

REVIEW

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Podocarpus falcatus as a next-generation biodiesel feedstock: comparative insights with *Jatropha curcas* on oil yield, production, properties, and spray behavior

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Abstract

Growing energy demand and volatile fossil fuel prices have intensified the search for sustainable alternatives, positioning biodiesel as a renewable option with properties similar to petroleum diesel. This review provides a systematic, side-by-side comparison of *Podocarpus falcatus* (PF) and *Jatropha curcas* (JC) as biodiesel feedstocks, evaluating oil yield, extraction efficiency, production methods, physicochemical fuel properties, and spray behavior in compression ignition engines. JC, widely studied for its favorable fuel characteristics, faces limitations including low drought tolerance, inconsistent oil yield, and poor oxidation stability, constraining its practical application. In contrast, PF, an underexplored indigenous African species, exhibits higher oil content (58.93% versus 51.7% for JC), superior drought resistance, and a fatty acid profile rich in monounsaturated compounds, enhancing cold flow properties, oxidation stability, and spray atomization performance. The review discusses six oil extraction methods traditional, mechanical, solvent, supercritical, ultrasound-assisted, and enzymatic highlighting trade-offs in cost, yield, and operational complexity, and identifies transesterification as the most efficient and economical biodiesel production route. By synthesizing dispersed experimental data on PF and benchmarking it against JC under comparable conditions, the review explicitly links fatty acid unsaturation to spray behavior, an aspect rarely addressed in feedstock-focused studies. Integrating agronomic resilience, processing requirements, and combustion-relevant spray characteristics with fuel quality metrics, this work demonstrates the technical and environmental potential of PF as a sustainable, next-generation biodiesel feedstock, addressing a clear gap in the literature and supporting informed selection of resilient and high-performance feedstocks for future CI engine applications.

Keywords Biodiesel, *Jatropha curcas*, Oil extraction, Physicochemical properties



1 Introduction

1.1 Background of this study

The primary motivation for looking for sustainable and alternative energy sources is the price volatility of fossil fuels combined with greenhouse gas emissions (GHGs) [1]. As a result of their increased efficiency, dependability, and longevity, compression ignition (CI) engines have become more and more common in the transportation industry. However, these engines release toxic exhaust gases that are dangerous to human health, including particulate matter (PM), carbon monoxide (CO), unburned hydrocarbon (UHC), and nitrogen oxides (NOx) [1, 2].

Because it is nontoxic, biodegradable, and ecologically benign, biodiesel has become a top contender in response, lowering carbon emissions and being compatible with diesel engines already in use [2, 3]. *Jatropha curcas* has been the subject of much research as a biodiesel feedstock because of its advantageous physiochemical characteristics and oil content [4, 5]. In terms of oil yield, its comparatively high oilseed content makes it a marginally better option than many other non-edible oilseeds. The oil's suitability for biodiesel generation is increased by the presence of oleic and linoleic acids [4]. However, obstacles including low energy content, unpredictable oil outputs, limited cultivation acreage, poor drought tolerance, and oxidation susceptibility make it difficult for biodiesel to be widely used as a feedstock [6–8]. This restriction has led scientists to look into other non-food oil sources for the creation of biodiesel. A potential feedstock should be plentiful, able to grow on wasteland, provide a lot of oil, and have a steady fatty acid concentration that is on par with or higher than that of current feedstocks for biodiesel [3]. *Podocarpus falcatus* (PF), an oilseed species native to eastern and southern African nations, is one such possible feedstock. Although PF is plentiful and versatile throughout different agro-ecological zones, it is still not widely used as a feedstock for the production of biodiesel. This evergreen tree, which is a member of the Podocarpaceae family, usually grows to a medium size, reaching 45–60 m in height and 57–92 cm in diameter [9, 10]. It is ecologically important, contributing to environmental sustainability and preventing soil erosion [9, 11]. This oilseed species is well-known for its high oil content, which is locally available and grown in wastelands [12]. However, its potential as a fuel source for CI engines and as a biodiesel feedstock is still mainly untapped [12, 13]. The availability of feedstock, oil content, production procedures, and physicochemical characteristics all have a substantial impact on fuel performance in CI engines, according to some earlier research [9]. In order to unleash its potential as a future alternative biodiesel source for CI engines, this comparative evaluation attempts to assess the oil content, physicochemical characteristics, and fatty acid compositions of innovative PF feedstock in relation to *Jatropha curcas*. It also covers the spray behavior for both feedstocks and different methods of oil production and extraction. In order to contribute to a cleaner and more varied energy portfolio, this investigation aims to demonstrate how PF biodiesel can improve engine performance, combustion efficiency, emissions reduction, and spray characteristics.

Unlike conventional oilseeds such as soybean and rapeseed, *Podocarpus falcatus* is a coniferous species with lipid-rich seeds, yielding up to 58.93% oil and a fatty acid profile dominated by oleic acid (78%), making it a promising biodiesel feedstock comparable to unconventional sources like rubber seed, neem, and moringa. While biodiesel research has extensively focused on *Jatropha curcas* for its oil yield, fuel properties, and

engine performance, it faces limitations including climatic sensitivity, variable oil yield, oxidation stability, and land use constraints. In contrast, scattered studies on *P. falcatus* indicate higher oil content, superior drought tolerance, and a favorable fatty acid composition, yet these findings have not been systematically compared with established feedstocks. This highlights a clear gap in the literature for a side by side assessment of *P. falcatus* and *J. curcas* across oil yield, production methods, physicochemical fuel properties, and spray behavior relevant to compression ignition engines. Filling this gap is crucial to evaluate the technical and environmental competitiveness of *P. falcatus* and to guide sustainable biodiesel feedstock selection, particularly in African agroecological contexts.

This review systematically compares *Podocarpus falcatus* and *Jatropha curcas* as biodiesel feedstocks by examining oil yield, extraction efficiency, physicochemical fuel properties, and spray and combustion characteristics within a single integrated framework. Its novelty lies in providing a focused side by side evaluation of *P. falcatus*, an underexplored indigenous African species, against the extensively studied *J. curcas*, addressing a clear gap in existing reviews that either concentrate solely on *J. curcas* or offer broad overviews of non-edible feedstocks without rigorous comparative analysis. The review critically synthesizes dispersed experimental evidence on *P. falcatus*, including fatty acid composition, extraction and transesterification performance, fuel quality metrics, and spray and evaporation behavior, and directly benchmarks these findings against *J. curcas* under comparable conditions. It further advances the literature by explicitly linking fatty acid unsaturation profiles to spray atomization characteristics, an aspect rarely examined in depth in feedstock focused reviews. By integrating agronomic resilience, processing requirements, and combustion related spray behavior with fuel property assessment, the review demonstrates the technical and environmental relevance of *P. falcatus* as a promising next generation biodiesel feedstock for compression ignition engine applications.

2 Literature review

This review adopts a structured and transparent methodology to identify, select, and analyze relevant literature on biodiesel feedstocks, with specific emphasis on *Podocarpus falcatus* and *Jatropha curcas*. A comprehensive literature search was carried out using major scientific databases including Scopus, Web of Science, ScienceDirect, Springer-Link, Wiley Online Library, MDPI, and Taylor and Francis. The search employed combinations of keywords such as biodiesel feedstock, *Podocarpus falcatus*, *Jatropha curcas*, oil extraction, transesterification, physicochemical properties, spray characteristics, and compression ignition engines, using Boolean operators AND and OR to refine results. The review primarily considers studies published between 2000 and 2024, and additional relevant papers were identified by screening the reference lists of selected articles. In total, 112 peer reviewed publications were identified and considered relevant to the scope of this review.

From the initially identified literature, studies were screened using predefined inclusion and exclusion criteria. Only peer reviewed journal articles and selected conference papers published in English and directly addressing oil yield, biodiesel production routes, fuel properties, spray behavior, or CI engine relevance were included. Duplicate records, non-scientific sources, and studies lacking sufficient experimental or analytical detail were excluded. Data extraction focused on key study characteristics such as

feedstock type, extraction method, biodiesel yield, physicochemical properties, and spray related findings. Due to the diversity of experimental methods and operating conditions, a narrative and comparative synthesis approach was adopted, enabling systematic evaluation, identification of research gaps, and development of robust conclusions to guide future biodiesel research and feedstock selection.

2.1 Overview of biodiesel as an alternative fuel

Because of their exceptional fuel efficiency, high torque production, and durability, diesel engines are widely employed in a variety of industries today, including transportation, agriculture, and the marine industry [16]. However, despite these benefits, diesel engines are notorious for discharging toxic exhaust emissions into the atmosphere, including particulate matter, carbon monoxide, nitrogen oxides, and unburned hydrocarbons (PM) [16, 17]. Biodiesel is quickly gaining traction as a viable and sustainable substitute for traditional diesel fuel in order to address these environmental issues [18, 19]. Made from edible and non-edible oils as well as animal fats, it is a low-carbon, renewable, biodegradable fuel. Biodiesel may be used directly in diesel engines with little to no modification because of its sustainable nature and similar fuel qualities to regular diesel fuel [5, 20]. Because biodiesel is oxygenated, has a high cetane number, a high flash point, and no sulfur, it is the ideal fuel for diesel engines. As seen in Fig. 1 below, it also has superior lubricating qualities that extend engine life and lessen wear and tear in comparison to diesel fuel [3].

Because carbon dioxide released into the atmosphere during combustion is balanced by carbon dioxide absorbed from the atmosphere during feedstock growth, biodiesel dramatically lowers greenhouse gas emissions (GHG) [3, 19]. Because of the feedstock's fatty acid composition and chemical makeup, biodiesel has a high viscosity. Transesterification is a commonly used method of reducing viscosity in which alcohol reacts with

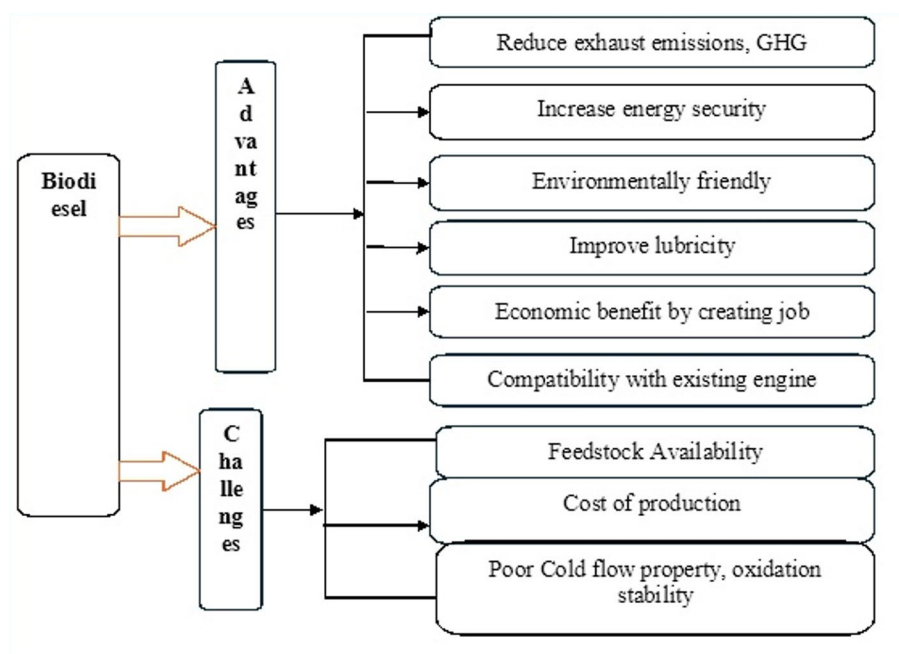


Fig. 1 Biodiesel advantages and challenges

fats or oils to produce methyl ester with the aid of a catalyst [20–22]. The availability of feedstock is essential to the production of biodiesel. The type of feedstock, oil content, production methods, and physicochemical characteristics all have a significant impact on the quality and performance of biodiesel. When assessing the efficacy of diesel engine fuel, these factors are crucial limitations [3, 5, 22]. Numerous factors, such as geographic location, climate, local soil properties, and agricultural practices, influence the choice of feedstock [22]. The following section delves into these constraints in detail.

2.2 Selection of feedstock for biodiesel production

The choice of feedstock is a critical step in optimizing biodiesel production, as it directly impacts efficiency, sustainability, cost, and quality [23]. A number of important considerations, including cost, availability, environmental impact, and oil yield, must be made when choosing the right feedstock. Oil yield is one of the most crucial of these since it determines how much biodiesel can be made from a specific amount of biomass [24, 25]. Higher oil content feedstock yields more biodiesel per unit of biomass, reducing production costs and improving the process's economic sustainability [23]. Furthermore, feedstock ought to be readily accessible and appropriate for large-scale production without jeopardizing food security. Since they guarantee that food supplies are not impacted, non-edible crops are favored for the production of biodiesel [26]. The feedstock's ability to adapt to local environmental factors, such as soil type, temperature, and rainfall, is another crucial factor. For example, because they do not put undue strain on fertile agricultural lands, plants that need little water or that can grow in marginal or degraded land are extremely valuable in the production of biodiesel [26]. Furthermore, choosing feedstock that grows in wastelands and uses little water can greatly improve the sustainability of biodiesel production [21, 26].

This type of feedstock will contribute to a more sustainable and eco-friendlier biodiesel industry, as they reduce the environmental impact of agricultural activities [19, 24]. Furthermore, the cultivation of biodiesel feedstock should ideally promote soil conservation and avoid excessive water consumption, which is a key factor in ensuring long-term agricultural sustainability [25]. Lastly, the oil extraction method plays a major role in feedstock selection. Feedstock that allows for easy and efficient oil extraction is preferred, as it reduces processing time and energy requirements, making biodiesel production more efficient and cost-effective [25]. Feedstock with seeds that have high oil content and can be processed through mechanical or solvent extraction techniques are ideal candidates for biodiesel production [26]. Studies have shown that optimizing extraction processes, such as through the use of supercritical extraction and ultrasonic and enzymatic extraction techniques, further enhances oil yield during the production of biodiesel [19, 24]. Selecting feedstock that is not only high in oil but also amenable to efficient extraction methods can significantly boost the commercial viability of biodiesel as a renewable fuel source [23, 24, 27]. The key selection criteria, such as oil content and yield, fatty acid composition, and physicochemical properties, along with various extraction techniques and production processes for novel *Podocarpus falcatus* and *Jatropha* seed, are discussed in detail in the next section.

Table 1 compares alternative biodiesel feedstocks soybean, palm, cottonseed, *Jatropha*, and *Podocarpus falcatus*—in terms of oil content, major fatty acids, advantages, and limitations. Soybean yields 18–20% oil, primarily linoleic and oleic acids, and benefits

Table 1 Comparative chart of alternative biodiesel feedstocks

Feedstock	Typical Oil Content (%) by Weight)	Main Fatty Acids (Major %)	Advantages	Limitations	Refer-ences
<i>Soybean (Glycine max)</i>	18–20%	Linoleic Oleic	Widely cultivated; established biodiesel industry; high-protein by-product	Competes with food; relatively low oil yield	[19–35]
<i>Palm (Elaeis guineensis)</i>	36–45%	Palmitic Oleic	Highest yield per hectare, stable supply, and good oxidative stability	Deforestation concerns; poor cold-flow properties	[36–40]
<i>Cottonseed (Gossypium hirsutum)</i>	18–24%	Linoleic Palmitic	Abundant by-product of cotton industry; low cost	High free fatty acids (FFA); requires refining	[22–26, 30–35, 40–47]
<i>Jatropha (Jatropha curcas)</i>	30–50%	Oleic Linoleic	Non-edible; grows on marginal land; favorable fuel properties	Sensitive to climate; variable oil yield; poor oxidation stability	[28, 29, 36–41, 48–57]
<i>Podocarpus (Podocarpus falcatus)</i>	50–59%	Oleic (≈ 78), Palmitic (≈ 9)	Indigenous; high oil yield; drought resistant; excellent cold-flow & spray	Underutilized; limited agronomic data; needs large-scale cultivation trials	[27–29, 36, 48–53]

from wide cultivation and a developed biodiesel industry but competes with food. Palm oil offers 36–45% oil with palmitic and oleic acids, providing high yield and oxidative stability, though deforestation and poor cold-flow remain concerns. Cottonseed contains 18–24% oil rich in linoleic and palmitic acids, is a low-cost by-product, but has high free fatty acids requiring refining. *Jatropha curcas* produces 30–50% oil, mainly oleic and linoleic acids, grows on marginal land, yet shows climate sensitivity and variable yield. *Podocarpus falcatus* stands out with 50–59% oil, dominated by oleic (≈ 78%) and palmitic (≈ 9%) acids, offering drought resistance, high oil content, and excellent cold-flow and spray properties, though it remains underutilized with limited agronomic data and requires large-scale cultivation trials [19–57].

2.3 Oil content of *Podocarpus falcatus* and *Jatropha* seed

The growing region, agro-ecological zone, and plant genotype are some of the factors that affect the oil content of *jatropha* seeds. The maturity of the seed is one of the most important factors influencing oil content [28, 29]. When the seed turned yellow, the oil content was at its highest; however, as the seed grew older and turned brown, the oil content dropped by about 6–9% [28].

Numerous studies have demonstrated that, in addition to genetic variations, environmental factors like temperature, rainfall, light availability, and soil nutrients also impact the oil content and quality in *jatropha* [48, 49]. Additionally, different oil extraction techniques have a significant impact on the oil content, leading to a range of oil yields. According to Gonfa et al. [50], the maximum oil content selected from different regions ranges from 45.79% to 48.29%. Satar et al. [51] investigated the oil content of *jatropha* seeds at different maturity stages, using gravimetric methods. According to their findings, fully matured seeds had the highest oil content, ranging from 45.8 to 51.7%. This finding emphasizes how important seed maturity is to oil yield [51]. Similarly, Derki et al. [52] found that the oil content of *Jatropha* seeds varies between 44.2 and 49.7% depending on the agro-ecological zone. The study emphasizes the environmental factors on the oil content of *jatropha* seeds by showing that climate and moisture content

have a significant impact on oil yield [52]. Mesafint et al. [53] found that the oil content of *Jatropha* seeds varies between 44.2 and 49.7% depending on the agro-ecological zone. The study emphasizes the environmental factors on the oil content of *jatropha* seeds by showing that climate and moisture content have a significant impact on oil yield. examined the oil content of *Jatropha* seeds that were gathered from different areas. According to their findings, the maximum oil content ranged from 33.65 to 37.01%, showing a notable variation depending on the seeds' geographic origin [53]. Jonas et al. [48] reported that the oil content of *Jatropha* seeds ranged from 38.7% to 45.8% across the four maturity stages investigated. This variation is attributed to the decrease in unsaturated fatty acid content in *Jatropha*, which reduces the seed oil content as the seeds mature. Yadav et al. [49] examined the physical and chemical characteristics of *Jatropha* seeds gathered from different areas, as well as their oil content. The study found that the seeds' maximum oil content was 52.28%. Furthermore, it was discovered that the temperature at which the seeds were extracted and the makeup of their fatty acids had a major impact on their oil content [49]. The oil content of PF seeds has also been examined by a number of researchers in a similar way to that of *Jatropha* seeds. These investigations concentrate on figuring out the oil content and evaluating the effects of extraction, maturity, and particle size on the oil yield [9, 13, 54].

According to a report by Feleke et al. [54], PF seeds can have an oil content of 50.89% to 57.64%. Particle size and extraction temperature are two important factors that affect the oil yield and determine the total amount of oil in the seeds. Solomon et al. [13] examined the impact of particle size and oil extraction temperature on oil content. The maximum oil content was 50.89%, indicating that both factors have a significant impact on the oil yield. Similarly, Bruno et al. [9] investigated the oil extraction process from *podocarpus* seeds. The results showed that at an extraction temperature of 66.8 °C and for a duration of 4.45 h, the maximum oil content of the seeds, as assessed by response surface methodology, was 58.93%. For *Jatropha curcas*, reported oil yields are strongly dependent on extraction parameters. Studies have indicated yields of 42–47% using Soxhlet extraction with n-hexane (temperature 65 °C, extraction time 6–8 h, solvent-to-seed ratio 6:1) [36]. Mechanical pressing typically recovers 25–30% oil, with efficiency increasing under preheating at 60–70 °C [37]. Aqueous enzymatic extraction yields around 35–38%, but requires longer reaction times of 12–24 h [15]. Similarly, Ngomade et al. [11] and Yigezu et al. [12] investigated the physicochemical properties of *Podocarpus* seed oil using the solvent extraction method. Oil content for PF ranges from 50 to 59%, with experimental maxima of up to 63% reported [38]. As shown in Table 2, overall, PF offers distinct benefits over *jatropha* in terms of its oil content and growth environment [52, 54].

Various experimental procedures, such as changes in seed preparation, solvent type, extraction temperature, and reaction duration, are used to determine the reported oil

Table 2 Comparison of oil content for *Podocarpus falcatus* and *Jatropha* seed

Feedstock	Oil Content (%)	Palmitic (C16:0)	Stearic (C18:0)	Oleic (C18:1)	Linoleic (C18:2)	Linolenic ((C18:3) C18:3)	References
<i>Jatropha curcas</i>	30–50	13–15%	5–7%	34–46%	29–44%	0.5–1.5%	[50–52]
<i>Podocarpus falcatus</i>	50–59	8–10%	3–4%	75–79%	7–9%	0.5–1.0%	[11, 38, 54]

content values. It is important to take this heterogeneity into account when comparing feedstock yields.

As seen in Table 2, *Podocarpus falcatus* consistently shows higher oil yields (50–59%) compared to *Jatropha curcas* (30–50%). Across the cited works ([11, 38, 54]), *Podocarpus falcatus* consistently shows a higher proportion of monounsaturated fatty acids and lower free fatty acid/acid values compared with *Jatropha curcas*. This suggests that PF requires less pretreatment (esterification) before transesterification and tends toward better oxidative stability and cold-flow properties; therefore, PF appears to be the superior raw material for biodiesel production under the conditions reported in these studies.

Jatropha struggles with low seed production on degraded or moisture-stressed land, even though it needs more fertile farmlands and is influenced by agro-ecological factors like rainfall, temperature, and soil nutrients [8, 55]. This demonstrates a major disadvantage of *Jatropha* cultivation, since its yield is heavily reliant on favorable environmental circumstances [56]. Its potential as a dependable source of biofuel is undermined when it is grown in unfavorable or infertile soils because of the significant decline in yield and oil content. Its viability is further limited by inadequate land allocation for *jatropha* cultivation and competition for fertile land with food crops, which raises questions about its sustainability as an energy crop [8, 55, 57]. PF can be cultivated on degraded and waste areas where *jatropha* crops may find it difficult to thrive [38]. The oil content of PF seeds is mostly determined by extraction techniques and particle size, as opposed to *Jatropha curcas*, whose oil content is greatly influenced by environmental factors, genotype variations, and agro-ecological conditions. This indicates that PF can reliably produce high oil content using an optimized extraction technique, such as solvent extraction and appropriate particle size reduction [38]. According to the aforementioned research, PF seed oil can have a higher content than *jatropha* seed, which emphasizes its potential as an excellent feedstock for the production of biodiesel. PF stands out as a viable and effective choice for creating green biodiesel fuel because it is less reliant on genetic and environmental variability and provides higher oil yields from wasteland cultivation [11, 13, 38].

Across the reviewed literature, *Podocarpus falcatus* consistently demonstrates higher oil yield, typically ranging from 50 to 59% by weight, while *Jatropha curcas* exhibits a broader range of approximately 30 to 50%. These differences highlight intrinsic feedstock potential as well as differential sensitivity to environmental and processing conditions.

2.4 Extraction methods for *Jatropha* and *Podocarpus falcatus* oil

One promising renewable feedstock for the production of biodiesel is triglyceride vegetable oil. Many methods, including enzymatic extraction, solvent or chemical extraction, mechanical and conventional pressing, supercritical fluid extraction, and ultrasound-assisted extraction, are used to extract the oils of *Podocarpus falcatus* (PF) and *Jatropha curcas* [39, 40]. These methods have been the standard for obtaining oil from *Jatropha curcas* and PF seeds or kernels [39].

Each extraction method has unique advantages and limitations. For example, mechanical screw pressing is solvent-free and straightforward, but it is relatively slow and requires a larger quantity of seed material [44]. Solvent extraction, in contrast, achieves higher yields, requires less time, and allows solvent reuse, but it involves handling organic solvents [31]. Ultrasound-assisted and supercritical fluid extraction provide high

oil recovery efficiencies but require higher energy consumption and equipment costs [30]. These processes, along with their benefits and drawbacks, are thoroughly examined and discussed in the literature to provide insights into the most efficient techniques for *Jatropha* and PF oil extraction [30, 31, 39–44].

2.4.1 Traditional and mechanical pressing oil extraction

Boiling water is used as a solvent in the traditional oil extraction process. This method involves shelling, drying, and roasting the seeds before extracting the oil. After being ground to the appropriate size, the roasted seeds are submerged in boiling water and heated for a predetermined amount of time while being mechanically stirred [39]. After being extracted from the paste, the oil is filtered using a variety of filtration techniques. Compared to other approaches, this technique produces lower oil recovery with higher water content and volatile compounds, despite having low operating costs and being achievable by semi-skilled workers [41]. According to earlier research, the oil yield from mechanical pressing is 75%, whereas the oil yield from traditional extraction is only about 67% [39, 42, 43].

The two primary categories of mechanical extraction are engine-powered screw presses and manual ram presses. The engine-powered screw press can recover roughly 75–80% of the available oil, whereas the manual ram press usually recovers 60–65% [44]. Despite outperforming conventional techniques in terms of oil yield efficiency, mechanical extraction is still less effective than solvent and supercritical fluid extraction techniques [44]. Oil extraction from novel PF seeds is also done using similar techniques [9, 10]. Both conventional and mechanical extraction techniques typically lead to reduced oil recovery and the presence of contaminants like water, metals, and dust, which lower the quality of the oil for the production of biodiesel [39]. Prior to the transesterification process, these inferior oils need to be further purified, which raises the cost of producing biodiesel overall and treating waste. Furthermore, both require skilled labor and are time- and labor-intensive [30, 42].

2.4.2 Solvent extraction methods

By continuously applying fresh solvent to the sample, the traditional solvent extraction method dissolves the oil from the powdered seed or kernel and collects it in a boiling flask for subsequent processing [36]. The solvent extraction method, which is frequently used in laboratory analysis to precisely ascertain the oil content of the biomass under investigation, mainly uses kernel powder as the feed material [31]. According to a study, solvent extraction with kernel powder was more effective than other techniques when used on the entire seed [32]. According to the study, the kernel's oil content was 55.2%, which was significantly more than the 25.5% oil that was extracted from seeds that still had their coats on. Typically, 90–98% of the available oil can be recovered using the solvent extraction method [33]. When compared to conventional and mechanical extraction techniques, these methods yielded a higher oil yield with less water and turbidity [34]. A number of process variables, such as the kind and amount of solvent used, the extraction time and temperature, the solvent-to-solid ratio, and the biomass particle size, have a significant impact on their efficacy [31, 32, 36]. Consequently, a great deal of research has been carried out to identify and simulate the ideal circumstances for producing more oil of superior quality and yield from *Jatropha curcas* seeds [30, 35, 36]. By

employing three organic solvents, Justin et al. discovered that the extraction temperature ranged from 24 to 80 °C, the extraction time varied from 2 to 8 h, the solvent-to-solid ratio was between 4:1 and 7:1, and the particle size ranged from 0.5 to 0.8 mm independently [36]. PF kernel oil can be extracted using solvent extraction techniques, just like *Jatropha* seeds. With a solvent-to-solid ratio of 12:1 v/w, an extraction temperature of 66.48 °C, and an extraction duration of 4.45 h, the maximum yield of 58.93% was obtained [11]. The solvent extraction method is the main strategy used in this study because it can yield large amounts of oil, guarantees that the extracted oil is clean and pure, and is simple to use with equipment [11]. Due to its low boiling point and low corrosiveness, N-hexane is frequently used as a solvent. Alternative oil extraction techniques are being investigated because these conventional organic solvents are hazardous and non-selective [36]. The maximum oil yield for PF biodiesel and *Jatropha curcas* using various methods is displayed in Table 2.

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2.4.3 Supercritical oil extraction method

Recently, oil from *Jatropha* seeds has been extracted using a novel technique called supercritical CO₂ extraction. Using a supercritical fluid as the solvent, this technique

operates at pressures and temperatures higher than the fluid's critical point [45]. This technique extracts oils from seeds using supercritical CO₂ as a solvent. Pure CO₂ is inexpensive to produce and simple to separate from the finished product [45]. At a CO₂ flow rate of 0.4 kg/h, a supercritical extraction technique may need a temperature range of 313 K to 333 K and a relatively high pressure of 200–400 bar [46, 47]. The primary determinants of oil recovery efficiency in supercritical extraction techniques are temperature, pressure, solvent-to-solid ratio, and particle size.

Numerous studies have identified the optimal conditions for these parameters [58]. According to Adil et al. [45], a maximum yield of 60% was obtained at a pressure of 40 MPa and a temperature of 313 K. Ishak et al. [59] reported a maximum oil yield of 67.2% with an extraction time of 30 min, an optimum temperature of 280 °C, a pressure of 12 MPa, and a solid-to-solvent ratio of 1:40 (*v/w*). Degumming and dehydration procedures are not necessary with supercritical CO₂ extraction. In addition, it provides a significant time and energy savings over conventional solvent extraction techniques [46]. Additionally, because this method uses little oil purification and no solvents, it is environmentally friendly [34, 59, 60]. The oil output from supercritical extraction is higher than that from mechanical and conventional methods when compared to solvent extraction [47, 60]. It is the quickest procedure, usually taking 10 to 60 min, whereas the liquid solvent extraction method, as indicated in Table 3 above, can take several hours to days [45, 59, 60]. However, supercritical methods are less effective than ultrasound-assisted extraction because of the weaker solvent-solute interaction and higher equipment and solvent costs [40].

2.4.4 Ultrasound-assisted extraction method

High-frequency, high-intensity sound waves are used in ultrasonication to interact with materials. This technique improves heat and mass transfer and has been successfully used in the extraction of oil [62]. There are several advantages to using ultrasound-assisted extraction for biodiesel production. Without the use of conventional solvents, it can increase extraction yields and enhance water-based (aqueous) extraction procedures [62]. Furthermore, when necessary, this technique enables the use of pure, environmentally friendly solvents to further improve extraction efficiency [63]. According to

Table 3 Comparative summary of biodiesel oil extraction methods

Extraction Method	Typical Yield (%)	Advantages	Limitations	References
Traditional (boiling/roasting + water)	20–30	Low cost, simple, minimal equipment	Labor-intensive; low efficiency; high impurities	[39, 43]
Mechanical pressing (ram/screw press)	35–75	Moderate cost; no solvents required; scalable	Incomplete extraction; residual oil in cake; higher FFA	[11, 34, 39, 43]
Solvent extraction (n-hexane, etc.)	50–60 (up to 90 in optimized lab tests)	High yield; widely used industrially; high purity oil	Solvent toxicity; costly solvent recovery; energy-intensive	[11, 13, 32, 43]
Supercritical CO ₂ extraction	60–67	Green technology; no solvent residues; fast	High pressure/temperature; expensive equipment	[45, 59, 60]
Ultrasound-assisted extraction	60–72	Short extraction time; eco-friendly solvents possible	Equipment cost: not yet widely commercialized	[58, 60, 61]
Aqueous enzymatic extraction (AEE)	30–40	Eco-friendly; lower FFA; improved oil stability	Long processing time, costly enzymes, moderate yield	[35, 62–64]

Farahan et al., under ideal circumstances, with an ethanol-to-sample ratio of 44.78 (v/w), an extraction time of 51.69 min with ultrasound assistance, and a temperature of 44.57 °C, the highest oil yield (61.94%) was obtained [63]. Tong et al. [33] reported a maximum oil yield of 71.9% with a solvent-to-solid ratio of 5.78:1 and an extraction time of 52 min. This method enhances the extraction of heat-sensitive compounds under typical circumstances, which would otherwise produce poor or insufficient yields [63, 64].

2.4.5 Enzymatic oil extraction

One promising technique for removing oil from feedstock is the aqueous enzymatic oil extraction (AEE) method [65]. Enzymes are used in this technique to extract oil from ground seeds [66]. Aqueous enzymatic extraction (AEE) has the advantage over solvent extraction in that it uses water rather than organic solvents, which makes it safer, more economical, and environmentally friendly [67]. Phospholipids can be simultaneously extracted using the aqueous enzymatic extraction method, negating the need for thorough oil purification. Compared to oil made using other extraction techniques, the oil obtained using AEE has a lower content of free fatty acids (FFA) and better oxidative stability [65]. AEE's long processing time is a disadvantage. By using ultrasonication as a pretreatment prior to aqueous oil extraction, this problem has been resolved [65]. When *Jatropha* seeds were ultrasonically treated for five minutes and then aqueously enzymatically oil extracted using an alkaline protease at pH 9.0, the highest oil yield (33.44%) was achieved [67]. However, aqueous enzymatic extraction techniques are less effective than traditional solvent extraction techniques in terms of oil yield, and the cost of enzymes is higher [68]. Particle size, enzyme and water concentrations, mixture pH, incubation temperature, residence time, and shaking speed are the main process variables that have a major impact on AEE performance [65–67]. Oil extraction can be carried out using several methods, each with unique features. The traditional method relies on simple pressing or heating, which is widely used but often less efficient. The mechanical method improves this by using advanced pressing equipment to increase yield. The solvent method employs chemical solvents, offering higher efficiency but with concerns about residues. A cleaner option is supercritical CO₂ extraction, which uses carbon dioxide under specific conditions to produce residue-free oil. Ultrasound-assisted extraction enhances efficiency by using sound waves to disrupt cell walls and improve solvent penetration. Lastly, the aqueous-enzymatic method combines water and enzymes to naturally release oil in an eco-friendly way [66].

Oil extraction results reported for *Podocarpus falcatus* and *Jatropha curcas* show clear feedstock dependent trends rather than purely process driven variation. *Jatropha curcas* exhibits wider dispersion in oil yield due to sensitivity to growing conditions and extraction parameters, whereas *Podocarpus falcatus* demonstrates more stable and comparatively higher oil recovery across optimized methods.

3 Biodiesel production from *Jatropha* and *Podocarpus falcatus*

This review considers biodiesel production routes specifically in relation to *Podocarpus falcatus* and *Jatropha curcas*, focusing on how feedstock characteristics such as free fatty acid content, oil composition, and purity influence pretreatment, catalyst selection, and conversion efficiency. The lower free fatty acid content and higher monounsaturated fatty acid fraction of *P. falcatus* reduce the need for extensive esterification pretreatment

compared with *J. curcas*, which is more sensitive to feedstock quality and processing conditions [11, 14, 15]. Oil extraction for both feedstocks involves husk removal and kernel separation, with methods including mechanical screw pressing, solvent extraction, ultrasound-assisted extraction, and supercritical fluid extraction, each presenting trade-off in cost, yield, and energy demand [13, 38, 61, 66, 67]. This targeted approach allows a clearer assessment of how feedstock-specific properties affect biodiesel production efficiency and fuel quality under practical conditions.

Historically, straight vegetable oils (SVO) have been tested as diesel fuels since the late 1800s [69]. However, their direct use caused technical issues such as piston sticking, injector clogging, excessive engine wear, and carbon deposition, primarily due to the high viscosity of SVO [69]. To address these challenges, various technologies, including blending, micro-emulsification, transesterification, and thermal cracking (pyrolysis), have been developed to reduce viscosity and improve fuel quality. These processes ensure that biodiesel meets international fuel standards for engine performance, combustion efficiency, and emission control [69].

3.1 Blending or dilution

Blending raw oil with diesel can effectively lower its viscosity, increasing its suitability for use in diesel engines. According to earlier research, diesel engines can run on 80% diesel fuel and 20% vegetable oil without any changes. However, because SVO has a high viscosity by nature, direct blending is limited [70, 71]. Gum formation, injector nozzle clogging, and carbon deposits on the piston head are just a few of the operational issues that can result from this increased viscosity and have a detrimental impact on engine longevity and performance [71]. Practically speaking, the high viscosity of PF oil and *Jatropha curcas* greatly diminishes their suitability for direct use in diesel engines. Therefore, even though blending provides a straightforward solution, additional modification using different techniques is essential to overcoming the aforementioned issues [72].

3.2 Micro-emulsifications

Microemulsion is an alternate technique for lowering the viscosity of vegetable oils. Three primary components make up microemulsions, which are transparent, stable, and isotropic mixtures: an oil phase, an aqueous phase, and a surfactant [73]. Microemulsion refers to a colloidal dispersion of an optically isotropic fluid. The spray properties are enhanced by the micelles' low boiling point components evaporating explosively. Vegetable oil, diesel fuel, cetane improver, surfactant, and alcohol are all included in a microemulsion in specific amounts [74, 75]. The maximum viscosity limit for diesel engines was established using micro-emulsions of solvents such as octanol, hexanol, butanol, ethanol, and methanol [74]. Alkyl nitrates are used to improve the cetane number of oils. Vegetable oil Micro-emulsion with alcohol met the maximum viscosity limit requirements. However, some challenges are associated with continuous use of macro-emulsion fuel in diesel engines, such as high carbon deposition on cylinder walls, sticking of the injector needle, and incomplete combustion [74–76].

3.3 Thermal cracking (Pyrolysis)

Pyrolysis is the process of changing one material into another without the presence of oxygen by applying heat or using a catalyst. The pyrolysis process creates biodiesel

from vegetable oil, waste oils, and animal fat [73, 77]. The 400–600 °C temperature range is where the thermal cracking process takes place. Gases and biodiesel are generated according to the rate of pyrolysis [78]. Based on the conditions of operation, the pyrolysis process is divided into three categories: flash, fast, and conventional pyrolysis. The properties of biodiesel made by pyrolysis were similar to those of regular diesel fuel [79]. Compared to diesel fuel, pyrolyzed vegetable oil has a lower pour point, flash point, cetane number, and viscosity [80]. The amount of moisture, sediments, sulfur, and copper corrosion value in pyrolyzed biodiesel is acceptable [79]. Biodiesel's ash content and carbon residue fall outside of a reasonable range. The process is expensive due to the high temperature required. Additionally, the amount of oxygen available in fuel is reduced when thermal cracking occurs [73, 78–80].

3.4 Transesterifications

Triglycerides and alcohol undergo a chemical reaction called transesterification, which yields glycerol and esters when a catalyst is present. Three consecutive reversible reactions are involved in the transesterification reaction. Glycerides are transformed into glycerol and ester in each stage [81]. The use of catalysts is intended to increase and improve reaction rate as well as speed up the process. Numerous researchers have investigated various catalyst types, such as magnesium, p-toluene sulphonic acid, alkane alumina, calcium oxide and carbonates, phase transfer catalysts, sulfuric acids, and dehydrating agents used as co-catalysts [82]. Base catalysts are favored over acid catalysts because of their high rate of reaction and low temperature requirements. Excess alcohol is used to stabilize the product because the transesterification reaction is reversible. Glycerol and esters are products of the transesterification reaction. Esters are the intended product of the transesterification reaction, and glycerol is also recovered, which is significant because of its numerous everyday uses. The temperature of the reaction, the molar volume ratio of alcohol to oil, the type and concentration of the catalyst, and the purity of the reactants are important factors that influence the transesterification process [81]. For biodiesel production from *Jatropha curcas*, commonly reported transesterification conditions include methanol-to-oil molar ratios of 6:1 to 9:1, catalyst concentrations of 0.5–1.0% wt. NaOH or KOH, temperatures of 60–65 °C, and reaction times of 60–120 min. In the case of *Podocarpus falcatus*, experimental studies have used a methanol-to-oil molar ratio of 6:1, an NaOH catalyst loading of 0.75% wt., and a reaction temperature of 65 °C, resulting in biodiesel yields of approximately 92–94% [83, 84].

Alcohols are organic compounds that contain a hydroxyl functional group. This group includes, for example, propanol, butanol, ethanol, methanol, and amyl alcohol. Methanol and ethanol are the two primary components used to make biodiesel. Methanol is preferred because it is less expensive and has polar and short-chain properties. To increase the amount of biodiesel produced, a high-volume ratio of alcohol to triglycerides is typically used. Alkaline, acidic, and enzyme catalysts can be used for the reaction [85]. Moisture content and free fatty acid have a detrimental effect on the production of biodiesel because they reduce catalyst effectiveness and cause soap formation, both of which can lower conversion efficiency. Water in oils and fats can prolong the transesterification process during the saponification process by causing a hydrolytic reaction that hydrolyzes triglycerides into diglycerides and produces more free fatty acids [81, 85]. The process of producing biodiesel, from extracting PF oil to converting it into pure biodiesel,

is shown in Fig. 2. The transesterification process is the most appropriate for producing biodiesel using alternative techniques because of its high oil yield and low cost.

3.5 Physicochemical properties of *Podocarpus falcatus* and *Jatropha* biodiesel

The feasibility of biodiesel as a sustainable substitute for diesel fuel depends heavily on its physicochemical characteristics. Density, viscosity, heating value, cetane number, flash point, cloud point, pour point, and iodine value (IN) are among the most crucial characteristics of fuel [20]. To evaluate the quality of the fuel, these characteristics must be evaluated [1, 20]. Viscosity is a measure of a fluid's resistance to flow; it rises with increasing molecular weight and falls with increasing temperature [5]. High viscosity oils should not be used directly as engine fuel [86]. The viscosity of *Jatropha curcas* oil is noticeably higher than that of diesel fuel. *Jatropha* biodiesel has a viscosity of 3.7 to 6.7 mm²/s at 40 °C [1, 5, 86]. Fuel viscosity has a significant impact on the properties of atomization and spray formation. Low viscosity is preferred because higher viscosity results in poor spray formation and atomization as well as increased fuel consumption [20]. The fact that *Jatropha* biodiesel is more viscous than diesel means that it is more difficult to use in colder climates. The primary measure of energy content is the fuel's heating value, also known as its calorific value [86]. According to a number of studies, *Jatropha* biodiesel has a calorific value between 38.5 and 40 MJ/kg, which is less than that of diesel fuel [1]. This means that there is less energy in each fuel unit, which results in the least amount of energy being produced [20]. There is a relationship between fuel density and viscosity. A greater density raises the energy concentration of the fuel,

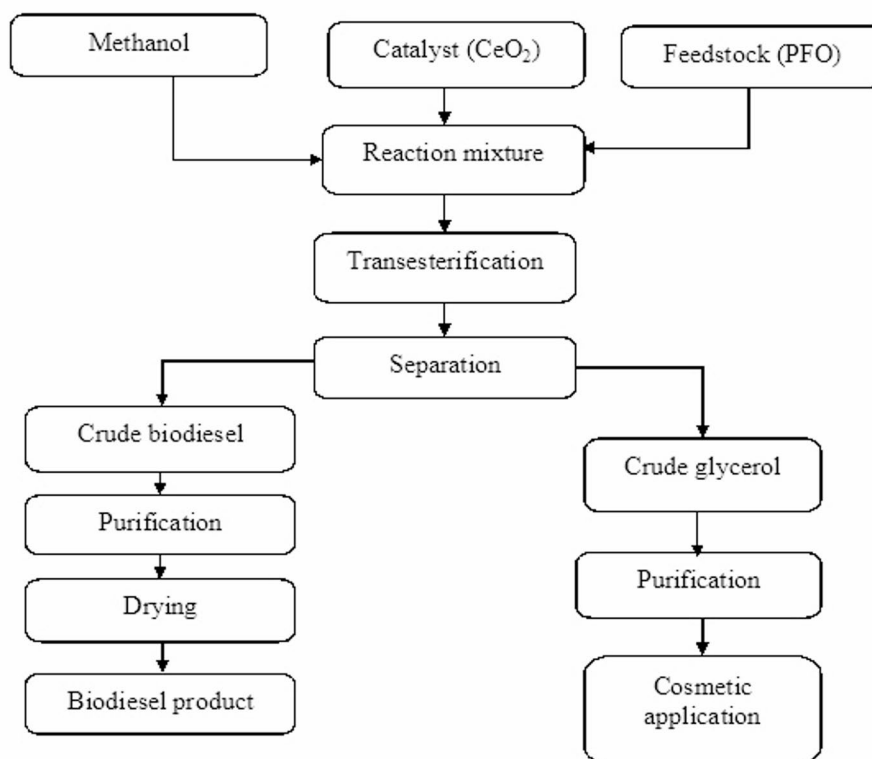


Fig. 2 Biodiesel production process flow chart by transesterification [82, 85]

increasing its energy content and decreasing the possibility of fuel leakage [87]. When density eases, biodiesel's compressibility decreases, which results in inefficiency in the fuel system. As the density of the fuel increased, more fuel could be injected by mass [88]. Depending on the measurement temperature and the region in which the plants are grown, the density of jatropha biodiesel can vary from 838 to 883 kg/m³ [1, 88]. In diesel engines, the cetane number is a crucial indicator of fuel quality [20]. A higher cetane number is indicated by a shorter ignition delay, and this is reversible. Fuels for diesel engines should have a higher cetane number [20]. For jatropha biodiesel, the cetane number ranges from 42 to 55 [89, 90]. The temperature at which biodiesel ignites when it comes into contact with fire is known as its flash point. Fuel filter and fuel line blockage may result from a lower flash point [90]. According to Table 3, the flash point of biodiesel made from *Jatropha curcas* ranges from 161 to 191 °C, which is still higher than that of diesel fuel. The cloud and pour points of biodiesel determine its cold flow characteristics [91]. High cloud and pour points of biodiesel limit its use in colder climates due to the risk of solidification, cold starting problems, and fuel filter blockages [90, 92]. *Jatropha curcas* biodiesel has pour and cloud points that range from 2 to – 6 degrees Celsius and 2 to 3 degrees Celsius, respectively [5, 93], demonstrating that it has better cold flow characteristics than diesel fuel. One crucial factor in determining the level of unsaturation in biodiesel is its iodine value (IV) [93]. IV quantifies the amount of unsaturated fatty acids in oil and biodiesel, which influences the fuel's ability to withstand oxygen exposure [93]. According to the research, the IV value of jatropha biodiesel ranges from 84 to 107 Ig/100 g of oil. According to EN 14214 (120 g/100 g), this value was related [21]. Higher levels of unsaturated fatty acids, which impact oxidation stability, are indicated by a higher IV [21].

Analogous research is being carried out to investigate the physiochemical characteristics of new *Podocarpus falcatus* (Zigba) (PF) biodiesel as a diesel engine substitute. PF biodiesel has a viscosity that ranges from 3.58 to 4.69 mm²/s [10, 11]. According to reports, PF biodiesel has a density of 860–872 kg/m³ at 15 °C [10]. This suggests that PF biodiesel has a slightly lower density and viscosity than jatropha biodiesel. PF biodiesel has a calorific value of 40.13 MJ/kg [10]. This suggests that PF biodiesel's slightly higher heating value than Jatropha biodiesel resulted in a higher energy content and output [11]. According to the findings, PF biodiesel has a cetane number of 52.07 [9]. Greater combustibility, improved ignition quality, and easier engine starting are all benefits of higher CN [91]. A fuel with a low cetane number, on the other hand, is associated with poor ignition quality, which contributes to carbon deposits, rough operation, engine noise, exhaust smoke, misfiring, especially in extremely cold temperatures, and increased knocking, which raises noise levels [9, 94]. Furthermore, the CN of jatropha and PF biodiesel are reported in a number of studies [94, 95]. PF biodiesel was found to have pour and cloud points of – 6 °C and – 7 °C, respectively [10, 95]. PF biodiesel's lower cloud point suggests superior cold flow characteristics over *Jatropha curcas* biodiesel, which lowers the possibility of fuel blockage and enhances cold starting capability. Furthermore, in colder climates, it improves atomization and combustion properties, leading to more effective burning and less incomplete combustion [9, 95]. Triglycerides, which are composed of different fatty acids joined to glycerine, make up the majority of vegetable oil. Thus, as shown in Table 4, the types of fatty acids present have a significant impact on the physicochemical characteristics of fats and oils [75, 91].

Table 4 Physicochemical properties of *Jatropha curcas* and *Podocarpus falcatus* biodiesel

Properties	Unit	Diesel	JB	PFB	ASTM D6751 Standard [96]
Density@ 15 °C	kg/m ³	833–881	838–883	860–872	860–900
Kinematic viscosity@40°C	mm ² /s	2.5–5.7	3.7–6.7	3.58–4.69	1.9–6
Calorific value	MJ/kg	42–45.9	38.5–40	40.13	–
Cetane number	–	45–55	42–55	52.07	48–60
Flash point	°C	50–96	161–191	158–162	≥ 130
Cloud point	°C	– 10 to 5	2–3	–7	–3 to 12
Pour point	°C	–20 to 5	2 to –6	–6	–15 to 10
FFA	%	0.06	0.18–3.4	0.215	–
Iodine value	g/100 g	–	84–107	–	–
Acid value	mgKOH/g	0.12	0.24	0.43	<0.8

Table 5 Fatty acid composition of *Jatropha curcas* and *Podocarpus falcatus* biodiesel

Fatty acid name and chemical formula	Structure	<i>Jatropha curcas</i> Biodiesel (% (w/w))	<i>Podocarpus falcatus</i> Biodiesel (% (w/w))
Palmitic acid (C ₁₆ H ₃₂ O ₂)	C16:0	14.1–15.3	8.87
Stearic acid (C ₁₈ H ₃₆ O ₂)	C18:0	3.7–9.8	4.45
Oleic acid (C ₁₈ H ₃₄ O ₂)	C18:1	34.3–45.8	78.4
Linoleic acid (C ₁₈ H ₃₂ O ₂)	C18:2	29–44.2	4.7
Linolenic acid (C ₁₈ H ₃₀ O ₂)	C18:3	0.5	3.04

Since important fuel properties like CN, oxidative stability, viscosity, lubricity, and cold flow characteristics are directly influenced by the fatty acid profile of the vegetable oil, fatty acid composition analysis is essential for evaluating the quality of both *Jatropha curcas* and PF biodiesel [91, 97]. Particularly, *Jatropha curcas* biodiesel has a high percentage of unsaturated fatty acids (78.9%), which has a major impact on oxidation stability [94]. In *Jatropha* oil, oleic acid (34.3–45.8%) is the most abundant fatty acid, followed by linoleic acid (29–44.2%). Palmitic acid (14.1–15.3%), stearic acid (3.7–9.8%), and palmitoleic acid make up the remaining composition [1, 94, 98]. Oleic (78.94%), linoleic (4.7%), palmitic (8.87%), stearic (4.45%), and linolenic acids make up the majority of the fatty acid composition of PF biodiesel, in contrast to 3.04% [10, 11]. Fuel stability and oxidation resistance are impacted by the presence of saturated fatty acid alkyl ester (FAAEs) [10].

Biodiesel's cold flow characteristics are influenced by its saturated fatty acid composition, whereas its stability during storage is influenced by unsaturated fatty acids [88, 91, 94]. Reduced levels of polyunsaturated fatty acids (PUFAs) and a balanced amount of saturated fatty acids (SFAs) are considered ideal for biodiesel feedstock [99]. Biodiesel produced from oilseeds high in SFAs has improved oxidation stability and a marginally higher heating value. However, compared to biodiesel produced from oils that contain more monounsaturated and PUFA fatty acids, it usually has worse cold flow characteristics because it solidifies at lower temperatures. Higher quality biodiesel is produced when monounsaturated fatty acids, such as palmitoleic acid, are concentrated with a lower concentration of PUFAs and SFAs [93]. Consequently, Table 5 shows that PF biodiesel has a lower concentration of unsaturated fatty acids and SFAs than *Jatropha curcas* biodiesel, as well as better oxidation stability and cold starting ability.

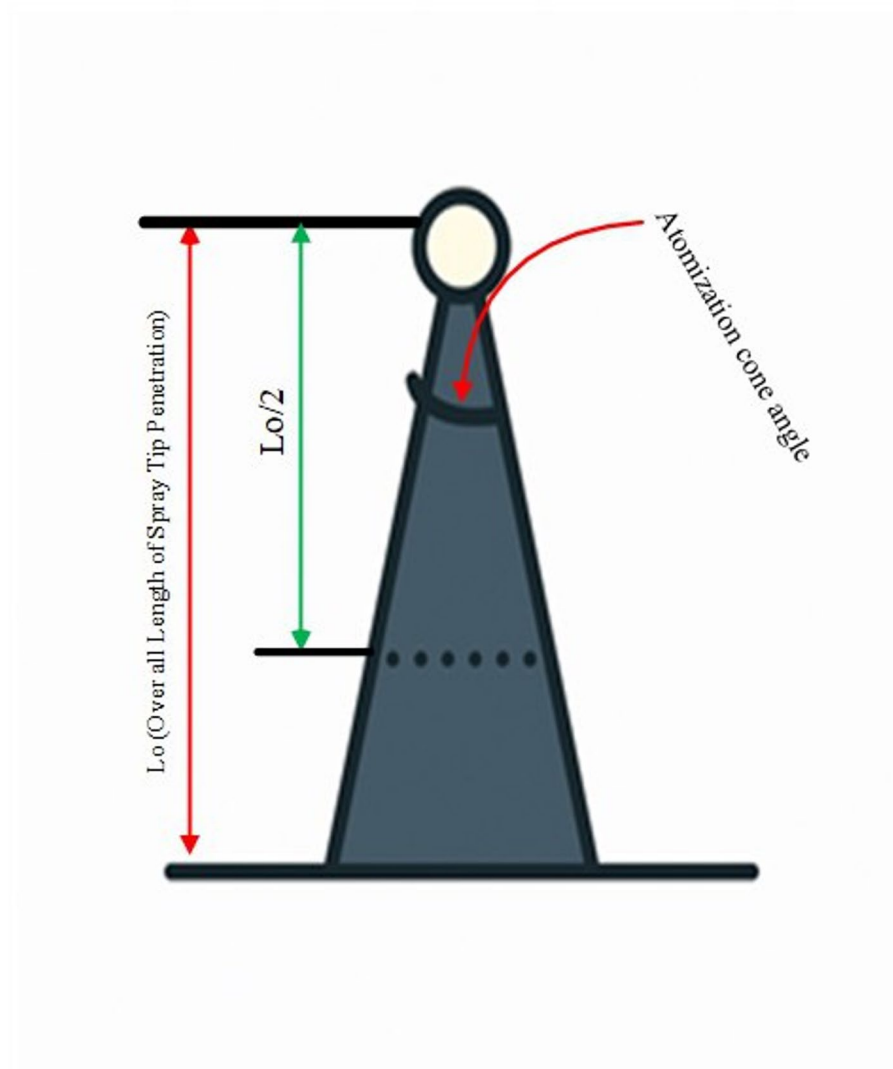


Fig. 3 Comparative spray characteristics of *Jatropha curcas* and *Podocarpus falcatus* biodiesel [105]

4 Effect of unsaturated fatty acid (UFAs) on spray and evaporation characteristics

Larger droplets in the spray can result in inadequate fuel-air mixing, incomplete combustion, and undesired exhaust emissions, so spray formation and evaporation properties are crucial in combustion [100]. Being aware of the phenomena that result in unfavorable performance and exhaust emissions. Thus, it is crucial to comprehend these engine evaporation properties in order to maximize combustion efficiency. Key indicators for assessing spray characteristics include Sauter mean diameter (SMD), spray tip penetration (STP), and spray cone angle (SCA). As seen in Fig. 3 below, these factors have a major impact on the fuel-air mixing process inside the engine cylinder [101, 102]. Spray parameters, including Sauter Mean Diameter (SMD), overall length of Spray Tip Penetration (L_o STP), and Atomization Cone Angle (ASCA), also vary according to injection pressure and orifice size. For instance, at 120 MPa injection pressure, PF biodiesel exhibited an SMD of 16–18 μm compared to 19–21 μm for JC biodiesel [103]. Similarly, STP at the same conditions was slightly lower for PF (18.5–19.0 mm) than JC (19.8–20.3

mm). SCA for PF reached 18–20° at 150 MPa, while JC biodiesel remained around 16–17°, indicating better atomization for PF under comparable test conditions [104].

SCA is measured at the midpoint of the STP along the axial direction, whereas STP is defined as the distance between the injector nozzle tip and the spray's furthest edge. While insufficient STP results in an unfavorable fuel-air mixing, excessive STP causes fuel to impinge on the combustion chamber wall [106]. A number of variables, including orifice size, injection velocity, injection pressure, and ambient gas density, affect the SCA's widest angle, which is formed by two straight lines that extend from the nozzle tip to the spray boundary. A large SCA indicates better fuel dispersion, which improves combustion by increasing spray volume and accelerating droplet distribution [102, 106]. Furthermore, a higher SCA encourages improved fuel-air mixing and air entrainment, which raises the rate of evaporation [107].

One important measure of fuel atomization performance is the SMD, which is the average droplet size generated by the injector. Finer droplets are associated with a smaller SMD, which increases the rate of evaporation and fuel vapor-air mixing [107]. The efficiency of biodiesel combustion is significantly influenced by these spray properties, especially SCA and SMD [100, 108]. Biodiesel's degree of unsaturation has a big impact on its spray and evaporation properties, which are essential for diesel engines to burn fuel efficiently [98]. Compared to saturated fatty acids, unsaturated fatty acids (UFAs) have a less rigid, more flexible, and less densely packed structure because they contain one or more double bonds in their hydrocarbon chain (SFAs) [109].

Enhancing the spray formation and evaporation properties of biodiesel is largely dependent on this structural feature. In particular, oleic acid (C18:1) and other mono-unsaturated fatty acids (MUFAs) with a single double bond in their hydrocarbon chain improve combustion performance by increasing fuel atomization, spray formation, and evaporation rate [106, 110]. Compared to SFAs, MUFAs improve the atomization of injected fuel by decreasing the viscosity of biodiesel [110]. Rapid evaporation is made possible by the smaller droplets produced by this enhanced atomization, which also offer a greater surface area for improved heat exchange. Increased combustion efficiency is the result of better fuel-air mixing brought about by faster evaporation [101].

The physical characteristics of *Jatropha curcas* biodiesel (JB), which is mostly made up of UFAs like oleic and linoleic acid, include decreased viscosity, surface tension, and enhanced volatility. According to studies, MUFAs produce a finer spray pattern at high injection pressure because they have a lower surface tension than SFAs [100]. By increasing the evaporation rate, this improved atomization eventually improves engine performance by accelerating ignition and reducing ignition delays. Compared to MUFAs, polyunsaturated fatty acids (PUFAs) further decrease the viscosity of biodiesel because linoleic acid (C18:2) and linolenic acid (C18:3) both contain multiple double bonds [109]. Better atomization and quicker evaporation are the outcomes of this [106]. By producing finer droplets, this enhances spray characteristics, increases surface area, promotes quicker evaporation, and increases combustion efficiency [106]. Although PUFAs can improve combustion and shorten ignition delays, their greater oxidation susceptibility in comparison to MUFAs may compromise fuel stability and result in long-term deposits in the combustion chamber [111].

PFB has higher MUFAs and PUFAs than JB, which may result in better atomization and spray formation when used as fuel in diesel engines, according to multiple studies [10, 11]. As a result, although both MUFAs and PUFAs enhance spray formation, atomization, and evaporation properties, their effects differ according to the degree of biodiesel unsaturation. However, MUFAs like oleic acid are favorable for the production of biodiesel because they balance atomization, evaporation, and oxidation stability and are marginally more resistant to oxidation stability. PFB with higher MUFAs may provide better atomization and evaporation, according to these studies. To completely comprehend its spray behavior and evaporation properties on diesel engines, more investigation is necessary.

Spray behavior and atomization characteristics in this review are based exclusively on experimentally reported data obtained under well-defined injection pressures, nozzle geometries, and ambient conditions. Fatty acid composition values used to interpret spray performance are verified from original sources, with data for *Podocarpus falcatus* and *Jatropha curcas* clearly distinguished throughout. Differences in spray tip penetration and cone angle are analyzed in relation to measured viscosity and fatty acid saturation levels.

5 Conclusions and future prospect

This review provides a systematic comparison of *Podocarpus falcatus* and *Jatropha curcas* as non-edible biodiesel feedstocks, focusing on oil yield, extraction and processing routes, physicochemical fuel properties, and spray and combustion behavior. The analysis shows that *P. falcatus* exhibits higher and more stable oil yields, reaching up to 58.9%, compared to the typically reported range of 45.8–51.7% for *J. curcas*. In addition, *P. falcatus* demonstrates greater drought tolerance and a higher proportion of oleic acid and monounsaturated fatty acids, which contribute to improved oxidative stability and combustion performance. In contrast, *J. curcas* oil yield and composition are more strongly influenced by environmental conditions, leading to greater variability.

From a processing perspective, *P. falcatus* generally presents lower free fatty acid content, which reduces pretreatment requirements and simplifies transesterification. Oil extraction efficiency for both feedstocks is highly dependent on the extraction method, with mechanical pressing offering simplicity but lower yield, solvent extraction providing higher recovery at the cost of chemical use, and advanced techniques such as ultrasound assisted and supercritical extraction achieving improved yields with higher economic and energy demands. Despite these differences, transesterification remains the most practical and scalable biodiesel production route for both feedstocks.

In terms of fuel properties and combustion behavior, *P. falcatus* biodiesel exhibits lower viscosity and density, superior cold flow characteristics, and a slightly higher calorific value compared to *J. curcas* biodiesel. Its higher monounsaturated fatty acid content enhances spray atomization, droplet evaporation, and combustion stability. While *J. curcas* biodiesel shows comparable cetane number and density, it generally suffers from poorer oxidation stability and less favorable cold flow performance, which may limit its suitability under low temperature operating conditions.

Future research on *Podocarpus falcatus* biodiesel should prioritize the incorporation of advanced experimental methodologies, beginning with long term agronomic field trials to capture realistic yield variability, oil productivity, and environmental resilience. At the

processing level, standardized and scalable extraction and transesterification pathways should be incorporated to enable reliable techno economic and life cycle assessments, supported by pilot scale validation to bridge laboratory and industrial applications.

Finally, future studies should incorporate multi scale modeling and machine learning techniques to accelerate process optimization and sustainability evaluation. Integrating experimentally measured fuel properties into computational fluid dynamics models will improve prediction of spray and combustion behavior, while machine learning based surrogate models can rapidly evaluate techno economic and environmental scenarios. The integration of experimental data, physics based modeling, and machine learning will be essential for informed decision making and the sustainable commercialization of *Podocarpus falcatus* biodiesel.

Abbreviations

JB	<i>Jatropha curcas</i> biodiesel
JC	<i>Jatropha curcas</i>
PF	<i>Podocarpus falcatus</i>
PFB	<i>Podocarpus falcatus</i> biodiesel
SVO	Straight vegetable oil
SFAs	Saturated fatty acids
UFAs	Unsaturated fatty acids
MUFAs	Monounsaturated fatty acids
PUFAs	Polyunsaturated fatty acids
FAAEs	Fatty acid alkyl ester
FFA	Free fatty acid
AEE	Aqueous enzymatic extraction
CN	Cetane number
IN	Iodine number
L _o STP	Spray tip penetration
ACA	Atomization cone angle
SMD	Sauter mean diameter

Author contributions

B.B. contributed to the conceptualization, data collection, analysis, methodology development, and preparation of the original draft, as well as reviewing and editing the manuscript. D.D. and K.Y. was involved in the conceptualization, data collection, analysis, and methodology and provided supervision in addition to reviewing and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data availability

Data in this paper are available upon request.

Declarations

Ethics and consent to participate

The study does not involve human subjects, animal experimentation, or sensitive data that requires ethical approval.

Consent to publish

The work does not contain any individual data, images, or materials requiring consent.

Human and animal rights

The study does not involve human participants, animals, or clinical interventions.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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References

1. Ruatpuia JVL, Halder G, Vanlalchhandama M, Lalsangpuui F, Boddula R, Al-Qahtani N, Niju S, Mathimani T, Rokhum SL. *Jatropha Curcas* oil a potential feedstock for biodiesel production: A critical review. *Fuel*. 2024;370:131829. <https://doi.org/10.1016/j.fuel.2024.131829>.

2. Suhara A, Karyadi; Herawan SG, Tirta A, Idris M, Roslan MF, Putra NR, Hananto AL, Veza I. Biodiesel sustainability: review of progress and challenges of biodiesel as sustainable biofuel. *Clean Technol*. 2024;6:886–906. <https://doi.org/10.3390/cleanotechnol6030045>.
3. Azad AK, Rasul MG, Khan MMK, Sharma SC, Hazrat MA. Prospect of biofuels as an alternative transport fuel in Australia. *Renew Sustain Energy Rev*. 2015;43:331–51. <https://doi.org/10.1016/j.rser.2014.11.047>.
4. Milano J, Silitonga AS, Tiong SK, Ong MY, Masudi A, Hassan MH, Bin Nur T, Nurulita B, Sebayang AH, Sebayang AR. A comprehensive exploration of *Jatropha curcas* biodiesel production as a viable alternative feedstock in the fuel industry – Performance evaluation and feasibility analysis. *Mech Eng Soc Ind*. 2024;4:17–37. <https://doi.org/10.31603/mesi.10610>.
5. Thapa S, Indrawan N, Bhoi PR. An overview on fuel properties and prospects of *Jatropha* biodiesel as fuel for engines. *Environ Technol Innov*. 2018;9:210–9. <https://doi.org/10.1016/j.eti.2017.12.003>.
6. Findlater KM, Kandlikar M. Land use and second-generation biofuel feedstocks: the unconsidered impacts of *Jatropha* biodiesel in Rajasthan, India. *Energy Policy*. 2011;39:3404–13. <https://doi.org/10.1016/j.enpol.2011.03.037>.
7. Hamzah NHC, Khairuddin N, Siddique BM, Hassan MA Potential of *Jatropha curcas* L. as biodiesel feedstock in Malaysia: a concise review. *Processes*. 2020;8:786. <https://doi.org/10.3390/pr8070786>.
8. Neupane D, Bhattarai D, Ahmed Z, Das B, Pandey S, Solomon JKQ, Qin R, Adhikari P. Growing *Jatropha* (*Jatropha Curcas* L.) as a potential second-generation biodiesel feedstock. *Inventions* 2021, 6, 60. <https://doi.org/10.3390/inventions6040060>.
9. Ngomade SBL, Fotso CG, Nguena KLT, Tchummege IK, Ngueteu MLT, Tamo AK, Nche GN-A, Anagho SG. Catalytic performances of CeO₂@SBA-15 as nanostructured material for biodiesel production from *Podocarpus falcatus* oil. *Chem Eng Res Des*. 2023;194:789–800. <https://doi.org/10.1016/j.cherd.2023.05.010>.
10. Ngomade SBL, Bhonsle AK, Rawat N, Kuete H-IT, Nana A, Nche GN-A, Anagho SG, Atray N. Biodiesel production from High-free fatty acids *Podocarpus falcatus* oil and identification of fatty acid Methyl esters by FT-IR, NMR (1H and 13 C) and GC/MS studies. *Iran J Sci*. 2024;48:865–78. <https://doi.org/10.1007/s40995-024-01649-1>.
11. Ngomade SBL, Tchoufon RDT, Tagne RFT, Ngueteu MLT, Patai HM, Nche GN-A, Anagho SG 2022 Optimization by response surface methodology of biodiesel production from *Podocarpus falcatus* oil as a Cameroonian novel nonedible feedstock. *J Chem* 202 3786602. <https://doi.org/10.1155/2022/3786602>.
12. Fekadu M, Feleke S, Bekele T. Selection of seed oil biodiesel producing tree species, emission reduction and land suitability. *Agric Eng Int CIGR J*. 2019;21:132–43.
13. Alemu GD, Solomon A, Girma SA, Sisay F. Effects of extraction temperature and particle size on quality of edible oil from *Podocarpus falcatus* seed by aqueous Method, Ethiopia. *J Food Sci Nutr Ther*. 2022;8:006–10. <https://doi.org/10.17352/jfsnt.000032>.
14. Mairapetyan S, Tadevosyan A, Tovmasyan A, Asatryan A, Efimenko S, Efimenko S, Matevosyan A. The influence of planting density on the oil and fatty acids content of soybean in hydroponic and soil conditions of the Ararat Valley. *Bioact Compd Heal Dis*. 2024;7:418–29. <https://doi.org/10.31989/bchd.v7i9.1441>.
15. Thangavel P, Anjum NA, Masood A, Khan NA, Umar S, Rasheed F. *Herbaceous Edible Oilseed-Bearing Plants: Origin, Botanical Insights, Constraints, and Recent Progress*; Anjum, N.A., Masood, A., Umar, S., Khan, N.A., Eds.; IntechOpen: London, UK, 2024. <https://doi.org/10.5772/intechopen.115469>
16. Mustayen AGMB, Rasul MG, Wang X, Negnevitsky M, Hamilton JM. Remote areas and Islands power generation: A review on diesel engine performance and emission improvement techniques. *Energy Convers Manag*. 2022;260:115614. <https://doi.org/10.1016/j.enconman.2022.115614>.
17. Nguyen VG, Pham MT, Le NVL, Le HC, Truong TH, Cao DN. A comprehensive review on the use of biodiesel for diesel engines. *Int J Renew Energy Dev*. 2023;12:720–40. <https://doi.org/10.14710/ijred.2023.54612>.
18. Bhatia SK, Gurav R, Choi T-R, Jung H-R, Yang S-Y, Song H-S, Kim Y-G, Yoon J-J, Yang Y-H. Effect of synthetic and food waste-derived volatile fatty acids on lipid accumulation in *Rhodococcus* sp. YHY01 and the properties of produced biodiesel. *Energy Convers Manag*. 2019;192:385–95. <https://doi.org/10.1016/j.enconman.2019.03.081>.
19. Singh D, Sharma D, Soni SL, Sharma S, Sharma PK, Jhalani A. A review on feedstocks, production processes, and yield for different generations of biodiesel. *Fuel*. 2020;262:116553.
20. Arbab MI, Masjuki HH, Varman M, Kalam MA, Imtenan S, Sajjad H. Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel. *Renew Sustain Energy Rev*. 2013;22:133–47. <https://doi.org/10.1016/j.rser.2013.01.046>.
21. Singh D, Sharma D, Soni S, Inda CS, Sharma S, Sharma PK, Jhalani A. A comprehensive review of physicochemical properties, production process, performance and emissions characteristics of 2nd generation biodiesel feedstock: *Jatropha Curcas*. *Fuel*. 2021;285:119110. <https://doi.org/10.1016/j.fuel.2020.119110>.
22. Mishra VK, Goswami R. A review of production, properties and advantages of biodiesel. *Biofuels*. 2018;9:273–89. <https://doi.org/10.1080/17597269.2017.1336350>.
23. Anwar M. Biodiesel feedstocks selection strategies based on economic, technical, and sustainable aspects. *Fuel*. 2021;283:119204. <https://doi.org/10.1016/j.fuel.2020.119204>.
24. Neupane D. Biofuels from renewable Sources, a potential option for biodiesel production. *Bioengineering*. 2023;10:29. <https://doi.org/10.3390/bioengineering10010029>.
25. Zulqarnain; Ayoub M, Yusoff MHM, Nazir MH, Zahid I, Ameen M, Sher F, Floresyona D, Nursanto EB. A comprehensive review on oil extraction and biodiesel production technologies. *Sustainability*. 2021;13:788. <https://doi.org/10.3390/su13020788>.
26. Bôas RNV, Mendes MF. A review of biodiesel production from Non-Edible Raw materials using the transesterification process with a focus on influence of feedstock composition and free fatty acids. *J Chil Chem Soc*. 2022;67:5433–44. <https://doi.org/10.4067/S0717-97072022000105433>.
27. Shaah MAH, Hossain S, Allafi FAS, Alsaedi A, Ismail N, Ab Kadir MO, Ahmad MI. A review on non-edible oil as a potential feedstock for biodiesel: physicochemical properties and production technologies. *RSC Adv*. 2021;11:25018–37. <https://doi.org/10.1039/d1ra04311k>.
28. Jonas M, Ketlogetswe C, Gandure J. Variation of *Jatropha Curcas* seed oil content and fatty acid composition with fruit maturity stage. *Heliyon*. 2020;6:e03285. <https://doi.org/10.1016/j.heliyon.2020.e03285>.
29. Georges Y. IRA Int J Educ Multidiscip Stud. 2022;18. <https://doi.org/10.21013/jas.v17.n4.p>.
30. Karmakar B, Halder G. Progress and future of biodiesel synthesis: advancements in oil extraction and conversion technologies. *Energy Convers Manag*. 2019;182:307–39. <https://doi.org/10.1016/j.enconman.2018.12.066>.

31. Mohadesi M, Moradi G, Ghanbari M, Moradi MJ. Investigating the effect of n-hexane as solvent on waste cooking oil conversion to biodiesel using CaO on a new support as catalyst. *Meas J Int Meas Confed*. 2019;135:606–12. <https://doi.org/10.1016/j.measurement.2018.12.022>.
32. Yusuff AS. Parametric optimization of solvent extraction of *Jatropha Curcas* seed oil using design of experiment and its quality characterization. *South Afr J Chem Eng*. 2021;35:60–8. <https://doi.org/10.1016/j.sajce.2020.11.006>.
33. He Y, Peng T, Guo Y, Li S, Guo Y, Tang L, Chen F. Nontoxic oil Preparation from *Jatropha Curcas* L. seeds by an optimized methanol/n-hexane sequential extraction method. *Ind Crop Prod*. 2017;97:308–15. <https://doi.org/10.1016/j.indcrop.2016.12.034>.
34. Yahaya S, Giwa SO, Ibrahim M, Giwa A. Extraction of oil from *Jatropha* seed kernels: optimization and characterization. *Int J ChemTech Res*. 2016;9:758–70.
35. Keneni YG, Marchetti JM. Oil extraction from plant seeds for biodiesel production. *AIMS Energy*. 2017;5:316–40. <https://doi.org/10.3934/energy.2017.2.316>.
36. Ntalikwa JW. Solvent extraction of *Jatropha* oil for biodiesel production: effects of Solvent-to-Solid Ratio, particle Size, type of Solvent, extraction Time, and temperature on oil yield. *J Renew Energy*. 2021;1:9221168. <https://doi.org/10.1155/2021/9221168>.
37. Agu CM, Menkiti MC, Ohale PE, Ugonabo VI. Extraction modeling, kinetics, and thermodynamics of solvent extraction of *Irvingia gabonensis* kernel oil, for possible industrial application. *Eng Rep*. 2021;3:e12306. <https://doi.org/10.1002/eng.2.12306>.
38. Mekonnen Y. Epoxidation of *Podocarpus falcatus* oil by sulphuric acid catalyst: process optimization and Physio-chemical characterization. *Am J Chem Eng*. 2021;9:84. <https://doi.org/10.11648/jajche.20210904.12>.
39. Aboubakar X, Goudoum A, Bébé Y, Mbofung CMF. Optimization of *Jatropha Curcas* pure vegetable oil production parameters for cooking energy. *South Afr J Chem Eng*. 2017;24:196–212. <https://doi.org/10.1016/j.sajce.2017.09.002>.
40. Shivani P, Khushbu P, Faldu N, Thakkar V, Shubramanian RB. Extraction and analysis of *Jatropha Curcas* L. seed oil. *Afr J Biotechnol* 2011, 10, 18210–3. <https://doi.org/10.5897/AJB11.776>.
41. Evon P, Kartika IA, Cerny M, Rigal L. Extraction of oil from *Jatropha* seeds using a twin-screw extruder: feasibility study. *Ind Crop Prod*. 2013;47:33–42. <https://doi.org/10.1016/j.indcrop.2013.02.034>.
42. Riyatsyah TMI, Sebayang AH, Silitunga AS, Padli Y, Fattah IMR, Kusumo F, Ong HC, Mahlia TM. I. Current progress of *Jatropha Curcas* commoditisation as biodiesel feedstock: A comprehensive review. *Front Energy Res*. 2022;9:1–19. <https://doi.org/10.3389/fenrg.2021.815416>.
43. Khalaf M, Abdel-Fadeel W, Abu Hashish HM, Wapet DEM, Mahmoud MM, Elhady SA, Esmail MFC. Experimental investigation of different extraction methods for producing biofuel from *Jatropha* seeds and castor seeds. *Int J Energy Res*. 2023;2023:1–15. <https://doi.org/10.1155/2023/1780536>.
44. Subroto E, Manurung R, Heeres HJ, Broekhuis AA. Optimization of mechanical oil extraction from *Jatropha Curcas* L: kernel using response surface method. *Ind Crop Prod*. 2015;63:294–302. <https://doi.org/10.1016/j.indcrop.2014.08.050>.
45. Mouahid A, Bouanga H, Crampon C, Badens E. Supercritical CO₂ extraction of oil from *Jatropha curcas*: an experimental and modelling study. *J Supercrit Fluids*. 2018;141:2–11. <https://doi.org/10.1016/j.supflu.2017.11.014>.
46. Soto-Armenta LC, Rivero JCS, Ruiz-Mercado CA, González-Coloma A, Rocha-Urbe JA. Bioactivity and kinetic study of *Jatropha Curcas* essential oil extraction using supercritical CO₂. *Am J Anal Chem*. 2020;11:322–34. <https://doi.org/10.4236/ajac.2020.118026>.
47. Pérez-Cisneros ES, Sales-Cruz M, Rodríguez-López V, Mena-Espino X, Viveros-García T. *A Supercritical Reactive Separation Process to Obtain Biopesticides (Phorbol-Esters) in the Biodiesel Production from Jatropha curcas Oil*; Elsevier Masson SAS: Paris, France, 2016; Volume 38. <https://doi.org/10.1016/B978-0-444-63428-3.50308-8>.
48. Chavda N, Rathod P. Study and synthesis of Bio-fuel from *Jatropha* vegetable oil. *Int J Res Appl Sci Eng Technol*. 2023;11:4810–7. <https://doi.org/10.22214/ijraset.2023.52791>.
49. Yadav A, Mishra SP, Kendurkar PS, Kumar A, Maurya R. Physicochemical characterization of *Jatropha* oil seed and suitability as biodiesel feedstock. *Trop Plant Res*. 2020;7:581–6. <https://doi.org/10.22271/tpr.2020.v7.i3.071>.
50. Keneni YG, Bahiru LA, Marchetti JM. Effects of different extraction solvents on oil extracted from *Jatropha* seeds and the potential of seed residues as a heat provider. *BioEnergy Res*. 2021;14:1207–22. <https://doi.org/10.1007/s12155-020-10217-5>.
51. Satar I, Permadi A, Ahmed WA. Evaluating physicochemical properties of mutated *Jatropha Curcas* seed oils and their feasibility as new feedstocks for biodiesel production. *Eng Agric*. 2022;42. <https://doi.org/10.1590/1809-4430-ENG.AGRIC.V42NEPE20220093/2022>.
52. Agyemang NS, Antwi K. Variations in oil content and biodiesel yield of *Jatropha Curcas* from different agro-ecological zones of Ghana. *Int J Renew Sustain Energy*. 2014;3:76–81. <https://doi.org/10.11648/j.ijrse.20140304.11>.
53. Tseke RE, Minale M, Tedila A. Seed oil content and variability of some provenance of *Jatropha Curcas* population in Ethiopia. *Adv Environ Waste Manag Recycl*. 2022;5:284–7. <https://doi.org/10.33140/aewmr.05.03.04>.
54. Feleke S, Haile F, Alemu A, Abebe S. Characteristics of seed kernel oil from *Podocarpus falcatus*. *J Trop Sci*. 2012;24:512–6.
55. Portner B, Ehrensperger A, Nezir Z, Breu T, Hurni H. Biofuels for a greener economy? Insights from *Jatropha* production in Northeastern Ethiopia. *Sustainability*. 2014;6:6188–202. <https://doi.org/10.3390/su6096188>.
56. Ntaribi T, Paul DL. Status of *Jatropha* plants farming for biodiesel production in Rwanda. *Energy Sustain Dev*. 2018;47:133–42. <https://doi.org/10.1016/j.esd.2018.09.009>.
57. Abdudeen A, Selim MYE, Sekar M, Elgendi M. *Jatropha's* rapid developments and future opportunities as a renewable source of Biofuel—A review. *Energies*. 2023;16:828. <https://doi.org/10.3390/en16020828>.
58. Liu J, Chen P, He J, Deng L, Wang L, Lei J, Rong L. Extraction of oil from *Jatropha Curcas* seeds by subcritical fluid extraction. *Ind Crop Prod*. 2014;62:235–41. <https://doi.org/10.1016/j.indcrop.2014.08.039>.
59. Ishak MAM, Hussain HH, Ismail K, Nawawi WI, Ab GZ, Ani AY. Extraction of oil from *Jatropha Curcas* L. Seed and kernel at supercritical hexane via High-Temperature High-Pressure batch wise reactor system. *Appl Mech Mater*. 2015;754–755:1102–6. <https://doi.org/10.4028/www.scientific.net/amm.754-755.1102>.
60. Fernández CM, Fiori L, Ramos MJ, Pérez Á, Rodríguez JF. Supercritical extraction and fractionation of *Jatropha Curcas* L. oil for biodiesel production. *J Supercrit Fluids*. 2015;97:100–6. <https://doi.org/10.1016/j.supflu.2014.11.010>.
61. Kumar G. Ultrasonic-assisted reactive-extraction is a fast and easy method for biodiesel production from *Jatropha Curcas* oilseeds. *Ultrason Sonochemistry*. 2017;37:634–9. <https://doi.org/10.1016/j.ultsonch.2017.02.018>.

62. Kumar G, Kumar D, Johari R. Time reducing process for biofuel production from Non edible oil assisted by ultrasonication. *Ultrason Sonochemistry*. 2014;21:1618–23. <https://doi.org/10.1016/j.ultsonch.2014.04.004>.
63. Farahani GT, Azari PY. Improving the oil yield of Iranian *Jatropha Curcas* seeds by optimising ultrasound-assisted ethanolic extraction process: A response surface method. *Qual Assur Saf Crop Foods*. 2016;8:95–104. <https://doi.org/10.3920/QAS2014.0547>.
64. Romuli S, Karaj S, Latif S, Müller J. Performance of mechanical co-extraction of *Jatropha Curcas* L. kernels with rapeseed, maize or soybean with regard to oil recovery, press capacity and product quality. *Ind Crop Prod*. 2017;104:81–90. <https://doi.org/10.1016/j.indcrop.2017.03.035>.
65. Yusoff MM, Gordon MH, Ezeh O, Niranjana K. Aqueous enzymatic extraction of Moringa Oleifera oil. *Food Chem*. 2016;211:400–8. <https://doi.org/10.1016/j.foodchem.2016.05.050>.
66. Herrera JM, Sánchez-Chino X, Corzo-Ríos LJ, Dávila-Ortiz G, Martínez CJ. Comparative extraction of *Jatropha Curcas* L. lipids by conventional and enzymatic methods. *Food Bioprod Process*. 2019;118:32–9. <https://doi.org/10.1016/j.fbp.2019.08.013>.
67. Steinbrenner J, Jeon J, Nägele HJ, Kirchner S, Böhlinger B, Lemmer A. Anaerobic digestion of aqueous *Jatropha* seed oil extraction residues and phorbol ester degradation. *Bioresour Technol Rep*. 2020;12:100601. <https://doi.org/10.1016/j.biteb.2020.100601>.
68. Zulqarnain; Yusoff MM, Ayoub M, Ramzan N, Nazir MH, Zahid I, Abbas N, Elboughdiri N, Mirza CR, Butt TA. Overview of feedstocks for sustainable biodiesel production and implementation of the biodiesel program in Pakistan. *ACS Omega*. 2021;6:19099–114. <https://doi.org/10.1021/acsomega.1c02402>.
69. Markov V, Kamaltdinov V, Devyanin S, Sa B, Zherdev A, Furman V. Investigation of the influence of different vegetable oils as a component of blended biofuel on performance and emission characteristics of a diesel engine for agricultural machinery and commercial vehicles. *Resources*. 2021;10:39–41. <https://doi.org/10.3390/resources10080074>.
70. Singh SP, Singh D. Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review. *Renew Sustain Energy Rev*. 2010;14:200–16.
71. Gülüm M, Bilgin A. A comprehensive study on measurement and prediction of viscosity of biodiesel-diesel-alcohol ternary blends. *Energy*. 2018;148:341–61. <https://doi.org/10.1016/j.energy.2018.01.123>.
72. Sidibe S, Blin J, Daho T, Vaitilingom G, Kouliadiati J. Comparative study of three ways of using *Jatropha Curcas* vegetable oil in a direct injection diesel engine. *Sci Afr*. 2020;7:e00290. <https://doi.org/10.1016/j.sciaf.2020.e00290>.
73. Koh MY, Tinia TI. A review of biodiesel production from *Jatropha Curcas* L. Oil. *Oil. Renew Sustain Energy Rev*. 2011;15:2240–51. <https://doi.org/10.1016/j.rser.2011.02.013>.
74. Jain S. The production of biodiesel using Karanja (*Pongamia pinnata*) and *Jatropha* (*Jatropha curcas*) oil. Amsterdam, The Netherlands: Elsevier Ltd.; 2019. <https://doi.org/10.1016/B978-0-08-102426-3.00017-5>.
75. Gebremariam SN, Marchetti JM. Biodiesel production technologies: review. *AIMS Energy*. 2017;5:425–57. <https://doi.org/10.3934/energy.2017.3.425>.
76. Chiamonti D, Bonini M, Fratini E, Tondi G, Gartner K, Bridgwater A, Grimm H, Soldaini I, Webster A, Baglioni P. Development of emulsions from biomass pyrolysis liquid and diesel and their use in engines—Part 1: emulsion production. *Biomass-Bioenergy*. 2003;25:85–99. [https://doi.org/10.1016/S0961-9534\(02\)00183-6](https://doi.org/10.1016/S0961-9534(02)00183-6).
77. Eloka-Eboka AC, Maroa S. 6—Advanced and sustainable biodiesel fuels: technologies and applications. In: Ray RC, editor. *Sustainable biofuels*. Cambridge, MA, USA: in Applied Biotechnology Reviews; Academic; 2021. pp. 131–61. <https://doi.org/10.1016/B978-0-12-820297-5.00005-0>.
78. GS A, Raphael MS. Cracking upgrading process of biomass. In: Rahimpour MR, editor. *Encyclopedia of renewable Energy, sustainability and the environment*. 1st ed. Oxford, UK: Elsevier; 2024. pp. 693–700. <https://doi.org/10.1016/B978-0-323-93940-9.00057-8>.
79. Gunawan ML, Novita TH, Aprialdi F, Aulia D, Nanda AS, Rasrendra CB, Addarajah Z, Mujahidin D, Kadja GT. Palm-oil transformation into green and clean biofuels: recent advances in the zeolite-based catalytic technologies. *Bioresour Technol Rep*. 2023;23:101546. <https://doi.org/10.1016/j.biteb.2023.101546>.
80. Wang YY, Chang C-C, Chang C-Y, Chen Y-H, Shie J-L, Yuan M-H, Chen Y-H, Huang L-X, Andrade-Tacca CA, Van Manh D, et al. Thermal cracking of *Jatropha* oil with hydrogen to produce bio-fuel oil. *Energies*. 2016;9:910. <https://doi.org/10.3390/en9110910>.
81. Shrestha K, Ghimire JR, Gwali MB. Biodiesel production from *Jatropha Curcas* (L.) oil of Nepal by transesterification process. *Int J Pharm Chem Biol Sci*. 2013;3:603–9.
82. Lin JJ, Chen YW. Production of biodiesel by transesterification of *Jatropha* oil with microwave heating. *J Taiwan Inst Chem Eng*. 2017;75:43–50. <https://doi.org/10.1016/j.jtice.2017.03.034>.
83. Naseef HH, Tulaimat RH. Transesterification and esterification for biodiesel production: A comprehensive review of catalysts and palm oil feedstocks. *Energy Convers Manag*. 2025;26:100931. <https://doi.org/10.1016/j.ecmx.2025.100931>.
84. Eyide O, Ulakpa WC, Nwabukei I. Optimization of biodiesel yield synthesized by calcium oxide Nano-catalyst Trans-esterified *Jatropha Curcas* oil. *J Appl Sci Environ Manag*. 2025;29:1029–38. <https://doi.org/10.4314/jasem.v29i4.3>.
85. Athar M, Imdad S, Zaidi S, Yusuf M, Kamyab H, Klemeš JJ, Chelliapan S. Biodiesel production by single-step acid-catalysed transesterification of *Jatropha* oil under microwave heating with modelling and optimisation using response surface methodology. *Fuel*. 2022;322:124205. <https://doi.org/10.1016/j.fuel.2022.124205>.
86. Mazumdar P, Borugadda VB, Goud VV, Sahoo L. Physico-chemical characteristics of *Jatropha Curcas* L. of North East India for exploration of biodiesel. *Biomass Bioenergy*. 2012;46:546–54. <https://doi.org/10.1016/j.biombioe.2012.07.005>.
87. Schaschke C, Fletcher I, Glen N. Density and viscosity measurement of diesel fuels at combined high pressure and elevated temperature. *Processes*. 2013;1:30–48. <https://doi.org/10.3390/pr1020030>.
88. Ewunie GA, Morken J, Lekang OI, Yigezu ZD. Factors affecting the potential of *Jatropha Curcas* for sustainable biodiesel production: A critical review. *Renew Sustain Energy Rev*. 2021;137:110500. <https://doi.org/10.1016/j.rser.2020.110500>.
89. Sparsh S, Ramakrishna CS, Sahu R, Narain RS, Sohal JK, Sahu M, Sharma N, Kumar V, Sharma A. Future prospects of biodiesel production from *jatropha* in India. *Mater. Today: Proc*. 2022, 63, A22–A26. <https://doi.org/10.1016/j.matpr.2022.07.273>.
90. Achari SC, KPS, Madhukumar K. *Jatropha* biodiesel as a fuel for future—a review. *Int. J. Comput. Eng. Res. Trends* 2023, 6. <https://doi.org/10.21884/IJTER.2019.6008.BDAFX>.
91. Lanjekar RD, Deshmukh D. A review of the effect of the composition of biodiesel on nox emission, oxidative stability and cold flow properties. *Renew Sustain Energy Rev*. 2016;54:1401–11. <https://doi.org/10.1016/j.rser.2015.10.034>.

92. Deshmukh S, Kumar R, Bala K. Microalgae biodiesel: A review on oil extraction, fatty acid composition, properties and effect on engine performance and emissions. *Fuel Process Technol.* 2019;191:232–47. <https://doi.org/10.1016/j.fuproc.2019.03.013>.
93. Atabani AE, Silitonga A, Ong H, Mahlia T, Masjuki H, Badruddin IA, Fayaz H. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. *Renew Sustain Energy Rev.* 2013;18:211–45. <https://doi.org/10.1016/j.rser.2012.10.013>.
94. Islam AKMA, Yaakob Z, Anuar N, Primandari SRP, Osman M. Physiochemical properties of *Jatropha Curcas* seed oil from different origins and candidate plus plants (CPPs). *J Am Oil Chem Soc.* 2012;89:293–300. <https://doi.org/10.1007/s11746-011-1908-7>.
95. Ngomade SBL, Rawat N, Ngueteu MLT, Anensong CSD, Bopda A, Nche GN-A, Anagho SG, Atray N. Optimization of the oil extraction process by response surface methodology from *Podocarpus falcatus* seed as a low-grade substitute feedstock for biodiesel applications. *Biomass Convers Biorefinery.* 2023;15:25909–21. <https://doi.org/10.1007/s13399-023-05122-8>.
96. Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels/, International ASTM. West Conshohocken, PA, USA, 2023. [Online]. Available: <https://store.astm.org/d6751-20a.html>
97. Aderibigbe FA, Mustapha SI, Adewoye TL, Mohammed IA, Gbadegesin AB, Niyi FE, Olowu OI, Soretire AG, Saka HB. Qualitative role of heterogeneous catalysts in biodiesel production from *Jatropha Curcas* oil. *Biofuel Res J.* 2020;7:1159–69. <https://doi.org/10.18331/BRJ2020.7.2.4>.
98. Khethiwe E, Clever K, Jerekias G. Effects of fatty acids composition on fuel properties of *Jatropha Curcas* biodiesel. *Smart Grid Renew Energy.* 2020;11:165–80. <https://doi.org/10.4236/sgre.2020.1110010>.
99. Abdullah BM, Yusop RM, Salimon J, Yousif E, Salih N. Physical and chemical properties analysis of *Jatropha Curcas* seed oil for industrial applications. *Int J Chem Mol Nucl Mater Metall Eng.* 2013;7:893–6.
100. Park SH, Kim HJ, Suh HK, Lee CS. International journal of heat and fluid flow experimental and numerical analysis of spray-atomization characteristics of biodiesel fuel in various fuel and ambient temperatures conditions. *Int J Heat Fluid Flow.* 2009;30:960–70. <https://doi.org/10.1016/j.ijheatfluidflow.2009.04.003>.
101. Shen Y, Li F, Liu Z, Wang H, Shen J. Study on the characteristics of evaporation e atomization e combustion of biodiesel. *J Energy Inst.* 2019;92:1458–67. <https://doi.org/10.1016/j.joei.2018.08.005>.
102. Wang XR, Xue W, Sun W, Tang S, Jiang G. Investigation of single drop evaporation characteristics of two-component fatty acid Methyl esters at high temperature. *Fuel.* 2023;334:126566. <https://doi.org/10.1016/j.fuel.2022.126566>.
103. Khuong LS, Hashimoto N, Fujita O. Spray, droplet evaporation, combustion, and emission characteristics of future transport fuels for compression-ignition engines: A review. *J Traffic Transp Eng Engl Ed.* 2024;11:575–613. <https://doi.org/10.1016/j.jtte.2024.04.003>.
104. Geng L, Wang Y, Wang Y, Li H. Effect of the injection pressure and orifice diameter on the spray characteristics of biodiesel. *J Traffic Transp Eng Engl Ed.* 2020;7:331–9. <https://doi.org/10.1016/j.jtte.2018.12.004>.
105. Fu W, Song L, Liu T, Lin Q. Experimental study of spray characteristics of biodiesel blending with diethyl carbonate in a common rail injection system. *Proc Inst Mech Eng Part D J Automob Eng.* 2019;233:249–62. <https://doi.org/10.1177/0954407017740792>.
106. Senthil R, Arun G. Review of physicochemical properties and spray characteristics of biodiesel. *Environ Sci Pollut Res.* 2023;30:66494–513. <https://doi.org/10.1007/s11356-023-27250-4>.
107. Liu Y, Tian J, Song Z, Li F, Zhou W, Lin Q. Spray characteristics of diesel, biodiesel, polyoxymethylene dimethyl ethers blends and prediction of spray tip penetration using artificial neural network. *Phys Fluids.* 2023;34:015117. <https://doi.org/10.1063/5.0077405>.
108. Pel R, Mounaïm-rousselle C, Bréquigny P, Hespel C. First study on ammonia spray characteristics with a current GDI engine injector. *Fuels.* 2021;2:253–71.
109. Sharma V, Hossain AK. Experimental investigation of neat biodiesels' saturation level on combustion and emission characteristics in a CI engine. *Energies.* 2021;14:5203.
110. Das M, Sarkar M, Datta A, Santra AK. Study on viscosity and surface tension properties of biodiesel-diesel blends and their effects on spray parameters for CI engines. *Fuel.* 2018;220:769–79. <https://doi.org/10.1016/j.fuel.2018.02.021>.
111. Cheng C, Hu Y, Jiang Y. Investigation of evaporation and combustion characteristics of diesel and fatty acid Methyl esters emulsified fuel droplets. *Fuel.* 2024;360:130609. <https://doi.org/10.1016/j.fuel.2023.130609>.

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