & Abdulkarim 1985) | (Fadhil et al. 2019) | (Booramurthy et al. 2022a, b) |

**Table 2** Characteristics of biodiesel feedstock

| Oil feed stock | Flash point (℃) | Viscosity 40 °C ($mm^2/s$) | Calorific value (MJ) | Density ($kg/m^3$) | Acid value (mg KOH $g^{-1}$) | Saponification no | Molecular weight (g/mol) | Ref |
|---|---|---|---|---|---|---|---|---|
| *Prosopis julifera* oil | 202–212 | 38–41.2 | 38–41 | 967–971 | 39–43.7 | 180–186 | – | (Rajeshwaran et al. 2018) |
| Sea mango oil | – | 29.57 | 40.86 | 919.8 | 0.24 | – | 860.9 | (Rohith Renish et al. 2021) |
| *Parinari polyandra* | 192 | 62 | 43.10 | | 0.94 | 176.4 | – | (Ogunkunle and Ahmed 2019b) |
| *Ailanthus altissima* oil | – | 36 | – | 910 | 0.64 | – | 873.40 | (Hoseini et al. 2018a) |
| *Michelia champaca* oil | 232 | 47.94 | 36.28 | 920 | 10.55 | 209.17 | 840.08 | (Hotti and Hebbal 2015) |
| *Abrus precatorius* oil | – | 23.4 | – | 920 | 5.74 | 227.8 | – | (Joseph et al. 2014) |
| *Crambe abyssinica* oil | 179 | 5.80 ± 0.04 | – | 874 | 0.48 ± 0.01 | – | 989.7 | (Costa et al. 2019) |
| *Aegle marmelos* | | 24.3 | 36.3 | 896 | 3.7 | 205.0 | 813.204 | (Katagi et al. 2011), (Krishnamoorthi et al. 2018), (Dhanamurugan and Subramanian 2015) |
| *Eichhornia crassipes* oil | 246 | 26.4 | 35.5 | 952 | – | – | – | (Venu et al. 2019) |
| *Melia azedarach* oil | – | 15.46 | – | 902 | 5.57 | 168.83 | 874.57 | (Stavarache et al. 2008) |
| Sal seed oil | 238 | 60.96 | 37–38 | – | 66.39 | 192.14 | – | (Hasan et al. 2020a), (Singh Pali et al. 2020) |
| Jojoba oil | 285 | 14.97 | 43.65 | 850 | 0.91 | – | 606 | (Agarwal et al. 2020), (El-Seesy et al. 2018) |
| *Garcinia indica* oil | – | – | – | – | – | 200 | – | (Hosamani et al. 2009) |
| *Raphanus sativus* L. oil | 280 | 19.77 | – | 918.8 | 2.01 | 210.62 | – | (Fadhil et al. 2019) |
| Tannery waste fat | – | 45.6 | – | 916 | 7.4 | – | – | (Booramurthy et al. 2022a, b) |

the production of biodiesel are soybean, sunflower and palm which leads to problems like starvation in developing countries (Anwar et al. 2010). Although neat edible oil poses a threat to food security, it is the most easily convertible feedstock for biodiesel production. In addition, for so many, the edible oil crop plantation is already well established, with certain crops generating good quality oil that delivers the greatest conversion to biodiesel via the transesterification process. A sustainable plantation can resolve the problem associated with edible oil biodiesel (Janaun and Ellis 2010). Many non-edible oils like Jatropha, castor, karanja, neem, tobacco and mahua have also been studied widely for biodiesel production. Singh et al. (2022) have produced biodiesel from Jatropha oil employing heterogeneous catalyst and optimise the engine performance and emission output fuelled with Jatropha biodiesel blend. Attia et al. (2022) have examined the diesel performance and particulate emission behaviour at different blending ratios of castor biodiesel in neat diesel. Kishore Khatri et al. (2023) have developed the predictive modelling for diesel engine performance behaviour fuelled with karanja biodiesel, using artificial neural network tool. Ansari et al. (2022) investigated the diesel engine performance and emission characteristics using mahua biodiesel–diesel blend. Vinodkumar and Karthikeyan (2022) have examined the diesel engine behaviour using neem biodiesel with an injection of *n*-decanol in the manifold. Arivarasu et al. (2023) have done work on production of biodiesel from tobacco seed oil by employing a tungstophosphoric acid catalyst. Due to the presence of some toxic substances, non-edible oils are not suitable for human foods. Non-edible resources of biodiesel require land that are not productive for crops (A. L. Ahmad et al. 2011). Some research shows that non-edible oil resources used for the production of biodiesel have the advantage over edible oil resources like resolving the problems of fuel versus food, environmental as well as economic issues related to edible oils resources (Gui et al. 2008). Generally, non-edible oils like waste oil, grease and animal fats are called ‘lipids’ (Rajak and Verma 2018). As compared to edible and non-edible oils, waste oils provide more efficiency. Waste oil consists of tallow, waste cooking oil, chicken fat, by-product of fish oil, etc. Waste oils possess more amount of ‘triglycerides’ contained in their composition which is very useful in the production of biodiesels by the process of transesterification in the presence of some alcoholic catalysts. Biodiesels produced from waste oils are more economical and eco-friendly as compared to biodiesel produced from edible and non-edible oils (Al-Kahtani 1991). Waste oils can be collected from various sources like restaurants, households and fast-food factories and then further recycled to come in

**Table 3** Characteristics of various methyl ester (biodiesel)

| Biodiesel feed stock | Cloud point (℃) | Pour point (℃) | Flash point (℃) | Viscosity (mm²/s) 40℃ | Calorific value (MJ) | Density (kg/m³) | Cetane number | Acid no | Ref |
|---|---|---|---|---|---|---|---|---|---|
| *Prosopis juliflera* biodiesel | 4 | – | 120 | 4.9 | 39 | 893 | 49 | 2.7 | (Rajeshwaran et al. 2018) |
| Lemon grass biofuel | – | – | 54 | 4.3 | 37.61 | 916 | 39 | 0.25 | (Viswanathan et al. 2021) |
| Tamarind seed biodiesel | – | – | 159 | 7.2 | 38.7 | 884 | 45 | – | (Raju et al. 2020) |
| Sea mango biodiesel | 8 | 6 | 159.5 | 4.86 | 39.92 | 869.7 | 51.71 | 0.17 | (Ong et al. 2014; Renish et al. 2022b) |
| *Parinari polyandra* biodiesel | 4.78 | 1.05 | 165.5 | 3.905 | – | 895 | 54.3 | 0.52 | (Ogunkunle and Ahmed 2019a), (Amos et al. 2016) |
| *Ailanthus altissima* biodiesel | 2 | −4 | 169 | 4.74 | 40.5 | 873 | 49 | 0.37 | (Hoseini et al. 2020) |
| *Michelia champaca* Biodiesel | −5 | −15 | 110 | 15 | 49.00 | 887.3 | 57 | 10 | (Hosamani et al. 2009) |
| *Azolla microphylla* biodiesel | – | −8 | 72 | 5.15 | 38.11 | – | 51 | – | (Thiruvenkatachari et al. 2021) |
| *Abrus precatorius* biodiesel | −2 | 1 ± 0.23 | 137 ± 0.02 | 3.34 ± 0.01 | 38.29 | 889 | 58.3 | 0.281 | (Joseph et al. 2014) |
| *Crambe abyssinica* biodiesel | – | – | 136 | 6 | 39.56 | 872 | – | – | (Uyaroğlu et al. 2018) |
| *Aegle marmelos* biodiesel | 8.4 | 2.4 | 69 | 4.82 | 42.35 | 1055 | 53 | 0.01 | (Baranitharan et al. 2019; Baranitharan 2020) |
| *Cuphea* biodiesel | −10 | −21.5, −22.5 | – | 2.4 | 37.9 | 874 | 56 | 0 | (Fisher et al. 2010; Knothe 2014) |
| *Eichhornia crassipes* biodiesel | | 7 | 212 | 3.96 | 36.9 | 887 | 52.5 | 0.42 | (Venu et al. 2019) |
| *Melia azedarach* biodiesel | < −10 | −28 | 131.3 ± 0.5 | 3.2 | 33.1 ± 0.4 | 900 | 49.2 ± 0.5 | 0.9 ± 0.0 | (Awais et al. 2020) |
| Cedar wood biodiesel | −3 | −8 | 110 | 4.67 | 40.58 | 885 | 51 | 1.00 | (Mehra 2018) |
| Sal biodiesel | – | 18 | 127 | 5.9 | 39.65 | 876.5 | 59–62 | – | (Pali and Kumar 2016), (Singh Pali et al. 2020), (Hajra et al. 2015) |
| Jojoba biodiesel | – | −4.50 | 180 | 3.01 | 40.30 | 860 | 63 | 0.47 | (Agarwal et al. 2020) |
| *Garcinia indica* biodiesel | 12 | 9.5 | 135 | 5.80 | 39.12 | 862 | | 0.3 | (Attal et al. 2014) |
| Taramira oil biodiesel | – | – | 52 | 5.9 | 35 | 881.1 | 48 | 0.4 | (Chakrabarti et al. 2011) |
| *Raphanus sativus* biodiesel | | −4.0 ± 0.50 | 186 ± 1.0 | 3.23 ± 0.15 | – | 877.8 ± 1.1 | 50.0 ± 0.50 | 0.25 ± 0.01 | (Fadhil et al. 2019) |
| Tannery waste biodiesel | 16 | | 153 | 4.4 | – | – | 62 | 0.4 | (Booramurthy et al. 2022a, b) |

transesterification and found 94.4 wt.% biodiesel yield. Pandian Sivakumar et al. (2013) have explored the production of biodiesel from *Ceiba pentandra* oil. Two-step acid–base transesterification served as the catalyst for the process. The conversion of biodiesel was measured to be 99.5% under optimal conditions of 1.0 wt.% KOH, 6:1 methanol oil molar ratio and at 65 °C for 45 min. See et al. (2022) used fuzzy optimisation tool for biodiesel production from karanja oil. The optimised conditions of the process were obtained as 5:1 methanol/oil ratio, catalyst loading of 0.85 wt.%, 79% duty cycle and time 89.35 min. From the last few years, microalgae possesses some excellent features like their high growth rate, availability and oil content (triglycerides) and do not require any high quality of agricultural land for their growth (Scott et al. 2010). The processes involved in the production of biodiesel are very challenging. The challenges are in releasing the lipids from their intracellular location in the most energy-efficient and economical way possible, avoiding the use of large amounts of solvents, such as hexane,

**Table 4** Transesterification parameter for biodiesel production

| Oil feedstock | Catalyst loading | Alcohol | Methanol/oil ratio | Reaction temperature (℃) | Reaction time (min) | Yield FAME (%) | Refs |
|---|---|---|---|---|---|---|---|
| *Prosopis julifera* biodiesel | 0.88% w/v of KOH | Methanol | 7.5:1 v/v | 60 | 120 | 73.01 | (Rajeshwaran et al. 2018) |
| *Prosopis julifera* biodiesel | 0.5% w/v of KOH | Methanol | 3:1 v/v | 65 | 90 | 93.5 | (Ramalingam et al. 2020) |
| *Prosopis julifera* biodiesel | 1.35% w/v of KOH | Ethanol | 3.62 v/v | 65 | 120 | 87.5 | (Ramalingam et al. 2020) |
| Tamarind biodiesel | 120 g NaOH | Methanol | 3 l:15 l (methanol/oil) | 70 | 180 | 76 | (Harun Kumar et al. 2020; Raju et al. 2018; Vallapudi et al. 2018) |
| *Cerbera manghas* (sea mango biodiesel) | 1% NaOH | Methanol | 9:1 (v/v) | 50 | 60 | 98.5 | (Ong et al. 2014) |
| *Parinari polyandra* | 2% KOH | Methanol | 6:1 (v/v) | 67.5 | 120 | 94.42 | (Ogunkunle and Ahmed 2019a) |
| *Ailanthus altissima* biodiesel | 1% KOH | Methanol | 7:1 | 50 | 2 | 91.73 (ultrasonic assisted) | (Hoseini et al. 2018c) |
| *Ailanthus altissima* biodiesel | CAC, KAC, CDS | Methanol | 3:1 | 60 | 90 | 94 | (Jabeen et al. 2022) |
| *Michelia champaca* biodiesel | 0.1 g MgO | 4 g Methanol | 4 g:20 ml (methanol/oil) | 60 | 600 | 87 | (Joshi et al. 2021) |
| *Michelia champaca* biodiesel | 1.5% NaOH | Methanol | 6:1 | 60 | 75 | 83.50 | (Hotti and Hebbal 2015) |
| *Abrus precatorius* biodiesel | 0.5% NaOH | Methanol | 6:1 | 60 | 120 | 86.1 ± 0.01 | (Joseph et al. 2014) |
| *Abrus precatorius* biodiesel | 1.75% NaOH | Methanol | 500 ml oil and 155 ml methanol | 60 | – | 98.3 | (Lakshmi et al. 2022) |
| *Crambe abyssinica* biodiesel | 8% Enzyme | Methanol | 6:1 | 65 | 120 | 84 ± 5 | (Costa et al. 2021) |
| *Aegle marmelos* biodiesel | 0.5% NaOH | Methanol | 9:1 | 65 | 60 | – | (Kolli et al. 2020a, b) |
| *Eichhornia crassipes* biodiesel | 0.9 KOH | Methanol | 6:1 | 65 | 60 | – | (Venu et al. 2019) |
| *Melia azedarach* biodiesel | 1% NaOH | Methanol | 9:1 | 36 | 40 | 46 | (Stavarache et al. 2008) |
| *Melia azedarach* biodiesel | 1% NaOH | Methanol | 6:1 | 60 | 150 | 90 | (Awais et al. 2020) |
| Cedar wood biodiesel | NaOH | Methanol | – | 60 | – | – | (Mehra 2018) |
| Sal biodiesel | 8.9 g/kg | Methanol | 10.87 | 62.21 | 81.81 | 98.94 | (Singh Pali et al. 2020) |
| Jojoba biodiesel | 1.35% KOH | Methanol | – | 25 | – | 83.5 | (Bouaid et al. 2007) |
| *Raphanus sativus* biodiesel | 1.0 KOH | Methanol | 6:1 | 60 | 60 | 95.55 | (Fadhil et al. 2019) |
| Tannery sludge | 9 wt.% of nanocatalyst (Ca/$Fe_3O_4$/$Cs_2O$) | Methanol | 20.1 | 65 | 300 | 98.6 | (K. Saravanan et al. 2022) |

use as a biofuel resource (Canakci 2007). Waste oil production has grown as a consequence of rising food consumption. In Spain, Canada and the EU, respectively, around 4000, 135,000 and 7000–10,000 tonnes of WCO are generated annually (Chhetri et al. 2008). García-Martín et al. (2018) have done an investigation on production of biodiesel from waste cooking oil and used this biodiesel as a fuel to analyse the performance behaviour of turbocharged diesel engine. Sivakumar et al. (2014) investigated the utilisation of cashew nut shell oil in diesel engine. The study reveals that the oil properties are nearly similar to the diesel fuel and it can be used in diesel engine as biofuel. Deepalakshmi et al. (2014) converted discarded avocado seed directly into biodiesel. The procedure used is in situ solvent-aided alkali-catalysed and utilising as much of the carbon in the biomass as liquid biofuel as possible, potentially with the recovery of minor high-value products (Krohn et al. 2011). There are many challenges which are associated with biodiesel production and use. The challenges are feedstock availability at large scale, cost-effective production of fuel, the policy of a country, lack of customer awareness about biodiesel and availability of infrastructure (Kant Bhatia et al. 2021).

In the past, only a few researchers undertook a detailed investigation of the numerous uncommon accessible feedstocks for biodiesel synthesis and their application as fuel for diesel engine behaviour studies. The current endeavour aims to investigate some uncommon feedstock for biodiesel production. In this study, a

**Fig. 1** *Prosopis juliflora* tree (Asokan et al. 2019)

**Fig. 2** *Prosopis juliflora* seed (Ramalingam et al. 2020)

novel comprehensive review is done on the availability of uncommon biodiesel feedstock, biodiesel production, fatty acid composition, the properties of resources and their biodiesel, as well as the effect of different blending proportions of biodiesel on diesel output behaviour. The feedstock that have been discussed in this work are *Prosopis juliflora* oil, sea mango oil, *Parinari polyandra* oil, *Ailanthus altissima* oil, *Michelia champaca* oil, *Abrus precatorius oil*, *Crambe abyssinica* oil, *Aegle marmelos*, *Eichhornia crassipes* oil, *Cuphea* oil, lemon grass oil, cedar wood oil, *Shorea robusta* oil, *Melia azedarach* oil, jojoba oil, *Garcinia indica* oil, taramira oil, *Raphanus sativus* L. oil, many strains of microalgae, *Chukrasia tabularis*, industrial waste and other feedstock.

## Fatty Acid Composition of Biodiesel Feedstock

Fatty acid composition is an essential parameter for any biodiesel feedstock since it impacts the efficiency of the biodiesel production process. The quantity and type of fatty acid composition are mostly determined by plant species and growing circumstances. The various fatty acids that are generally found in the biodiesel feedstock are caprylic acid, capric acid, lauric acid, myristic acid, palmitic acid, palmitoleic acid, stearic acid, oleic acid, linoleic acid, linolenic acid, ricinoleic acid, arachidice acid, eicosenoic acid, eicosadienoic acid, behenic acid, tricosanoic acid, lignoceric acid, nervonic acid and keto acid. The fatty acid content of different biodiesel feedstock proven appropriate for biodiesel production is shown in Table 1.

## Characteristics of Feedstock and Biodiesel

The physical properties of biodiesel feedstock and biodiesel have been presented in Tables 2 and 3, respectively. The physical characteristics of biodiesel feedstock determine whether a particular oil is appropriate for producing biodiesel or not. Similarly, the physical characteristics of biodiesel have also been discussed. The physical characteristics of biodiesel fall under the ASTM, IS, EN or other standards for use in the engine.

## Transesterification summary biodiesel feedstock

The transesterification method for biodiesel production is one of the most effective and widely used ways. The high biodiesel yield is one of the advantages of this method. The transesterification method to produce biodiesel from some rare feedstock is presented in Table 4.

## Feedstocks and Engine Behaviour

The various rare feedstock-related details for biodiesel production and the effect of biodiesel on engine performance and emission characteristics are discussed below.

**Table 5** Engine performance and emission behaviour of *Prosopis juliflora* biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Single-cylinder 4-stroke TAF1 kirloskar diesel engine | B10, B20, B30 Juliflora biodiesel–diesel blend | In comparison to other blends, B20 had the greatest SFC on all loads and was the closest to base diesel. B20 blend shows the considerable improvement BTE. In comparison to conventional diesel at full loads, *Prosopis juliflora* blends have lower HC, CO and smoke emission and higher $NO_x$ and $CO_2$ emission | (Venkatesan et al. 2022) |
| Single-cylinder, 4-stroke compression ignition diesel engine | B10 to B100<br>(Juliflora seed biodiesel) | At maximum load, the BSFC for B20 is 0.27 kg/kWh, which is quite similar to the 0.26 kg/kWh of diesel. Maximum value of BTE is 32.05% for D100 and minimum value is found 29.9% for B20. In comparison to other diesel fuels, biodiesel and its blends have reduced CO and HC emissions and more $NO_x$ emissions. B20 and B30 seem to have a lower smoke opacity than diesel while operating at full load | (Asokan et al. 2019) |
| 1-Cylinder diesel engine | Juliflora biodiesel blend + isopropanol + EGR | According to experimental findings, adding 30% (biodiesel + isopropanol) to the fuel mix and 30% EGR concurrently reduced $NO_x$ as well as smoke emissions significantly while just slightly degrading engine performance. In addition to this, with increasing EGR rates, both CO and HC emissions decrease | (Raja and Premjeyakumar 2021) |
| 1-Cylinder, CRDI diesel engine | B10, B20, B30 (Juliflora seed biodiesel + DMC + EGR) | The combination of DMC additives and EGR decreases $NO_x$ and smoke while boosting CO, HC emissions. Also, the EGR with DMC additive somewhat enhances thermal efficiency and overall performance | (Ramesh et al. 2022) |

## Prosopis juliflora

It belongs to the family of the Fabaceae and grows primarily in dry tropical climatic conditions. *Prosopis juliflora* is a shrub that is found in Mexico, Venezuela, Peru and the Caribbean, and it is used to treat poison and in making medicine or biodiesels (Asokan et al. 2019). It is also found in the southern part of India (Masimalai and Kuppusamy 2015). The fruit of *Prosopis julifera* is flattened and straight, measuring 6–30 cm in length, 5–16 mm in width and 4–9 mm in thickness. The mature pods will enlarge, become pulpy and appear yellowish brown in colour. Up to 6.5 mm in length, seeds weigh between 0.25 and 0.3 g (25,000–30,000 seeds/kg). Depending on the circumstances and ecology, pod output may range from 5 to 40 kg per tree (Rajeshwaran et al. 2018). Biodiesel produced with the help of *Prosopis juliflora* seed oil has flash point, specific gravity and kinematic viscosity which are more than diesel, and the calorific value of diesel is more than biodiesel due to the presence of oxygen in biodiesel (Asokan et al. 2019). The production of biodiesel with the *Prosopis juliflora* seed oil was done by the process of transesterification (Islam et al. 2015). Soon, *Prosopis juliflora* might serve as an appealing alternative biodiesel feedstock and the average oil production is 5000 l/ha (Ramalingam et al. 2020). As these plants thrive in salty soil, they have little competition for farmland. Oleic acid is dominant in the concentration of *Prosopis juliflora* seed oil. Figure 1 shows the *Prosopis juliflora* tree and the *Juliflora* seed is depicted in Fig. 2. The engine performance and emission

**Table 6** Engine performance and emission behaviour of *Prosopis juliflora* biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| 1-Cylinder, 4-stroke direct injection diesel engine | B20, B40, B60 (lemon grass biodiesel) | B20 blend has a thermal efficiency that is 0.36% greater than diesel and superior to other mixes. In comparison to diesel fuel at full load, the exhaust gas emissions of CO, smoke opacity for B20 and UBHC were significantly reduced by 36%, 25% and 14%, respectively. In comparison to diesel fuel, B20 increased the BSFC, increased the $NO_x$ emission by 7.6% and 21%, and lowered smoke opacity by 36% | (Kotaiah et al. 2020) |
| 1-Cylinder, 4-stroke, water-cooled DI diesel engine | B30 (lemon grass biodiesel) + 50 ppm metal oxide nanoparticles ZnO, $TiO_2$ and $Al_2O_3$ (additives) | Brake thermal efficiency above 3% is heavily dependent on the B30 biodiesel mix with 50 ppm ZnO. The results showed that, compared to the other two nano-additives, lemon grass biodiesel with green produced zinc oxide nanoparticles had improved performance, emission and combustion characteristics above 5% | (Sunil Kumar et al. 2021) |
| 1-Cylinder, 4-stroke, diesel ignition diesel engine | B30 (lemon grass biodiesel) + propyl gallate (PG) and ternary butyl hydroquinone (TBHQ) in 300, 600 and 900 ppm nanoparticles (antioxidant) | BTE was shown to be greater with antioxidants compared to diesel, whereas SFC was found to be lower. Decreased emissions of CO, $O_2$ and hydrocarbons were seen in the samples treated with antioxidants. The levels of $NO_x$ were found to be lowered in the presence of TBHQ. As a whole, PG outperformed TBHQ except in terms of $NO_x$ emissions | (Ganesan et al. 2021) |
| 1-Cylinder, 4-stroke, diesel ignition diesel engine | B20 (lemon grass biodiesel) + $Al_2O_3$ (10, 20, 30 ppm) nanoparticles | The results show that as compared to B100, for B20 blend with 20 ppm $Al_2O_3$, the BTE increases 11.9%, HC decreases 40%, CO decreases 6%, $NO_x$ emission lowered by 31% and smoke emission lowered by 39% | (D. Balasubramanian et al. 2019) |
| Kirloskar 1C, DI (air-cooled diesel engine), electrical dynamometer | B25 with (2.5–5%) ethanol | Increases in BSFC 15.8% for 2.5% blend of ethanol and 9.1% increases for 5% blend of ethanol. Increases in BTE 11.74% for ethanol blend of 2.5% and 13.9% for 5% blend of ethanol. CO decreases and $NO_x$ increases by 32% for 2.5% ethanol and 36.8% increases for 5% blend of ethanol and smoke emission decreases 36.8% for 2.5% ethanol and 32% for 5% ethanol | (Sathiyamoorthi and Sankaranarayanan 2017) |
| 1C, 4S VCR water-cooled diesel engine | B10, B20, B30 (lemon grass biodiesel) | Maximum BTE for B20 is around 26.12%, which is somewhat greater than that for diesel (24.91%). Experiments with different blends of biodiesel indicated that their respective $CO_2$ and HC emissions were decreased by 6% and 5% when compared to diesel, but CO emissions were comparable for B20. The $NO_x$ emission increases by 26% to the diesel | (Dhivagar et al. 2018) |

characteristics of the engine with *Prosopis juliflora* biodiesel are shown in Table 5.

## Cymbopogon citratus (Lemon Grass)

Lemon grass is a plant that produces lemon grass oil. It is obtained from lemon which is found in Australia and Asia. Approximately 90% of lemon grass oil is created and 250 tonnes of oil is refined in an area of 4000 ha in the waste lands of India (Kotaiah et al. 2020). The engine behaviour with lemon grass biodiesel is discussed in Table 6.

## Tamarindus indica L. (Tamarind)

Tamarind seed oil is produced from the seed of the tamarind tree. It has a long life span to grow up to a medium height of 12–30 m. Tamarind tree is found in Africa, Pacific islands, Sri Lanka, Malaysia and India; Thailand has the largest plantation of tamarind tree. In India, tamarind tree is mainly found in Maharashtra, Karnataka and Tamil Nadu. The saponification value of tamarind seed oil is 186 mg/g. Oil content of tamarind seed oil is found between 7 and 8%/kg of seeds. Tamarind seed oil contains fatty acids like lauric acid (0.3%), oleic acid (19.6–27%), palmitic acid (8.7–14.8%), linoleic acid (7.5–55.4%) and arachidic acid (3.7–12.2%) (Kumbhar et al. 2022). The tamarind seed and fruit are shown in Figs. 3 and 4, respectively. Table 7 presents the engine behaviour with tamarind biodiesel blend.

## Cerbera odollum (Sea Mango)

*Cerbera odollum* is also called sea mango. The *Cerbera odollum* tree is very toxic since it is a member of the Apocynaceae family (Gaillard et al. 2004). *Cerbera odollam* survives in the salt marshes and coastal streams of southern India, as well as in the middle and southern regions of Vietnam, Cambodia, Sri Lanka, Myanmar, Madagascar and Malaysia (Kumar and Sharma 2011). The sea mango tree is around 12 m in height and is evergreen. Fruits of this tree are 5–10 cm in length and have an egg form, while the leaves are glossy dark green and grouped in a spiral (Rohith Renish et al. 2021). This tree is often found along the coasts of South India, Malaysia, Vietnam, Sri Lanka, Madagascar and Myanmar (Renish et al. 2022a). The seed of sea mango contains 54% oil (Kumar and Sharma 2011). Among the *Cerbera odollam* oil's fatty acids, oleic acid makes up 48.1%, palmitic 30.3%, linoleic 17.8% and stearic 3.8% (Kansedo et al. 2009). A viable substitute feedstock for the production of biodiesel is *Cebrera odollam* oil (Kansedo et al. 2009). Sea mango fruit is depicted in Fig. 5. The performance and emission behaviors of a diesel engine fueled with sea mango biodiesel are presented in Table 8.

**Fig. 3** Tamarind seed for oil extraction (Idris et al. 2022)

**Fig. 4** Tamarind fruit (Dhana Raju et al. 2018)

## Parinari polyandra L. (Sand Apple)

*Parinari polyandra* is also known as the sand apple. The *Parinari polyandra* seed is often found in West Africa. It comes from the Rosaceae family, which mostly grows in tropical savanna regions. These places include Nigeria, Ghana, Senegal, Ivory Coast, Mali, Cameroon and Sudan. Evergreen *Parinari polyandra* trees may grow to heights of 10–12 m. Its profile is low and bushy, and its bark is smooth. The blossoms are fleshy and are around 1.3–2 cm in length. The freshly harvested seed kernel has an oil content ranging from 31 to 60%, based on the variety and the time of year it was harvested (Ogunkunle and Ahmed 2019b). It has been discovered that the *Parinari polyandra* seed oil has a high oil yield content, which may be used for the

**Table 7** Engine performance and emission behavior of tamarind biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Direct injection 4-stroke diesel engine | B10, B20, B30 (tamarind seed oil) + 20 ppm of $Al_2O_3$ (nano-additive) | At full load BSFC is higher for B30 + 20 ppm of $Al_2O_3$ (0.29 kg/kWh) and is 10% lower than diesel BSFC (0.3 kg/kWh), and the BTE is found in B30 + 20 ppm $Al_2O_3$ (30.26%) similar to diesel (29.54%). The biodiesel blends with $Al_2O_3$ (20 ppm) have higher $NO_x$ emissions and lower CO emissions than diesel. With the incorporation of high concentrations of nanoparticles, HC emissions are shown to be significantly decreased | (Shaisundaram et al. 2020) |
| Kirloskar DI, water-cooled CI diesel engine | Tamarind seed methyl ester (TSME) + butylated hydroxyl anisole (BHA) 1000–2000 ppm (additive) | B20 blended with BHA 2000 ppm shows decrement in BSFC as compared to B20 at full load. B20 blended with BHA 2000 ppm shows 1.79% increment in BTE as compared to B20 at full load conditions. B20 blended with BHA 2000 ppm shows a 23.32% reduction in $NO_x$ emission as compared to B20 at full load and B20 with BHA 2000 ppm (0.09%) increase in CO emission as compared to B20 (0.096%). HC emission decreased compared to diesel | (Saibabu et al. 2022) |
| Single-cylinder direct injection compression ignition engine | B20 biodiesel blend of tamarind seed oil methyl ester with 19°, 23° and 27° injection timing | Concentrating on the findings at full load, it was found that brake thermal efficiency had increased by 3.18%, and there had been a noticeable decrease in CO, HC, $NO_x$ and smoke by 17.3%, 57.3%, 31.34% and 8.1% when compared to standard injection timing (23°). At 19° bTDC, BTE for B20 is found to be closer to that of diesel. BSFC for B20 is found (0.315 kg/kWh) at 19° injection timing which is slightly greater than BSFC for diesel (0.265 kg/kWh) | (Harun Kumar et al. 2020) |
| Single-cylinder 4-stroke diesel engine | B20 (tamarind biodiesel) + $Al_2O_3$ having conc. 30, 60, 90 ppm | It has been shown that the BTE, BSFC of B20 is significantly improved when nanoparticles of $Al_2O_3$ are added at different doses (30, 60 and 90 ppm) in comparison to 20% biodiesel mix. The testing findings of the TSME 20 with 60 ppm $Al_2O_3$ mix show that the maximum brake thermal efficiency is 34.94%, minimum BSFC (0.24 kg/kWh). Alumina nanoparticles in tamarind oil methyl ester blend reduce HC and CO emissions significantly and NOx emission increases. 60 ppm nano-additive in B20 blend found best for better engine performance and reduction in emission | (Raju et al. 2019) |

**Table 7** (continued)

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Single-cylinder 4-stroke CI engine | Tamarind seed oil biodiesel with 30 and 60 ppm of $Al_2O_3$ and multiwall carbon nanotube | Alumina oxide added at 60 ppm to TSME blend increased BTE by 1.6%. Nanoparticle-added TSME mix reduces CO and UHC emissions by 15–51% and 24–68%, and NOx emission decreased by 7–9%, respectively. Nanoparticle addition to TSME blend improved combustion comparison to TSME–diesel blend | (Raju et al. 2018) |
| Kirloskar TAF 4-stroke single-cylinder water-cooled diesel engine | B20 (tamarind seed methyl ester) + EGR (exhaust gas recirculation) 10%, 20%, 30% | Compared to diesel, $NO_x$ emissions are decreased by 45.67% in the B20 blend with 20% EGR rate, and by 52.69% in the B20 blend but brake thermal efficiency has somewhat decreased. As the EGR% increases, the BTE decreases and BSFC increases, CO emission increases and HC emission decreases for B20 blend. B20 blend with a 20% EGR rate is the best strategy for improved $NO_x$ emission reduction | (Raju and Kishore 2017) |
| Kirloskar TV1 stroke single-cylinder water-cooled diesel engine | B20 (tamarind seed methyl ester) at 180, 200 and 220 bar with 10% EGR and 20% EGR | At peak load, increasing injection pressure (220 bar) increases efficiency by 2.29% while decreasing emissions by 53.84%, 56.25% and 75.15%, respectively, except nitrogen oxides, which are shown to be increased by 11% (compared to 200 bar) in the experiments. When adding 10% EGR to a 220-bar engine, $NO_x$ emissions are decreased by 80.5% without significantly impacting engine performance | (Vallapudi et al. 2018) |
| Kirloskar TV1 stroke single-cylinder water-cooled diesel engine | B20 blend (tamarind seed methyl ester) + butanol (5%, 10%, 15%) | The results show that 5% butanol in B20 blend increases the BTE by 3.21% as compared to B20 blend. The exhaust emissions of carbon monoxide, hydrocarbons and smoke opacity were found to be marginally reduced by 7.25%, 6.52% and 6.2%, respectively, for 5% butanol in B20 blend, as compared to those of tamarind biodiesel blend operating at full load | (Swamy et al. 2019) |

**Fig. 5** Sea mango fruit

manufacturing of biodiesel and alkyd resin (Motojesi et al. 2011). For fruits harvested in April, the main components of *Parinari polyandra* benth seed oil are *n*-hexadecanoic acid (46.3%), 9,12-octadecadienoic acid (18.10%) and phytol (26.0%), whereas for fruits harvested in November, the main components are *n*-hexadecanoic acid (4.69%), 9,12-octadecadieonic acid (8.31%), arachidonic acid (43.38%) and stigmasterol (13.41%) (Ogunkunle and Ahmed 2019b). The research revealed that the oil extracted from seeds collected in April of the year would be suitable for the production of biodiesel (Motojesi et al. 2011). The fruit and nut of *Parinari polyandra* feedstock are shown in Fig. 6.

The performance of CI engine sand apple ethyl ester used with its blends B5, B10, B15, B20 and B25 has been evaluated. It is observed that BSFC is decreased from 4.50 to 3.59 g/kWh when the loading condition increased. BSFC for B5, B10, B15, B20 and B25 ranges from 5.16 to 4.73, 6.12–5.38, 6.97–6.34, 8.68–6.98 and 11.46–9.47 g/kWh,

**Table 8** Engine performance and emission behavior of sea mango biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Single-cylinder 4-stroke VCR engine without heating the engine | B20 (*Cerbera odollum*) + compression ratio (CR) (16:1, 17:1, 18:1) | BSFC of diesel at CR 17:1 is 0.32 kg/kWh. BSFC of B20 blend at CR 16:1, 17:1 and 18:1 is 0.37, 0.34 and 0.3 kg/kWh, respectively. BSFC of B20 blend at CR 18:1 is 6.25% lower than diesel. BTE of diesel at CR 17:1 is 28.36%. BTE of B20 blend at CR 16:1, 17:1, 18:1 is 26.21%, 27.55% and 29.94%, respectively. BTE of B20 blend at CR 18:1 is 5.57% higher than diesel<br>CO, HC and $NO_x$ emission of diesel at CR (17:1) is 0.28%, 65 ppm and 1044 ppm, respectively. CO emission of B20 blend at CR 16:1, 17:1, 18:1 is 0.26%, 0.24%, 0.21%, and CO emissions of B20 blend at CR 18:1 is 26.71% lower than diesel<br>HC emission of B20 blend at CR 16:1, 17:1, 18:1 is 58, 54, 45 ppm, and HC emissions of B20 blend at CR 18:1 is 37.76% lower than diesel<br>$NO_x$ emission of B20 blend at CR 16:1, 17:1, 18:1 is 1052, 1107, 1193 ppm, respectively, and $NO_x$ emissions of B20 blend at CR 18:1 is 14.27% higher than diesel | (Renish et al. 2022a) |
| Single-cylinder 4-stroke VCR engine | B10, B20, B30, B40 (sea mango biodiesel blends) at variable compression ratio | A greater compression ratio (CR) was shown to be beneficial to an engine's efficiency, emissions and combustion. BTHE, SFC and EGT all increased by 8.78%, 11.18% and 2.52% at CR 18:1, respectively, as compared to CR17. In addition, at CR 18:1, the CO, HC and smoke emissions decreased by 14.65%, 18.56% and 11.56%, respectively. The rise in $NO_x$ emissions was 6.77%. This study found that sea mango methyl ester blends at CR 18:1 can replace diesel without engine changes | (Renish et al. 2022b) |

**Fig. 6** *Parinari polyandra* fruit and nut (Ogunkunle and Ahmed 2019a)

**Fig. 7** *Ailanthus* tree (Hoseini et al. 2018a)

**Fig. 8** *Ailanthus* tree shrub (Hoseini et al. 2020)

**Fig. 9** *Ailanthus* seed (Hoseini et al. 2018a)

respectively. BTE decreases when the load on the specimen increases. BTE for B5, B10, B15, B20 and B25 ranges from 76.98 to 83.97, 64.54–73.62, 56.86–62.46, 45.64–56.73 and 34.84–42.13%, respectively (Saleh et al. 2021). The diesel engine testing has been done with automotive gas oil and biodiesel blends B5, B10, B15 and B20. It is observed that BSFC is increased when the loading condition increases. BSFC for B5, B10, B15 and B20 ranges from 4.73 to 5.6, 5.38–6.12, 6.34–6.97 and 6.98–8.68 g/kWh, respectively. Brake thermal efficiency increases for the B5 blend when the load on the specimen increases. BTE for B5, B10, B15 and B20 ranges from 71.26 to 16.26, 15.29–14.02, 13.07–12.43 and 11.95–10.64%, respectively (Ahmed 2018). Engine emissions and engine performance analysis is done for diesel engines fuelled with *Parinari polyandra* biodiesel and its blends B10, B20 and B30. In the performance testing of biodiesel blends in marine diesel engines, the BSFC is increased when the content of biodiesel increased in the blended fuel. BTE increased when the biodiesel content increased in blended fuel. For B10, B20 and B30, total $CO_2$ emission is reduced by 53.8%, 33.5% and 21.7% as compared to diesel. For B10, B20 and B30, total CO emission is reduced by 53.4%, 67.8% and 81.7% as compared to diesel. For B10, B20 and B30, total hydrocarbon emissions is reduced by 7.8%, 11.0% and 13.8% as compared to diesel (Ogunkunle and Ahmed 2020).

**Table 9** Engine performance and emission behaviour of *Ailanthus* biodiesel

| Engine | Fuel type | Engin e performance and emission | Ref |
|---|---|---|---|
| Air-cooled 1C (Lombardino diesel engine) + eddy current dynamometer | B10, B20 blend (*Ailanthus altissima* biodoesel) with nanographene oxide (60 ppm) having surface area 900 $m^2/g$ and average particle size of 150 nm | BSFC for diesel (415.26 g/kWh), BFSC for B10, B20, B20GO60 are 423.13, 436.34, 395.65 g/kWh. CO emission for diesel (1.36% vol) and CO emissions for B10, B20, B20GO60 are 1.24, 1.21, 1.09% vol. HC emissions for diesel (227.79 ppm) and HC emissions for B10, B20, B20GO60 are 204.37, 171.13, 135.83 ppm. $CO_2$ emission for diesel (3.7% vol) and $CO_2$ emissions for B10, B20, B20GO60 are 3.37, 3.35, 3.55% vol. The addition of nano-additive increases the $NO_x$ emission | (Hoseini et al. 2018a) |
| Air-cooled 510 cc single cylinder (Lombardino diesel engine) + eddy current dynamometer | B0, B10, B20 blend (*Ailanthus altissima* biodoesel) with nanographene oxide (30, 60 and 90 ppm). Mean particle thickness is 1.2 nm | Research found that adding GO to fuel blend considerably boosted engine power, torque and EGT, while decreasing SFC. GO-nanoparticle additives reduced CO and UHC emissions by 7–20% and 15–28%, respectively, but increased $CO_2$ and $NO_x$ emissions by 6–10% and 5–8%, respectively. This reveals that *Ailanthus altissima* biodiesel–diesel blend with GO nanoparticle can be utilised as eco-friendly fuel in diesel engines for operation | (Hoseini et al. 2018b) |

**Fig. 10** *Michelia champaka* flower fruit and seed (Hotti & Hebbal, 2015)

## Ailanthus altissima (Tree of Heaven)

*Ailanthus altissima* is also called the fruit of the tree of heaven. *Ailanthus altissima* belongs to the Simaroubacae family. The growth rate of *Ailanthus altissima* tree roots and leaves is very high compared to other oil resources of biodiesel resources. The plant of *Ailanthus altissima* is environment-friendly. The tree of *Ailanthus altissima* grows up to 12–18 m; within 25 years after cultivation, they start to produce seeds which amount to around 80,000 seeds per tree and increase up to 3 lakhs, and weight of *Ailanthus altissima* seeds varies from 7 to 22 kg (Hoseini et al. 2020).

**Fig. 11** Azolla algal biomass (Kannan and Christraj 2018)

The *Ailanthus* tree, shrub and seed are shown in Figs. 7, 8 and 9, respectively. The emission and performance of diesel engine running on *Ailanthus altissima* biodiesel is presented in Table 9.

## Michelia champaca L.

*Michelia champaca* is an evergreen tree. *Michelia champaca* belongs to the Magnoliaceae family, which has 9 genera and 70 species. It is a tall, attractive evergreen tree with a straight stem and smooth, dark-brown bark. The tree blooms in hot, wet weather and bears fruit in late August(Hosamani et al. 2009). The size of *Michelia champaca* is small or sometimes medium. *Michelia champaca* tree cultivates in Nepal, India, Sri Lanka, Bangladesh, China, Indo-China, Myanmar, Thailand, Malaysia, Indonesia, etc. *Michelia champaca* requires moist condition, well-drained sandy loam soil (Hotti and Hebbal 2015). *Michelia champaca* seed contains 45% oil. It is generally used in pharmaceuticals industries and perfumery industries (Khan et al. 2014). The saponification value (SV), iodine value (IV) and cetane number (CN) of *Michelia champaca* methyl esters indicate their viability for biodiesel synthesis (Hosamani et al. 2009). The important fuel property of *Michelia champaca* biodiesel, ethanol and diesel blend has been analysed for utilisation of blend as fuel in engine (Chandra et al. 2020). The flower fruit and seed of *Michelia champaka* is shown in Fig. 10.

## Azolla

An example of a bio-oil derived from algae is *Azolla* oil. There are seven different species of azolla, all of which have the same genus and common names: *Azolla caroliniana*, *Azolla filiculoides*, *Azolla microphylla*, *Azolla mexicana*, *Azolla africanna*, *Azolla nilotica* and *Azolla pinnata*. Azolla oil yields around 25 to 30 ml per kilogramme of *Azolla* biomass. It forms a symbiotic relationship with the blue-green alga *Anabaena azolla*, which grows in the cavities of azolla leaves. Azolla is able to utilise atmospheric nitrogen (Narayanasamy and Jeyakumar 2019). The azolla algal biomass is shown in Fig. 11. The performance of diesel engines fuelled with azolla algal biodiesel is discussed in Table 10.

## Abrus precatorius

*Abrus precatorius* is a non-edible oil and belongs to the family of Fabaceae. It grows 10–20 ft tall when supported by other plants (Kuete 2014). The seed oil yield is 2.52% (w/w). *Abrus precatorius* seed is found in India, Thailand, Sri Lanka, South Chinaa and Nigeria. *Abrus precatorius* seed contains moisture (5.06%), crude protein (39.20%), oil content (2.5%) and carbohydrates (42.4%) (Attal et al. 2010). The *Abrus precatorius* seed is shown in Fig. 12.

## Crambe abyssinica Oil

A more sustainable fuel may be produced using non-edible oils from *Crambe abyssinica* oil (Costa et al. 2018). The species *Crambe abyssinica*, often referred to as '*Crambe*', which is a member of the Cruciferous family, is one of the non-food oil crops having a significant potential for the generation of biodiesel. It is native to Ethiopia and Tanzania and comes from the Mediterranean area, but because of its resistance to pests and illnesses, it can also adapt to the widest range of climatic circumstances (cold and dry places) (Falasca et al. 2010). The short yearly cycle (90–100 days) of *Crambe*, which allows for its use as a second crop, especially in crop rotation, makes it feasible to produce a lot of biodiesel (Rosa et al. 2014). The seed has a high oil content of around 38% weight, and mechanical pressing may readily extract that oil (de Aquino et al. 2018). *Crambe* can withstand heavy metals and salt, making it suitable for cultivation in marginal areas or polluted soils; nevertheless, further research is needed to improve crop yields (Ionov et al. 2013). In an attempt to evaluate the full viability of *Crambe* through seeding, harvesting, oil extraction and biodiesel production, the entire cycle of seeding, harvesting, oil extraction and biodiesel production was carried out; probably the first study of this species to be conducted in Portugal (Costa et al. 2019). The diesel engine fuelled with *Crambe abyssinica* biodiesel is discussed in Table 11. The *Crambe abyssinica* crop is presented in Fig. 13.

## Aegle marmelos Oil

*Aegle marmelos* species falls under the Rutaceae plant family (Krishnamoorthi snd Malayalamurthi 2018). It is a little tree with powerful, straight, cutting spines. The

**Table 10** Engine performance and emission behaviour of azolla biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Single-cylinder direct injection, water cooled eddy current dynamometer | Azolla oil methyl ester (B20) + nanoparticles $TiO_2$ (25, 50, 75, 100) ppm with particle size 99.2 nm | BFSC for diesel, B20, B20 + 25, B20 + 50, B20 + 75, B20 + 100 at min BP condition 0.65, 0.73, 0.66, 0.65, 0.62, 0.58 kg/kWh, respectively. BTE for diesel, B20, B20 + 25, B20 + 50, B20 + 75 and B20 + 100 at minimum BP conditions 12.82, 11.35, 11.97, 12.32, 12.57 and 12.73, respectively. The BSFC decreases and BTE increases with the addition of nanoparticles. CO emission for diesel, B20, B20 + 25, B20 + 50, B20 + 75, B20 + 100 at min BP condition 0.088, 0.096, 0.091, 0.082, 0.078 and 0.075, respectively. $NO_x$ emission for diesel, B20, B20 + 25, B20 + 50, B20 + 75, B20 + 100 at min BP condition is 51, 41.33, 48.33, 58.66, 61.66 and 68, respectively | (Narayanasamy and Jeyakumar 2019) |
| Single-cylinder 4-stroke diesel engine | Azolla oil methyl ester (B20) blend + BaO nanoparticle added 50 and 100 ppm. The average particle size is 50–100 nm | With the addition of BaO nanoparticle in B20 mixture of the fuel the CO, UHC and $O_2$ emissions all decrease; however, NO emissions increase. There are fewer emissions in biodiesel fuel mixes including nanoparticles because there is more oxygen for better fuel burning | (Kannan and Christraj 2018) |
| Four-stroke compression ignition engine | Azolla biodiesel (water fern) B10, B20 and B0 | In terms of engine performance parameters, it was found that the B10 blend exhibited behaviour that was more similar to that of pure diesel fuel. On the other hand, B10 demonstrated a considerable decrease rate when compared to diesel fuel in terms of emission metrics like $NO_x$ and HC | (Naik et al. 2022) |
| Single-cylinder constant speed 4-stroke diesel engine | B20 blend of azolla biodiesel at 300 bar and 900 bar injection pressure | The combustion is improved when the injection pressure rises, the fuel atomisation improves, and other spray properties are improved. Under full load circumstances, the BTE of diesel fuel at 300 bar injection pressure is 3% lower than the B20 BTE at 900 bar injection pressure. When compared to diesel, the HC, CO and smoke emissions from the B20 engine at 900 bar injection pressure were decreased by 13.3%, 28.5% and 12.3%, respectively | (Thiruvenkatachari et al. 2022) |

**Fig. 12** *Abrus precatorius* seed (Bhutia and Maiti 2011)

fragrant, foliate leaves are a greenish white colour (Katagi et al. 2011). The bael (*Aegle marmelos*) tree produces non-edible seeds that might be used to make biodiesel. In Southeast Asia, including Thailand, China and Malaysia, as well as the arid Indian subcontinent, these seeds are commonly accessible. The oil content in bael seeds ranges from 42 to 55 weight percent on average, and the potential for its production makes it more competitive than any other non-edible seed(Kolli et al. 2020a, b). Due to the salient feature like huge availability, medicinal benefits, bio-fertiliser usages, high oil content species nature,

**Table 11** Engine performance and emission behaviour of *Crambe abyssinica* biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Single-cylinder, direct ignition diesel engine | B30 *Crambe abyssinica* biodiesel–diesel blend | Maximum in-cylinder pressures were similarly low across all tested fuels. The greater calorific value of D100 compared to biodiesel–diesel fuels resulted in a higher heat release rate at all engine loads. Compared to D100 test fuel, biodiesel–diesel mixtures caused longer delays in ignition. BTE of biodiesel–diesel blend is found 26%. The CO and HC emission of biodiesel blend is found lower as compared to diesel. Biodiesel blends emit less soot than D100 because biodiesel has more oxygen. The $NO_x$ emission of biodiesel blend is higher than diesel | (Uyaroğlu et al. 2018) |
| Antor/6LD400 1-cylinder, direct injection diesel engine | *Crambe abyssinica* biodiesel diesel blend with organic manganese additives (5 µmol/l) | The least SFC was attained with regular diesel fuel for all engine load conditions. Incorporating organic manganese into biodiesel fuel improved knock resistance. In a diesel engine, the addition of organic manganese to the biodiesel fuel resulted in a considerable decrease in CO, HC and smoke emissions while causing a modest rise in $NO_x$ levels | (Uyaroğlu et al. 2021) |

**Fig. 13** *Crambe* crop after 15 days (left) and *Crambe* crop after 55 days (right) (Costa et al. 2019)

**Fig. 14** *Aegle marmelos* plant with fruit (Palatty et al. 2013)

**Fig. 15** Seed cake after oil extraction (Paramasivam et al. 2019)

minimum requirements of irrigation and superiorly non-edible feedstock advantages, *Aegle marmelos* is selected as a biomass material. The *Aegle marmelos* plant with fruit and seed cake after oil extraction are shown in Figs. 14 and 15, respectively. Table 12 presents the diesel engine performance and emission behaviour fuelled with *Aegle marmelos* biodiesel.

## Cuphea

An oil extracted from the seeds of the subtropical flowering plant *Cuphea* (Lythraceae), which grows in the eastern United States, Mexico and Brazil, is a novel feedstock that is being researched as a biodiesel fuel. About 260 different species of cuphea have been identified. Similar to coconut oil, cuphea oil has a high concentration of medium-chain fatty acids (Lovestead et al. 2010). Based on the species, one fatty acid dominates the content of seed oil, comprising nearly between 50 and 85% of all fatty acid contents. The oil is found in the plant's embryo, which typically has a weight-to-oil ratio of 30–33% (Graham et al. 2016). *Cuphea* oil serves as a feedstock because it is substantially concentrated in decanoic acid, which enhances the qualities of the biodiesel fuel produced from it. However, agronomic challenges must be resolved before *Cuphea* production can be scaled up for commercial use (Knothe 2014). Fisher et al. (2010) investigated the diesel engine behaviour fuelled with *Cuphea* biodiesel at different injection timing. The results show that the timing of the injection had a greater impact on biodiesel liquid lengths. The early direct-injection and late-cycle injection may be advantageous for *Cuphea* biodiesel. Knothe et al. (2009) suggested the *Cuphea* oil looks to be a promising prospective resource for biodiesel and may serve as a paradigm for other possible feedstocks with high decanoic acid concentration even if it faces substantial technical challenges with respect to its commercial availability.

## Eichhornia crassipes

The water hyacinth, or *Eichhornia crassipes* Martius, is a monocotyledonous freshwater aquatic plant that is endemic to the regions of Brazil and Equador. It is a member of the family Pontederiaceae, which is closely related to the lily family, the Liliaceae. In addition to its beauty, it is widely recognised as a decorative aquatic plant found in water gardens and aquariums. It has lovely blue to lilac-coloured blooms, round to oblong curved leaves and waxy coated petioles. The water hyacinth is a kind of plant that can both survive and multiply in fresh water, where it floats freely on the top (Vidya Sagar and Kumari 2013). The fatty acid composition of *Eichhornia crassipes* oil is tetradecanoic acid (0.4%), eicosanoic acid (3.4%), hexadecanoic acid (2.7%), *cis*-9-hexadecenoic acid (0.9%), octadeconoic acid (2.6%), *cis*-9-octadecenoic acid (65.2%), *cis*, *cis*-9 acid, *cis*-12 octadecenoic acid (24.2%) and tetracosanoic acid (0.6) (Venu et al. 2019). Venu et al. (2019) investigated the viability of running a compression engine on biodiesel derived from *Eichhornia crassipes* as a viable alternative energy source. The feedstock used to make the biodiesel comes from the Tamil Nadu region of India's Pondicherry district. Investigators examined samples of 10%, 20%, 30%, 40% and 100% quantities of blended biodiesel as well as pure diesel. It has been concluded that although HC and CO emissions were decreased, the engine's thermal efficiency had increased. The amounts of $CO_2$ and $NO_x$ emissions did, however, modestly increase when blending was introduced. The *Eichhornia crassipes* plant and stem are depicted in Figs. 16 and

**Table 12** Engine performance and emission behaviour of *Aegle marmelos* biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Single-cylinder 4-stroke direct injection diesel engine | 50% diesel + 35% biodiesel + 15% diethyl ether with 100 ppm graphene nanoparticle (optimum blend) | At optimum fuel blending the CO emission, particulate matter, UHC and $NO_x$ emission is decreased by 41%, 45%, 39% and 13.5%, respectively, as compared to diesel. The BTE increase of 31.5% (3% more) at optimum blend as compared to diesel. When compared to pure diesel, optimal mix demonstrated a downward trend in BSFC at all loads, with a maximum drop of 5.5%. The maximum cylinder pressure of 79 bar is obtained at the optimum blend | (Kolli et al. 2020a, b) |
| Kirloskar direct injection, water-cooled diesel engine | B00, B5, B10, B15 and B20 blending of *Aegle marmelos* pyrolysis biodiesel–diesel blend | For B20 fuel, a lower BSFC of 0.37 kg/kWh at maximum engine load has been discovered and the highest BSFC of 0.69 kg/kWh has been recorded using B5 fuel. At 100% load, neat diesel fuel mode had a BSFC of 0.38 kg/kWh. At full load, the highest BTE for B20 fuel has been measured at 22.87% and the lowest BTE for B5 fuel was determined to be 14.22%. *Aegle marmelos* bio-oil opus increased engine performance and exergy efficiency compared to B00. Fuel blend B20 has superior exergy analysis and performance than other bio-oil blends | (Baranitharan 2020) |
| Kirloskar, VCR multi-fuel, vertical, water-cooled, direct injection, naturally aspirated engine | Blending of *Aegle marmelos* biodiesel, diesel and diethyl ether at different compression ratio, injection timing and injection pressure<br>Fuel B1: 80% diesel + 15% bael oil, and 5% diethyl ether (DEE) | The compression ratio and injection pressure increases the BTE. At CR 18, IP 230 bar and IT 23° bTDC, the highest BTE for was observed. As the compression ratio increased, the BSFC dropped, and the lowest BSFC was recorded at 23° bTDC for test fuel B1. The decrease in CO and HC emission is obtained from compression ratio 16.5 to 17.5. At a CR of 16, IP of 250 bar and IT of 25° bTDC, 205.8 ppm of $NO_x$ was measured for B1, compared to 220.3 ppm for neat diesel. When DEE is added to a combustion process, it speeds up the combustion and lessens the amount of smoke produced | (Krishnamoorthi and Malayalamurthi 2017) |

**Fig. 16** *Eichhornia crassipes* plant (Abdul Wahhab and Al-Kayiem 2021)

**Fig. 17** *Eichhornia crassipes* stem (Venu et al. 2019)

17, respectively. The diesel engine behaviour fuelled with *Eichhornia crassipes* biodiesel is discussed in Table 13.

## Melia azedarach

The *M. azedarach* (syringa tree) is a member of the Meliaceae family. *Melia azedarach* is a deciduous tree that reaches heights of 7 to 12 m. It is found in southern China, India and Australia. The toxic (non-edible) dried syringa berries have an oil concentration of around 10% (Stavarache et al. 2008). This is a non-edible oil which has capability to produce biodiesel through transesterification reaction with 89.37% methy ester yield (Ogunkunle et al. 2021). Syringa oil has a high content of unsaturated fatty acids, particularly oleic (21.8 wt.%) and linoleic (64.1 wt.%) acids. Other components that make up more than 1 wt.% include saturated fatty acids like palmitic (10.1 wt.%) and stearic (3.5 wt.%) acids (Kumar and Sharma 2011). The *Melia azedarach* tree, fruit and dry seed are presented in Figs. 18, 19 and 20, respectively.

## Cedar wood oil

Cedar wood (*Cedrus deodara*) is a member of the Pinaceae family and is a reasonably big tree that may grow up to 85 m tall. It has scattering branches with 2–5 cm needle-like leaves that are rough black in colour (Mehra 2018). This tree has a 600-year lifespan. In October and September, flowers bloom. This tree is found in portions of Tibet, western Nepal, north Pakistan and north central India. This tree can only be found in the dry parts of the Himalayas since it cannot survive in moist environments (AHMED et al. 2011). Oil has been employed in the pharmaceutical industry in the past. Now in current times this non-edible cedar wood oil can be utilised for the biofuel production. Cedar wood (*Cedrus deodara*) trees would be planted more often in forested regions if the oil extracted from them could be used to make biodiesel (Majid et al. 2015). The source of cedar wood oil is wood (EdwinGeo et al. 2021). Sridhar Raja and Ganesan (2022) investigated the diesel engine performance and emission behaviour with cedar wood biodiesel blend incorporated with magnesium oxide nanoadditive. The result shows that B30 blending performs better than other biodiesel blending. EdwinGeo et al. (2021) have analysed the diesel engine performance and emission characteristics of diesel engine fuel with cedar wood biodiesel blend (B20). The experimental results show that the BTE and $NO_x$ emission is higher for biodiesel blend as compared to neat diesel. $CO_2$ emissions were lower with biodiesel blends because of fewer carbon contents in the fuel. The biodiesel blends reduced smoke emissions because there was more oxygen and the combustion process was better. This helps to cut down on HC and CO emissions as well. The cedar wood tree is shown in Fig. 21.

## Shorea robusta (Sal)

Sal oil comes from the seeds of trees, and about 0.18 million tonnes of sal seed oil are made each year. It is a non-edible oil source (Rai and Sahoo 2021b). Sal trees cover roughly 5% of India’s forested land and sal oil has the capability to produce biodiesel (Vedaraman et al. 2012). The oil extraction from the sal seed kernel produced a yield of 20.16% (Hasan et al. 2020a). The sal seed is processed into sal butter than transesterification method for biodiesel production (Kumar Rai and Rekha Sahoo 2020). The *Shorea robusta* tree, leaf, seed and butter are shown in Fig. 22. Table 14 presents the engine

**Table 13** Engine performance and emission behaviour of *Eichhornia crassipes* biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Kirloskar, 4-stroke, air-cooled, single-cylinder DI diesel engine | B10, B20, B30, B40, B100 water hyacinth biodiesel–diesel blending | Compared to diesel fuel, biodiesel blends were shown to have lower levels of BTE in the tests. The 20% water hyacinth biodiesel blend performed the best in terms of increased performance and decreased tailpipe emissions. When compared to diesel fuel, biodiesel and its blend resulted in decreased ignition delay, peak cylinder pressure and immediate heat release under all load circumstances. Fuel-bound $O_2$ atoms in biodiesel and its blend reduced HC, CO and smoke emissions. The $NO_x$ and $CO_2$ emission increases with biodiesel blend as compared to neat diesel | (Venu et al. 2019) |
| 1-cylinder, 4-stroke TWD290F diesel engine | B10, B20 and B30 water hyacinth biodiesel–diesel blend | Tests conducted on diesel engines revealed that the BTE improved by 2.6%, 4.2% and 6.3% when blended with B10, B20 and B40, respectively, compared to pure diesel. The results of the exhaust tests reveal a moderate decrease in the emissions of CO (0.85–0.39%) and HC (2.48–6.03%). $NO_x$ levels are 1.87–7.83% higher as compared to neat diesel | (Abdul Wahhab and Al-Kayiem 2021) |

performance and emission of diesel fuelled with *Shorea robusta* biodiesel blend.

**Fig. 18** *Melia azedarach* tree

## Simmondsia chinensis (Jojoba)

The jojoba tree is a member of the Simmondsiaceae family. This is a perennial shrub that is native to the Sonoran and Mojave deserts of Mexico, Arizona and California. The lipid content of the seeds, which ranges from 45 to 55% of yields, is in the form of long-chain esters of fatty acids and alcohols (wax esters) (Atabani et al. 2013). This oil has potential to produce biodiesel. The dry jojoba seed and seed with tree are depicted in Figs. 23 and 24. The engine behavior of diesel engine fuelled with Jojoba biodiesel blend is given in Table 15.

**Fig. 19** *Melia azedarach* fruit

## Garcinia indica (Kokum)

*Garcinia indica* is a member of the Guttiferae plant family, which has more than 630 species spread across 40 genera. It is a slender evergreen tree with branches. It grows naturally in the tropical forests of the Western Ghats, Konkana, North Kanara, South Kanara, Bombay, Goa and Coorg

**Fig. 20** *Melia azedarach* dry seed

(Hosamani et al. 2009). The oil content of *Garcinia indica* seeds is 45.5% (Atabani et al. 2013). The characteristics of *Garcinia indica* methyl esters have promoted its usage as a possible source for the production of biodiesel (Khan et al. 2014). The *Garcinia indica* tree, fruit, etc. are shown in Figs. 25, 26, 27 and 28. The engine performance and emission of engine with *Garcinia indica* biodiesel is presented in Table 16.

## Eruca sativa L. (Taramira)

*Eruca sativa*, a member of the Cruciferae family of plants, is used to make various traditional medicines and treatments. It grows in South Asia, India and Pakistan and is called taramira (Flanders & Abdulkarim 1985). It can be figured as a non-edible feedstock for biodiesel. *Eruca sativa* L. has a production of 1106 kg oil per hectare, and the oil yield is 30%(Chakrabarti et al. 2011). Mumtaz et al. have performed the optimisation for biodiesel production from *Eruca sativa* oil (Mumtaz et al. 2012).

## Raphanus sativus L. (Radish Seed)

The radish (*Raphanus sativus* L.), which is commonly planted in some regions of Brazil and Asia, has physical and chemical properties favourable to the manufacture of biofuels. It is a member of the family of oilseeds known as Brassicaceae (Faria et al. 2018). It is a herbaceous plant that climbs vertically to a height of more than 1.8 m. Since it can withstand frigid temperatures, it might potentially be planted there (e.g. winter frosts). Moreover, it helps the soils recover micronutrients, particularly nitrogen and phosphorus. It has a quick growth rate that lasts between 150 and 200 days. Also, its agriculture has less agronomic requirements and cheaper per-hectare production costs (Fadhil et al. 2020). The oil content of radish seeds is rather high, at around 35% on average; however, this oil is not considered edible since it includes erucic acid (C22:1), a poisonous substance (Stevanato and da Silva 2019). Cold pressing of radish seed results in an average yield of 284 L/ha of oil since the productivity is 1500 kg/ha (Stevanato and da Silva 2019). Chokkalingam et al. (2022) have investigated and optimised the engine output behaviour fuelled with *Raphanus sativus*

**Fig. 21** Cedar wood tree (Mehra 2018)

**Fig. 22** *Shorea robusta* tree, leaf, seed and butter (left to right) (Kumar Rai & Rekha Sahoo, 2020)

biodiesel blend incorporated with alumina nanoparticles. At biodiesel blend ratio B20, 60 ppm nano-$Al_2O_3$, injection timing 27° before top dead centre and 220 bar pressure, BTE is increased and BSFC and EGT are lowered on favoured full load condition, whereas at 23° before top dead centre injection time and 180 bar pressure, the CO, $CO_2$, $NO_x$ and HC emissions are found lower. Senthilkumar et al. (2019) have taken non-edible wild radish oil for biodiesel production. The oil from seeds has been mechanically extracted, and the oil yield was discovered to be 46.2 wt.%. Taguchi and RSM tool is used for the catalytic transesterification process optimisation, and under optimised conditions, 94.58% biodiesel production is attained.

## Industrial Feedstock

The industry-based feedstock can also be utilised to produce biodiesel. Saravanan et al. (2022) have taken tannery sludge to produce biodiesel with nanoparticles as catalyst through transesterification reaction. In process of reaction at a 20:1 molar ratio of methanol to oil, 9 wt.% catalyst loading, reaction temperature of 65 °C, 300 min reaction duration and at 450 rpm stirring rate, the optimum biodiesel yield of 98.6 wt.% has been obtained. Booramurthy et al. (2022ab) transesterified the fat recovered from tannery sludge with a short-chain alcohol and a nanocatalyst ($Fe_3O_4$/BaO) and produced biodiesel. In the work, influence of different process factors was studied to achieve an optimal biodiesel yield of 97.6%. Booramurthy et al. (2022ab) had taken nanocatalysts (ferric-manganese doped sulphated zirconia) to make biodiesel from tannery waste. At the optimum conditions of 12:1 methanol to fat, 6 wt.% catalytic loading at 65 °C and 450 rpm stirring for 300 min, the highest biodiesel production of 96.6 wt.% has been obtained. Booramurthy et al. (2020) have used waste sheep fat to produce biodiesel using nano-sulphated zirconium catalyst and at optimised conditions, 98.7% biodiesel yield is obtained. Saravanan Arumugamurthy et al. (2019) explored the production of biodiesel from industrial waste using heterogeneous acid catalyst made up of brewer's spent yeast. The reaction has been carried at constant 25 Hz ultrasonic frequency. At certain optimum reaction input parameters, 87.8% of biodiesel yield is obtained. Balasubramanian et al. (2018) had looked at using activated sludge from milk processing plants as a cheap feedstock to make biodiesel. The conventional transesterification reaction is used to make biodiesel from sludge. Sivakumar et al. (2011) have studied the biodiesel production from dairy waste scum oil. While using 1.2 wt.% of potassium oxide, 75 °C for the reaction, 30 min and a 6:1 methanol/oil ratio at 350 rpm, the production of biodiesel achieved 96.7%. The various industrial wastes have great potential to produce biodiesel and they can be a promising feedstock for biodiesel production.

## Algae

Algae-derived biodiesel is seen as a viable third-generation feedstock. Moreover, algae may be produced in fresh, marine or sewer water, requiring no arable land and competing with food production (Ashokkumar et al. 2017). Microalgae are chosen over other species of algae because of their high lipid content (5–70 wt.% on a dry basis) and rapid development rate (20–30 times faster than agricultural plants) (Almutairi 2020). In some conditions, some algae species can have a maximum lipid content of up to 90 wt.%. Moreover, it may be often harvested and use ambient $CO_2$ as a main supply of carbon (Arunachalam Sivagurulingam et al. 2019). Since marine microalgae have a high tolerance for various environmental variables including salinity, temperature and contaminations that occur during open pond production, it has the greatest potentials to satisfy the feedstock needs and are economically practical (Chew et al. 2018). Arunachalam Sivagurulingam et al. (2022) have done a microalgal biodiesel production. In this work, marine microalgae from the Bay of Bengal were separated, and their capacity to produce

**Table 14** Engine performance and emission behaviour of *Shorea robusta* (Sal) biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Single-cylinder 4-stroke direct injection diesel engine | B10, B20, B30 and B40 blending of *Shorea robusta* biodiesel–diesel blend | As engine load increases, the BSEC and BSFC of each sal biodiesel blend fuel decreased. The BSFC and BSEC are lower at full load for all biodiesel blends as compared to diesel. BTE of diesel is found higher than the biodiesel blends. The CO, UHC emission is found lower and $NO_x$ emission is found higher for biodiesel blend as compared to diesel | (Rai and Sahoo 2021a) |
| Single-cylinder 4-stroke direct injection VCR diesel engine | B10, B20, B30 and B40 blending of *Shorea robusta* biodiesel–diesel blend at variable compression ratio | The VCR engine performance, combustion and heat transfer characteristics of engine are analysed and optimised using Taguchi–Gray rational approach. The results show that at 17 compression ratio, 10 kg engine load and B30 fuel blending, the optimum engine characteristics are obtained | (Kumar Rai and Rekha Sahoo 2020) |
| Single-cylinder 4-stroke direct injection VCR diesel engine | *Shorea robusta* biodiesel–diesel blend (up to 40% blend) | The higher BTE is obtained at higher load for lower blending ratio. At higher blending ratio, the BSFC of biodiesel blend is similar to diesel. The CO, HC emission of biodiesel blend is found lower and higher emission for $NO_x$. B10 had a greater rate of combustion heat release (1215.15 J) as compared to diesel. The biodiesel blend has reduced the ignition delay. Up to B40 blending of biodiesel can be used in engine performance | (Pali and Kumar 2016) |
| Single-cylinder constant speed diesel engine | *Shorea robusta* biodiesel | According to research using *Shorea robusta* biodiesel as fuel in direct injection diesel engines, CO, HC and $NO_x$ exhaust emissions are decreased by 25%, 45% and 12%, respectively, when compared to diesel, with no appreciable change in thermal efficiency. This research suggests that *Shorea robusta* biodiesel may be utilised as fuel without engine modifications | (Vedaraman et al. 2012) |

**Fig. 23** Dry jojoba seed (Agarwal et al. 2020)

**Fig. 24** Jojoba seed with tree (Kumar and Sharma 2011)

biodiesel is examined. Five distinct microalgae strains were found, and each strain was used to produce biodiesel. The maximum biodiesel production yield of 97% has been found for *Nannochloropsis salina* microalgal strain. Arunachalam Sivagurulingam et al. (2019) have used calcium methoxide as a catalyst in optimisation and kinetic studies for biodiesel generation from the microalga (*Euglena sanguinea*). The biodiesel output is 94.83% at its optimum condition. Ashokkumar et al. (2017) investigated the brown marine macroalgae *Padina tetrastromatica* for biodiesel production and found 7.8% biodiesel yield through tranestrification.

### Chukrasia tabularis L.

*Chukrasia tabularis* is also known as Indian mahogany. It is an indigenous tree to India, Bangladesh, Cambodia, China, Sri Lanka, Vietnam and Malaysia, and is a medium to big deciduous or evergreen tree that produces non-edible oil. The fruits, leaves and stem of this tree contain anti-inflammatory, anti-malarial and antiviral effects (Mursiti et al. 2019). Eswaramoorthi et al. (2022) have revealed a novel source of *Chukrasia tabularis* L. seed for biodiesel production. The maximum oil yield from seed is obtained as 32 wt.%. This oil must undergo a single-step esterification cum transesterification process due to its high free fatty acid (FFA) concentration. Maximum biodiesel conversion was achieved by analysing the conditions influencing the biodiesel process, which resulted in a 98.5% yield.

### Other Feedstocks

Some more biodiesel feedstock that has the potential to produce biodiesel is presented in Table 17.

## Future Scope

Biodiesel has recently gained popularity due to its economic and environmental advantages. Biodiesel has a promising future since it is a clean renewable energy source. This fuel will contribute to the global goal of net zero emissions by 2050. Cost-effective large-scale production is needed for commercialising biodiesel in the market; however, the biodiesel market is not yet mature enough. The various local feedstock needs to be promoted as per the geography of the location. The government must build infrastructure and implement blending policies to allow biodiesel to be used in diesel engines. In the future, hybrid biodiesel can be a wise strategy for cost-effective biodiesel production and commercialisation. In recent years, Kukana and Jakhar (2022b) have investigated the overall engine using composite biodiesel from waste cooking oil–*Hibiscus cannabinus* oil. Kukana and Jakhar (2022a) examined the effect of ternary blends diesel/*n*-propanol/composite biodiesel on diesel engine operating parameters. Harisha et al. (2021) have done research on hybrid biodiesel production and optimisation.

## Conclusion

Biodiesel is gaining popularity as a cleaner alternative to conventional diesel. It is produced using plant oils, animal fats, recycled cooking greases or oils, and different combinations of these feedstocks. In the current scenario, biodiesel is gaining attention because it has several benefits,

**Table 15** Engine performance and emission behaviour of jojoba biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| 5.2-kW 4-stroke constant speed DI engine | Various jojoba biodiesel–diesel blending | The RSM (CCD) has been applied for the optimisation of engine parameters. The optimal combination of input parameters is recorded at 25° bTDC fuel injection timing, 21.52 MPa fuel injection pressure, 24% jojoba biodiesel blending with diesel, and 80% engine load with maximum BTE and Pmax and minimal EGT and UHC emission of the engine | (Sharma et al. 2019) |
| 5.2-kW 4-stroke constant speed DI engine | B20 biodiesel blending incorporated with 25, 50, 75 ppm of CuO nanoparticle | The B20 fuel with 50 ppm CuO had a better BTE as compared to other jojoba biodiesel fuel samples. Hydrocarbon, carbon monoxide and smoke emissions were all shown to be reduced when CuO nanoparticles were introduced to B20 for use in engines. The minimum BSFC is found for diesel and with an increase in nanoparticle concentration in biodiesel blend the BSFC decreases. The cylinder pressure and HRR are found maximum for 75 ppm CuO in biodiesel blend. Copper oxide added to B20 speeds up the chemical reaction, which shortens the ignition delay | (Rastogi et al. 2021) |
| 4-Cylinder variable speed V3300 Kubota tractor engine | B5, B10 and B15 jojoba biodiesel blend | Diesel fuel has a higher peak pressure than any of the three biodiesel blends, but all three blends have the combustion characteristics same as diesel fuel at different speeds and loads. B5 and B10 have HRRs that are almost the same as diesel. The ignition delay and combustion duration are similar to diesel. The $NO_x$ and $CO_2$ emission of B10 is more than diesel. B10 was found to be a better replacement than the other blends | (Azad et al. 2019) |

**Fig. 25** Kokum fruit with tree (Pandey et al. 2009)

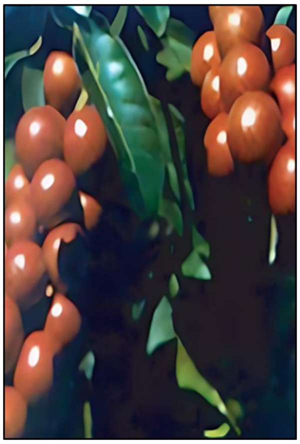

**Fig. 26** *Garcinia indica* fruit (Swami et al. 2012)

**Fig. 27** *Garcinia indica* seed with pulp (Swami et al. 2012)

**Fig. 28** Dried kokum (Pandey et al. 2009)

i.e. it is renewable with no sulphur or polycyclic aromatic compounds in it, it can replace fossil diesel fuel and can be used directly in existing diesel equipment with slight to no modification, lowers greenhouse gas emissions, reduces engine exhaust emissions, it is non-toxic and biodegradable, it is appropriate for sensitive environments, it can be made locally using recycled or agricultural materials and contains extra oxygen for better combustion. Greenhouse gas emissions are drastically reduced when biodiesel is used instead of petroleum. In comparison to fossil fuel diesel, B100 has been determined to produce 74% less greenhouse gas emissions across its whole life cycle. As biodiesel use and production rise, additional rare feedstocks are being investigated. Some examples include *Prosopis juliflora* oil, sea mango oil, *Parinari polyandra* oil, *Ailanthus altissima* oil, *Michelia champaca* oil, *Abrus precatorius* oil, *Crambe abyssinica* oil, *Aegle marmelos*, *Eichhornia crassipes* oil, *Cuphea oil*, lemon grass oil, cedar wood oil, *Shorea robusta* oil, *Melia azedarach* oil, jojoba oil, *Garcinia indica* oil, taramira oil, *Raphanus sativus* L. oil, many strains of microalgae, *Chukrasia tabularis*, industrial waste and other feedstock. These resources include a high concentration of free fatty acids and triglycerides, which are used in the production of biodiesel. Even though there is not much biodiesel made from these feedstocks now on the market, they have a lot of potentials to increase the supply. There are many challenges which are associated with biodiesel production and use. Transesterification is the most common and efficient method for producing biodiesel with a high yield. Since biodiesel has a higher cetane number than diesel, it may be blended with diesel at ratios to enhance engine performance and reduce emissions. There are many challenges which are associated with biodiesel production and use. The addition of nanoparticles in biodiesel boosts engine performance characteristics and reduces emissions. The challenges are feedstock availability at a large scale, cost-effective production of fuel, the adaption policy of a country, lack of customer awareness about biodiesel and availability of infrastructure. The biodiesel can be utilised as a substitute of diesel fuel for the operation of diesel engines.

**Abbreviations** KAC: Potassium hydroxide (KOH)-activated Ailanthus cake; CAC: Calcined Ailanthus cake; CdS: Cadmium sulphide; FMAE: Fatty acid methyl ester; BSEC: Brake specific energy consumption; BSFC: Brake specific fuel consumption; DMC: Dimethyl carbonate; RSM: Response surface methodology; CCD: Central composite design; VCR: Variable compression ratio; BTE: Brake thermal efficiency; EGT: Exhaust gas temperature; EGR: Exhaust gas recirculation; HRR: Heat release rate; CR: Compression ratio; UHC: Unburned hydrocarbon;

**Table 16** Engine performance and emission behaviour of jojoba biodiesel

| Engine | Fuel type | Engine performance and emission | Ref |
|---|---|---|---|
| Three-cylinder 4-stroke diesel engine | Diesel, kokum biodiesel and B20 kokum biodiesel and diesel blend | Diesel fuel produced the highest BTE, which was 33.85%. It was found that adding 20% kokum oil methyl ester by volume to petroleum-based diesel caused the thermal efficiency to drop by 4 to 5%. The $NO_x$ emission of B20 blend was found comparable to diesel fuel. The CO, HC and smoke emission of biodiesel blend is found lower as compared to diesel | (Attal et al. 2014) |

**Table 17** Non-edible resources with details for biodiesel production (Atabani et al., 2013)

| S.N | Feedstock name | Part | Country/region | Oil content (%) |
|---|---|---|---|---|
| 1 | *Jatropha curcas* L | Seed | The plant is found in Central America, Brazil, Paraguay, Africa, Bolivia, Peru, Mexico, India and Argentina | 43–59 |
| 2 | Karanja | Seed | Indian subcontinent, Southeast Asia, USA, Australia, China, New Zealand | 30–40 |
| 3 | *Croton megalocarpus* | Seed | East Africa | 40–45 |
| 4 | *Moringa oleifera* | Seed | Cambodia, North and Central America, and Philippines | 40 |
| 5 | *Aleurites moluccana* | Kernel | Australian state of Queensland and subtropical and tropical India | 15–20 |
| 6 | *Pachira glabra* | Seed | Tropic and subtropic area and native tree of Brazil | 40–50 |
| 7 | Castor | Seed | Australia, China, USA, Brazil and Central Africa | 46–55 |
| 8 | Polanga | Seed | Southeast Asia, India, Australia and East Africa | 65–75 |
| 9 | *Sterculia feotida* L | Seed | 35° South latitude–30° North latitude (subtropical and tropical area) | 50–60 |
| 10 | *Madhuca indica* | Seed | India | 35–40 |
| 11 | *Sapium sebiferum* (Chinese tallow) | Seed | India, China, Japan and southern coastal area of USA | 45–60 |
| 12 | *Aleutites fordii* (Tung) | Seed, fruit and kernel | India, Argentina, USA, Paraguay, China | 30–40, 14–20 and 53–60 |
| 13 | *Azadirachta indica* (Neem) | Seed and kernel | Sri Lanka, Pakistan, India, Japan, Malaysia, Indonesia, Burma and Australia's tropical region | 20–30 and 40–50 |
| 14 | *Hevea brasiliensis* (rubber seed) | Seed and kernel | Thailand, Malaysia, India, Liberia, Sarawak, Indonesia | 50–60 and 40–50 |
| 15 | Rice bran | By-product | India and China | 12–25 |
| 16 | *Nicotiana tabacum* (tobacco) | Seed | Found in more than a hundred countries like Turkey, in South and North America, Macedonia, South Siberia | 35–49 |
| 17 | *Crambe abyssinica* (Hochst) | Seed | Europe, highlands of East Africa, Mediterranean region, from Tanzania to Ethiopia | 35.6–42.8 |
| 18 | *Thevettia peruviana* (yellow oleander) | Kernel | India, Nigeria, Guyana, Mexico, Brazil, Tropical America, Puerto Rico | 67 |
| 19 | *Sapindus mukorossi* (Soapnut) | Seed | Europe, America, India (Jammu Kashmir, Uttaranchal, Himachal Pradesh and outer Himalaya of Uttar Pradesh) | 23 |
| 20 | *Cerbera odollam* (sea mango) | Seed | Madagascar, South India, riverbanks in southern and central Vietnam, Sri Lanka Cambodia, Malaysia and Myanmar | 54 |
| 21 | *Euphorbia lathyris* L | Seed | Southwest Asia, western China, southern Europe and north-western Africa | 48 |
| 22 | *Idesia polycarpa* | Seed and pulp | India and Ethiopia | 26.15 and 26.26 |
| 23 | *Guizotia abyssinica* | Seed | India and Ethiopia | 30 |
| 23 | *Argemone mexicana* L | Seed | Ethiopia, Mexico, India, Western US | 22–36 |
| 24 | *Putranjiva roxburghii* | Seed | India | 41–42 |
| 25 | *M. azedarach* | Seed | Southern China, India and Australia | 10 |
| 26 | *Simarouba glauca* | Seed | Florida in US, South America | 50–65 |
| 27 | *Simmondsia chinensis* (jojoba) | Seed | Mojave, California, Sonoran deserts of Mexico and Arizona | 45–55 |
| 28 | Cuphea | Seed | USA and Mexico | 35 |
| 29 | *Michelia champaca* | Seed | India, China and Burma | 45 |
| 30 | *Garcinia indica* | Seed | India (Goa, Bombay, Coorg, Konakana, Western Ghat, North and South Kanara) | 45.5 |

Table 17 (continued)

| S.N | Feedstock name | Part | Country/region | Oil content (%) |
|---|---|---|---|---|
| 31 | *Hibiscus sabdariffa* L. (Roselle) | Seed | Central, southeastern, northern part of Thailand and China | 18 |

US: United States; HC: Hydrocarbon; CO: Carbon monoxide; GO: Graphene oxide; DI: Direct injection; CI: Compression ignition; IEA: International Energy Agency; WCO: Waste cooking oil; IP: Injection pressure; IT: Injection timing; bTDC: Before top dead centre; B00: 100% Biodiesel; B10: 10% Biodiesel + 90% diesel; B15: 15% Biodiesel + 85% diesel; B20: 20% Biodiesel + 80% diesel; B30: 30% Biodiesel + 70% diesel; B40: 40% Biodiesel + 60% diesel; D100: Neat diesel; BP: Brake power; CuO: Copper oxide; $Al_2O_3$: Aluminium oxide; ppm: Parts per million; PV: Photovoltaic; EU: European Union

**Acknowledgements** The author would like to acknowledge Center for Alternative and Renewable Energy and Department of Mechanical Engineering, Rajkiya Engineering College, Azamgarh for the work.

**Data Availability** The data used to support the findings of this study are included in the article.

## Declarations

**Conflict of Interest** The authors declare no competing interests.

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