Type of contribution:
Editorial
Research Paper
Case Study
▶ Review Paper
Scientific Data
Report of Tech. Application

e-issn. 2798-5245

Mechanical Engineering
for Society and Industry
Vol. 4, No. 1 (2024) pp 17-37
https://doi.org/10.31603/mesi.10610

A comprehensive exploration of jatropha curcas biodiesel production as a viable alternative feedstock in the fuel industry – Performance evaluation and feasibility analysis

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This article contributes to:
7 AFFORDABLE AND CLEAN ENERGY
SUSTAINABLE DEVELOPMENT GOALS

Highlights:

- Jatropha Curcas offers non-edible oil with favorable properties for biodiesel.
- With yields of up to 40% oil weight per seed, Jatropha Curcas enhances the economic feasibility of biodiesel production and offers significant oil output potential.
- This paper provides a comprehensive review, exploring engine performance, emissions, and fuel properties of Jatropha Curcas, contributing valuable insights to sustainable energy solutions.

Abstract

Jatropha Curcas stands out as a promising plant-based feedstock, offering a non-edible oil that holds great potential as an alternative fuel to traditional diesel. Notably, Jatropha oil boasts favourable fuel properties, including a higher oil content compared to other alternatives. This attribute makes it an attractive candidate for biodiesel production. Importantly, as a non-edible oilseed feedstock, Jatropha Curcas helps mitigate concerns related to food prices and the ongoing food versus fuel debate, offering a sustainable solution to the growing energy demands. Furthermore, the plant exhibits impressive yields, with the potential to produce up to 40% oil weight per seed. This high yield not only enhances the economic viability of Jatropha-based biodiesel but also underscores its efficiency as a feedstock. The discussion extends beyond mere fuel properties, encompassing a comprehensive comparative review that delves into engine performance and emission characteristics associated with Jatropha Curcas. The novelty of this paper lies in its exploration of the crude oil aspects of Jatropha curcas, shedding light on an essential facet often overlooked. By presenting a thorough analysis of fuel properties, engine performance, and emission characteristics, the paper contributes valuable insights to the discourse on sustainable energy solutions. Moreover, it goes beyond technical aspects and provides perspectives on the current economic status, offering a holistic view of the potential impact of Jatropha Curcas in the broader context of renewable energy and economic development.

Keywords: Jatropha; Biodiesel; Engine performance; Fuel properties; Economic feasibility

Article info
Submitted:
2023-11-30
Revised:
2023-01-29
Accepted:
2023-03-17

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Publisher
Universitas Muhammadiyah Magelang

1. Introduction

There is a demand to find an alternative energy source to meet the increasing energy needs of the world. Because of the inevitable future decline of fossil fuel resources and the current increasing prices of such fuels, biodiesel fuels (BDFs) are considered a potential replacement for diesel and have some advantages, such as a higher cetane index and lower emissions of carbon dioxide. Biodiesel is the name of a clean-burning mono-alkyl ester-based oxygenated fuel made from natural, renewable sources such as new/used vegetable oils and animal fats. According to data from the International Energy Agency (IEA), global biodiesel production is approximately 22 billion litres in 2010 to approximately 2-fold in 2019, which almost reaches 43 billion litres. Half of world biodiesel production continued to be in Germany. Significant production increases also took place in Italy and the United States (where production more than tripled). In Europe, supported by new policies, biodiesel gained broader acceptance and market share. The aggressive expansion of biodiesel production was also occurring in Southeast Asia (Malaysia, Indonesia, Singapore, and China), Latin America (Argentina and Brazil). Malaysia's ambition is to capture 10% of the global biodiesel market by 2010 based on its palm oil plantations [1]. Biodiesel is one of these promising alternative resources for diesel engines. It is renewable, biodegradable, environmentally friendly, non-toxic, portable, readily available, and eco-friendly fuel [2]–[4].

Biodiesel as an alternative and clean fuel because it does not contain any sulphur, aromatic hydrocarbons, metals, crude oil residues and contributes a minimal amount of net greenhouse gases to the atmosphere [5]. Currently, more than 95% of the world's biodiesel is produced from edible oils such as rapeseed (84%), sunflower oil (13%), palm oil (1%), soybean oil, and others (2%). Biodiesel is gaining worldwide attention. Edible oils are considered the first generation of biodiesel feedstock. Biodiesel has been produced in the US and Europe using edible oils because they have a surplus of them, can achieve high biodiesel yield and easy processing due to their low free fatty acids. However, their use has raised many concerns such as food versus fuel problems and some environmental problems such as serious destruction of vital soil resources, deforestation, and usage of much of the available land as can be seen in many countries especially highly populated countries such as China and India. All of these factors negatively affected the economic viability of biodiesel production from edible oils. It is known that the cost of feedstock alone represents 75% of the cost of biodiesel. Therefore, the exploration of new low-cost agricultural non-edible crops and the utilization of by-products in biodiesel production may significantly reduce the cost of biodiesel, especially in poor countries which can hardly afford the high cost of edible oils [6]–[8].

During this past decade, energy supply and its security have become a major issue around the world. The combustion of fossil fuels provides the energy that makes technological advancement and economic growth of a country. Fossil fuels cause the emission of greenhouse gases and other types of air pollutant that leaves a negative impact on the environment. Rakesh et al. reported that biodiesel, an alternative renewable fuel made from transesterification of vegetable oil with alcohol, is becoming more readily available for use in blends with conventional diesel fuel for transportation applications [9]. Increasing environmental concern, diminishing petroleum reserves, and agriculture-based economy of our country are the driving forces to promote biodiesel as an alternate renewable transportation fuel.

The emissions that come out by the burning of fossil diesel fuel are considered as one of the major sources of environmental pollution. Pollutant emissions from diesel engines have a serious impact on the ecological system as well as human health. Several factors such as worldwide environmental concerns, price hiking of the petroleum products as well as the expected depletion of fossil diesel fuel have promoted to look over the clean combustion of a diesel engine using alternative fuel sources. Since the last decades, research around the world have been trying to find new alternative fuels that are available, technically feasible, economically viable, and environmentally acceptable.

Biodiesel as an alternative fuel is one of the best choices among other sources due to having immense potential to reduce pollutant emissions and to be used in compression ignition engines [10]. It has similar properties to diesel fuel. The major advantages of biodiesel are (i) it can be blended with diesel fuel at any proportions, (ii) can be used in a diesel engine without any modification, (iii) does not contain any harmful substances, and (iv) it produces less harmful emissions to the environment [11]–[15]. As a summary, the advantages of biodiesel are:

a. Produced from sustainable/renewable biological sources.
b. Eco-friendly and oxygenated fuel.
c. Sulphur free, less CO, HC, particulate matter, and aromatic compounds emissions.

d. Income to the rural community.
e. Fuel properties similar to conventional fuel.
f. Used in existing unmodified diesel engines.
g. Reduce expenditure on oil imports.
h. Non-toxic, biodegradable, and safe to handle.

Searching for sustainable feedstock is crucial for the biodiesel industry as the success of biodiesel production depends on cultivation practices, processing methods and economic viability. Hence, non-edible oil derived from Jatropha curcas is suitable for biodiesel production. As a bioenergy crop, jatropha curcas considered one of the potential feedstocks as it do not conflicts with food production and cultivated in marginal lands. Their oil content is relatively high which makes it a good source of biodiesel production. More information will be discussed in the following chapter and **Figure 1** shows the non-edible Jatropha curcas oil process flow chart for biodiesel production.

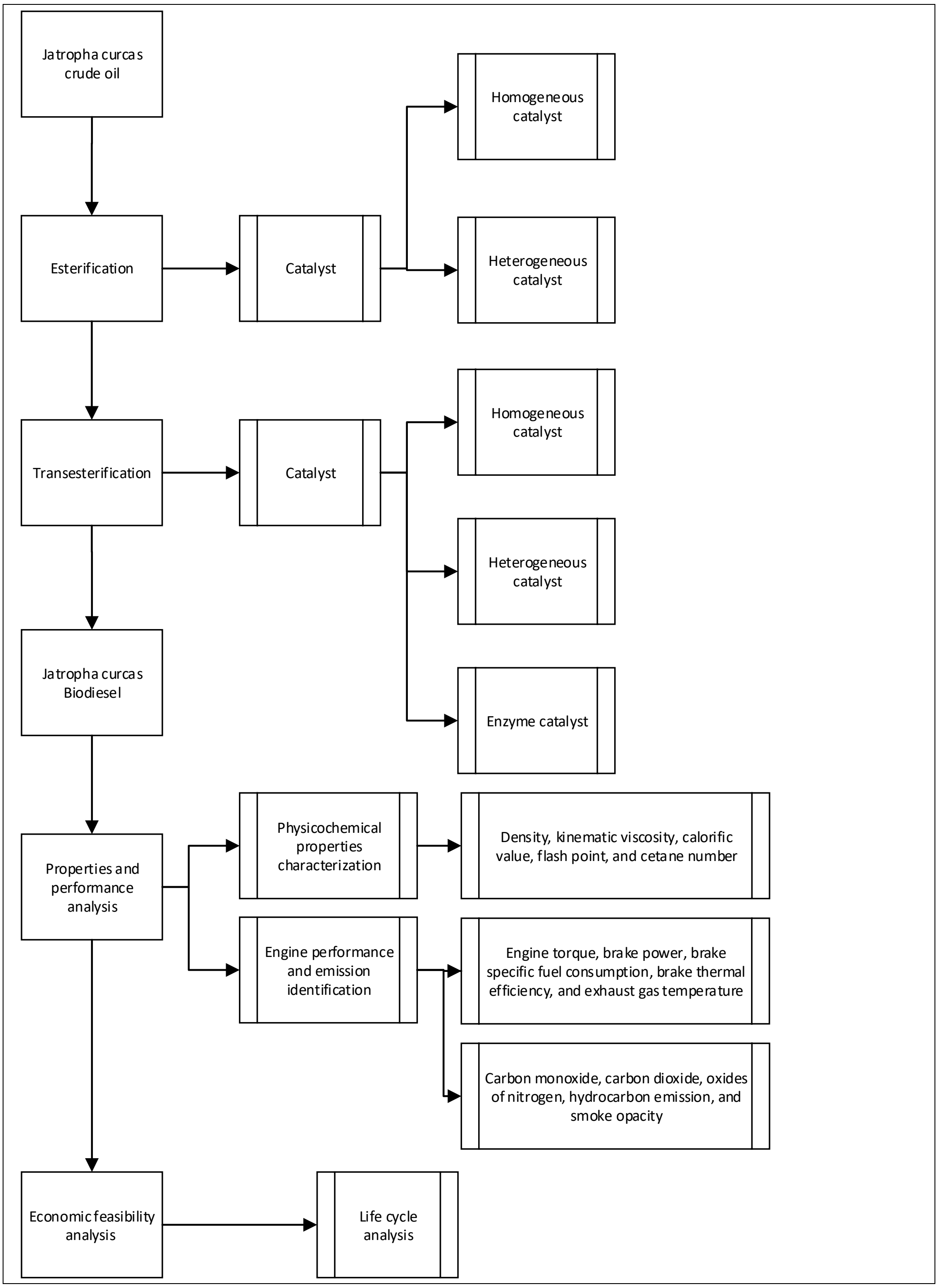

Figure 1.
The flow chart of feasibility of jatropha curcas biodiesel production as a sustainable feedstock

2. Chemistry of Biodiesel Production

Biodiesel is produced by transesterification of large, branched triglycerides into smaller, straight-chain molecules of methyl esters, using alkali or acid or enzyme as the catalyst. There are three stepwise reactions with intermediate formation of diglycerides and monoglycerides resulting in the production of three moles of methyl esters and one mole of glycerol from triglycerides. The overall reaction is as presented in **Figure 2**.

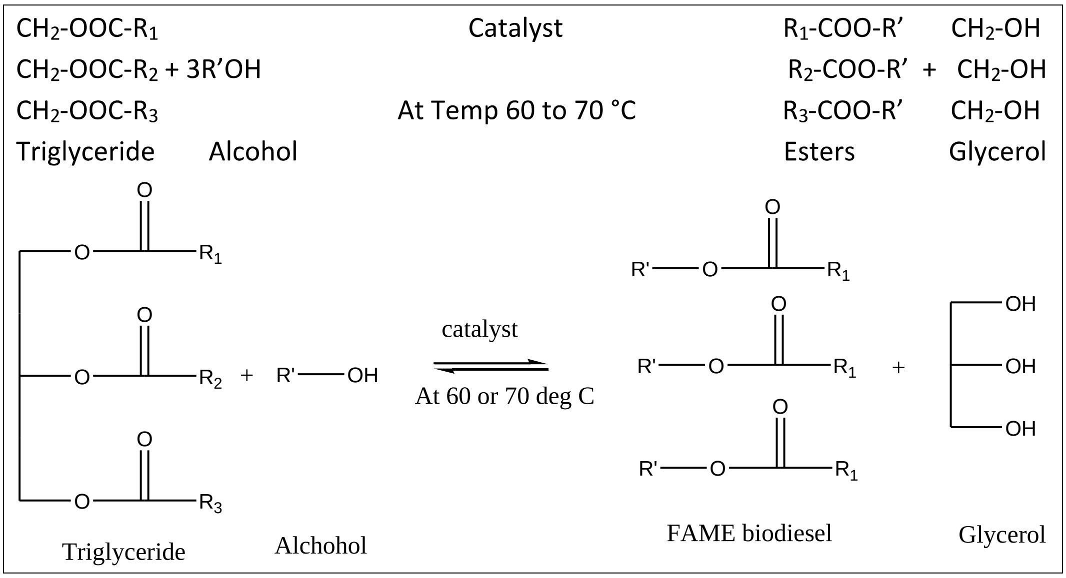

Figure 2. Transesterification process

Alcohols such as methanol, ethanol, propanol, butanol, and amyl alcohol are used in the transesterification process. Methanol and ethanol are used most frequently, especially methanol because of its low cost, and physical and chemical advantages. They can quickly react with triglycerides and sodium hydroxide is easily dissolved in these alcohols. The stoichiometric molar ratio of alcohol to triglycerides required for transesterification reaction is 3:1. In practice, the ratio needs to be higher to drive the equilibrium to a maximum ester yield [16]–[18].

Some plant-derived oil with high free-fatty acid will require a pre-treatment process such as the esterification process. Esterification is a reversible reaction in which the free fatty acid will be converted to alkyl esters using acid catalyses [19]. In this process, the acid value of the plant-derived oil will be reduced in a shorter processing time and lower operating cost. The esterification process will lower the acid value of the oil until it is suitable for the further process called the transesterification process.

Biodiesel, alternative diesel fuel, is derived from a chemical reaction called transesterification of plant-derived oil. It is the chemical conversion of oil to its corresponding fatty ester in the presence of a catalyst. The reaction converts esters from long-chain fatty acids into mono-alkyl esters. Chemically, biodiesel is a fatty acid methyl ester. The transesterification process helps reduce the viscosity of the oil. The process proceeds well in the presence of homogenous catalysts such as sodium hydroxide (NaOH), potassium hydroxide (KOH), and sulphuric acid (H_2SO_4) [20]. Forming fatty acid methyl esters (FAME) through transesterification of seed oils requires raw oil, 50% of methanol & 5% of sodium hydroxide on a mass basis. However, transesterification is an equilibrium reaction in which excess alcohol is required to drive the reaction very close to completion [21].

Biodiesel could also be produced using a solid catalyst or a heterogeneous catalyst. The advantage of using these types of catalysts is that they are easy to separate, unlike homogeneous catalysts, which is complicated and requires a long period for separation. This solid catalyst could also be used for several cycles and reduced production costs. Lastly, the amount of soap was also decreased by minimizing chemical waste. The chapter below will describe further details of the catalyst used in esterification and transesterification.

2.1. The Catalyst Used for the Esterification Process

Jatropha oil is an alternative resource for biodiesel production, and it required an esterification process as raw Jatropha oil has a very high acid value ~ 42.6 mg KOH [22]. However, a few researchers reported that the acid value of the jatropha oil is about 3.2 mg KOH [23]. The esterification process normally required mineral acid to reduce the free fatty acids. Hence, a homogeneous catalyst such as H_2SO_4 is normally used as an acid catalyst for the jatropha oil to be converted to alkyl esters [24], [25]. Some effort is being made to develop an efficient solid catalyst to convert plant-based oil. The reusable solid acid catalyst, such as Nanoporous titanosilicates [26], $SiO_2{\cdot}HF$, and ZnO/SiO_2 [27], [28], Amberlyst-15 [29], Sulphated zirconia [30] and etc [31]. Solid catalysts possessed high surface area and nano porosity with high catalytic activity. Most solid catalyst has high reusability, which is more than 5 cycles of utilization. Hydration or carbonation does not deactivate the catalyst during the esterification reaction.

2.2. The Catalyst Used for the Transesterification Process

After the esterification process, the esterified oil will be synthesised into biodiesel using base-catalysed for transesterification. The esterified oil's FFA content will be reduced to 2% for it to proceed with transesterification for high-quality biodiesel. The homogenous and heterogeneous base catalyst was adopted for this process. Homogeneous catalysts that are commonly used in transesterification process are KOH and NaOH, that has been adopted for commercial biodiesel production. Other catalysts used for the transesterification process were discussed in the following chapters.

2.2.1. Alkaline Solid Catalyst

CaO could also be produced from the eggshell [32]. Eggshells comprise a high content of 30-35% calcium carbonate and a trace amount of magnesium, carbon, and oxygen. After washing with hot water, the shell was dried and calcined at 900 °C for 2.5 h. At low content of catalyst loading (2 wt.%), the yield of biodiesel reached 90%. This catalyst showed insignificant loss activity up to six cycles [33]. Another interesting approach to fabricate solid alkaline catalysts was reported from waste animal bone. The animal bone was soaked in KOH aqueous solution before calcining in the range of 500-1100 °C. This catalyst consists of CaO, $Ca(OH)_2$, and hydroxyapatite as confirmed by XRD. They stated that the biodiesel-based *Jatropha* yield was 96% after 3 h of reaction time. This catalyst also exhibits good reusability as the biodiesel yield remained 86% after fourth-time utilization. The decreasing performance may be attributed to the hydration and leaching of catalyst active sites. They also verified the catalyst loading and temperature in the transesterification reaction [34]. Doping CaO with lanthanum oxide (La_2O_3) showed no significant improvement in esterification performance. This phenomenon occurred due to a considerable increment of catalyst surface basicity which enhances the tendency to the side reaction [35]. Recently, CaO/MgO was doped with Strontium (Sr) for biodiesel production from *Jatropha*. They revealed that adding Sr increased the catalyst activity with high stability until four cycles. At 5 wt.% of catalyst loading, 99.6% of FAME could be obtained at MeOH to oil ratio of 9:1 [36]. Lately, waste orange peel was calcinated at 600 °C for 120 minutes, and these were used as the heterogeneous catalyst for the transesterification process of waste orange peel oil [37].

2.2.2. Carbon and Porous Support

Carbon is another promising catalyst in biodiesel production. This catalyst could be produced from agricultural waste such as reported by Mardhiah et al. [38]. They used de-oiled *Jatropha* seed cake waste as a carbon precursor. The precursor was carbonized at 350 °C with surface modification using sulfuric acid. The synthesized catalyst produced 99.13% of FAME in its optimum condition and could be reused until the 4th cycle. The solid catalyst modification could also be conducted by impregnation. Impregnation is a process of mixing solid support in a homogenous solution. Murteja et al. [39] used impregnated SiO_2 with KOH in various ratios. From their study, the increasing ratio of potassium increased per-particle surface area of the silica matrix which affected the biodiesel yield. Additionally, the high ratio of K increased water tolerance even at 1 wt.% moisture. Porous materials such as clay could become potential catalysts resources. This material was reported by Negm et al. [40] where montmorillonite was functionalized with silica before modifying with sulfonated phenyl. This catalyst exhibited excellent stability during transesterification with 98% of biodiesel yield at 1:6 oil to methanol ratio using 5% of catalyst weight. Hydrotalcite is a naturally anionic clay that consists of di- and three valent cations in each layer. This clay could be produced in the laboratory by mixing some of the ionic compounds using saccharose as fuel. The hydrotalcite-like clay became more crystallized after contacting carbonate and reach optimum biodiesel conversion at 20 wt.% of saccharose. However, this study only yielded low FAME conversion at 75% using 4 wt.% of the catalyst with methanol to oil ratio of 12:1

and 6 h of reaction time [41]. Rodriguez et al [42] utilized an extraordinary catalyst in *Jatropha* oil transesterification. The catalyst was sodium zirconate (Na_2ZrO_3) and impregnated with Cesium (Cs). After modification, this catalyst exhibited more active basic sites with higher efficiency. The existence of Cs was four times faster than Na_2ZrO_3. This catalyst also demonstrates high durability with decreasing yield from 98.8% to 95% after nine cycles attributing to more water resistance.

2.3. Magnetic Catalyst

A simple catalyst separation could be obtained by using a magnetic based catalyst. A mix of Ca-Fe composites showed promising activity in biodiesel production. This catalyst exhibits an 86% yield of biodiesel with instant catalyst recovery [43]. A core-shell magnetic structure of $CaSO_4/Fe_2O_3\text{-}SiO_2$ exhibited excellent performance even after the ninth cycles. One pot transesterification displayed 94% FAME yield and became 80% at cycles nine, but with convenient catalyst separation. The high activity of this catalyst due to a combination of small sizes, high surface area, and high order of porous structure [44]. Zhang et al. [45] demonstrated the *Jatropha* deoiled seed as carbon support of which the catalyst surface was modified with magnetic properties. Additionally, they also transformed the magnetic catalyst with either acidic ($-SO_3H$) and base catalyst ($-Na_2SiO_3$). The acidic catalyst successfully reduced the FFA from 17.2 to 1.3 mg KOH/g, while the base catalyst yielded 97% of biodiesel in the subsequent reaction. *Jatropha* shows high free fatty acid (FFA) and requires pre-treatment before biodiesel production in the conventional route. Recently, Wang et al reported one step production without pre-treatment using a magnetic amphoteric catalyst. The catalysts are ferrite doped with metal and chelated with a cellulose-based compound. This catalyst could be recovered with a permanent magnet with 90% efficiency and stable performance until 10 cycles with a biodiesel yield of 95% [46].

2.4. Enzyme Catalyst

Some drawbacks of chemical-based catalysts in biodiesel from *Jatropha* were reported in some literature. The drawbacks consisted of necessity to pre-treatment, glycerol recovery, catalyst removal, and extensive energy for wastewater treatment. Enzymes could become an alternative catalyst for biodiesel production which is more convenient for separation, selective to the desired product, and also lower temperature. Two lipases such as *Rhizopus oryzae* and *Carica papaya* were studied to produce *Jatropha* based biodiesel. They revealed that these biocatalysts suppressed the glycerol formation. However, the biodiesel yield only in the range 51-65% which was obtained at 4 h of reaction period [47]. The utilization of enzymes in the industry was hindered by its high cost. Basir et al. [48] had simulated a mathematical modeling approach to reduce the amount of enzyme which could be achieved by immobilizing to biomass support. Thus, the enzyme could be reused. Meanwhile, the enzyme inactivation after contacting alcohol could be minimized by controlling its stirring speed. The enzyme immobilization approach was evaluated by Abdulla et al. [49]. They used Burkholderia cepacia lipase which is a cross-link to glutaraldehyde in a hybrid polymer of alginate and carrageenan. This technique yielded almost 100% of FAME with good stability at 73% after six successive cycles at the optimized condition. This study verified that the hybrid polymer could become a potential candidate as enzyme support.

3. Botanical Description of Jatropha Curcas L.

The genus Jatropha belongs to the tribe Jatropheae in the Euphorbiaceae family and contains approximately 170 known species [51]–[53]. The botanical name of the genus Jatropha was derived from the Greek word “Jatros” meaning a doctor and “trophe” meaning food which incorporates the historical medicinal uses of this plant [54]. Jatropha Curcas L. is a dense shrub or small tree 3 - 5 m in height (**Figure 3**). It can reach up to 10 m under favourable conditions. It is a diploid species with 2n = 22 chromosomes [51].

Figure 3.
Jatropha plants [50]

The plant has its native distributional range in Mexico, Central America, Africa, Brazil, Indian subcontinent, Peru, Argentina, and Paraguay, although nowadays it has a pantropical distribution with distinct *Jatropha Curcas* L. seed provenances. In Indonesia, it can be produced in most parts especially in the dry southeastern part of the Nusa Tenggara Islands [50], [55]–[59]. *Jatropha Curcas* L. can grow under a wide range of rainfall regimes from 250 to over 1200 mm per annum [60]. The temperature for the growth is 20 – 26 °C, this plant also can adapt to fertile soil, good drainage, not stagnant, and pH from 5.0 to 6.5 [61]. This plant grows on well-drained soils with good aeration and is a well-adapted to marginal soil with low nutrient content shedding the leaves in the dry season [60], [62]. Heller reported that plantation spaces of 2 m x 2 m, 2.5 m x 2.5 m, and 3 m x 3 m are satisfactory and give larger yields of fruit [58]. It bears fruit from the second year of its establishment, and the economic yield stabilizes from the fourth or fifth year onwards.

There are two genotypes found in Mexico classified as toxic and non-toxic [66]. The life span of the plant is up to 50 years [67] and the ability for production after 5 years [62]. It is a deciduous plant with an articulated growth habit with morphological discontinuity. The root system constitutes the main taproot and four shallow lateral roots [51], [58], [68]. The branches are glabrous with smooth greenish-bronze-coloured bark and translucent latex. The leaves are smooth simple, 5-lobed and heart-shaped, 10 - 15 cm long, dark green, cordate or round, acute at the apex, cordate at the base, alternate and may fall once a year [69], [70]. The flowers are in axillary clusters with a stalk of 3 - 5 cm long, bracts entire, lanceolate or linear, densely pubescent, yellowish-green, with prominent glandular discs in the flowers (**Figure 4**) [63]. Male flowers with 5 ovate-elliptic sepals, less than 4 mm long and 5-oblong-obovate petals united in the lower half, densely hairy inside, 6 - 7 mm long, 8 stamens. Female flowers with free oblong petals and larger sepals, 4 mm long [71], [72].


Figure 4. Jatropha flowers [63]


Figure 5. Jatropha plant with fruit [64]


Figure 6. Jatropha seeds with shells [65]

The fruit (**Figure 6**) is a kernel that contains three seeds each. It gives about 2 - 4 kg/seed/tree/year. In poor soils, the yields have been reported to be about 1 kg/seed/tree/year [64]. The oil yields of Jatropha Curcas L. is reported to be 1590 kg/ha [73]–[75]. Fruits are ovoid capsules 23 to 30 mm long by 28 mm wide, slightly trilobite, splitting into three cells. Jatropha seeds are thin-shelled ones with back color oblong shape [76]. The matured *Jatropha* seeds are 2½ cm long and they can be easily crushed to extract the oil from them. The blackish seeds (**Figure 6** and **Figure 7**) of most provenances contain toxins, such as phorbol esters, curcin, trypsin inhibitors, lectins, and phytates, to such levels that the seeds, oil, and seed cake are not edible without detoxification [59], [72].

Within this family, the plants of major economic significance include:

a. Roots: Manihot esculenta (cassava)
b. Rubber: Hevea brasiliensis

Figure 7.
Jatropha seeds [65]

c. Nuts: caryodendron orinocense (tacay nut)

d. Vegetables: sauropus androgynous (katuk)
e. Oils: Ricinus communis linn (castor bean); Aleurites spp. (tung trees)
f. Sapium sebiferum (Chinese tallow tree); J. Curcas L.
g. Physic nut. Hydrocarbon: Euphorbia spp.
h. Medical: Croton spp.; Jatropha spp.

4. Characteristics of Raw Jatropha Oil and Jatropha Based Biodiesel

Jatropha oil has similar characteristics to fossil diesel fuel, and it can directly be used in the diesel engines of buses, trucks, and other diesel engines. The high stability in low temperatures makes it very attractive for use in jet fuels, and this has been tested successfully.

4.1. Characteristics of Raw Jatropha Oil

Herrera et al. carried out an experimental study to evaluate the chemical composition, toxic/anti-metabolic constituents, and effects of different treatments on their levels in four provenances of Jatropha from Mexico [77]. The authors reported the proximate composition, total soluble sugars, and starch content of defatted and processed seed kernel meal of Jatropha seeds from different agro-climatic regions in Mexico. There were some variations in the contents of crude protein, CP (31 - 35%) and lipid (55 - 58%). The CP contents of defatted kernels varied from 62.0% in Coatzacoalcos to 65.0% in Castillo de Teayo. In some treatments, the CP content in the samples was higher. The fibre content of Jatropha meals in their study was lower than that in soybean meal but similar to those of other different seed provenances collected from Cape Verde (4.7%), Senegal (5.6%), Burkina Faso (5.3%), India (4.5%) and Nicaragua (3.8%), described in a previous publication [78]. The gross energy of whole kernels was relatively similar (31.1 - 31.6 MJ/kg). The contents of starch and total soluble sugars were below 6%. Fuel properties of the Jatropha oil from various sources were tabulated and summarised in **Table 1**. The difference in kinematic viscosity of the Jatropha oil produced from different countries varies by almost 15 cSt. The differences may relate to the purity of the crude Jatropha oil and possibly due to the soil and climatic conditions of the plantation of the Jatropha oil. The difference in the acid value is also quite large, where the maximum acid value found is 42.6 mg KOH/g while the lowest is 3.2 mgKOH/g. The high acid value of the crude oil may be due to storage conditions [22]. Besides, the flash point of the crude Jatropha oil is above 210 °C, which is considered an important factor in relation to storage safety and spill-ignite prevention. The calorific value of the jatropha oils is similar and below 40 MJ/Kg, indicating that the calorific for this oil is rather stable and

The authors also compared the fatty acid composition of the oils in the different Jatropha seeds with the other reported values. The fatty acids found common in all the oil samples were oleic, linoleic, palmitic, and stearic. The major fatty acid in the Veracruz samples was oleic acid, whereas in the Morelos sample it was linoleic acid. This variation is possibly due to soil and climatic conditions. The results showed that the oil is composed mainly of unsaturated fatty acids (oleic and linoleic acid). The results obtained are very similar to those reported for Jatropha seed provenances from different countries [58], [79]–[82].

4.2. Characteristics of Raw Jatropha Biodiesel

Characteristics of Jatropha biodiesel is extremely important since they determine the final properties of the fuel. The physicochemical and thermal properties of Jatropha biodiesel and mineral oil were characterized and presented in **Table 2**. Properties such as density, kinematic viscosity, calorific value, flash point and cetane number of various Jatropha biodiesel and the standard required by ASTM D6751 standard were also presented. The density of Jatropha biodiesel was 872–891 kg/m3, and the standard required by the ASTM D6751 is 880 kg/m^3. Diesel's density is slightly lower than biodiesel. Viscosity is one of the important properties determining biodiesel's usability in compression engines. Hence, the transesterification process reduces the viscosity of the crude Jatropha oil in the range of 34–50 cst to biodiesel with viscosity in the range of 4.3–5.7 cst. The viscosity of diesel is approximately 2.9–3.5 cst, corresponding to different countries. Calorific value Jatropha biodiesel is between 37 – 40 MJ/kg, higher calorific value indicating the high quality in biodiesel. The calorific value of biodiesel is lower than diesel fuel (42–45 MJ/kg), indicating biodiesel is 11.5% lower in calorific value than diesel fuel. The flash point of Jatropha oil is very high which above 200 °C, then by converting the Jatropha oil to biodiesel, the flash point has reduce approximately 26% (219 °C to 163 °C) [83]. The flash point of diesel is much lower than biodiesel, which makes biodiesel safer to handle, store and transport. Jatropha biodiesel was recorded to have a cetane number in the range of 48 to 59, whereas else the diesel has a cetane number between 47 to 50, which is slightly lower than biodiesel's cetane number.

The main fatty acid contains in crude *Jatropha* curcas oil (CJCO) is oleic (44.5%) followed by linoleic (35.4%), palmitic (13.0%), and stearic (5.8%). CJCO consists of 80.9% of unsaturated fatty acids (oleic and linoleic acids), indicating low-temperature properties [50]. The fatty acid composition structure has a direct correlation to biodiesel properties. Generally, nonedible oil is composed of a high number of the double carbon chain, and this structural fatty acid composition influences the physicochemical properties of biodiesel such as cetane number, oxidation stability heat of combustion, and viscosity [84]. Pinzi et al. [85] reported that high carbon chain length leads to a higher heating value which greatly influences the cold properties of biodiesel. The high number of saturation chain level reduces the cloud point of biodiesel. In other words, higher concentrations of unsaturated fatty acids can improve the cloud point and cold filter plugging points of biodiesel [86]. The comparison of biodiesel derived from Mahua and *Jatropha* was reported recently. *Jatropha* is more prone to oxidation compared to Mahua due to its higher unsaturated fatty acids content. *Jatropha* was blended with petroleum diesel (B20) and blended with Mahua oil (M50:J50) which improved 85% and 37% of its oxidation stability, respectively. It can be seen that Jatropha biodiesel has potential to be utilize as an additive to diesel fuel.

Table 1. Fuel properties of jatropha oil

Properties	Jatropha Oil					Calophyllum oil
Density @ 15 °C, g/ml	918	0.913^a	917	918.35	915.1	60.73
Kinematic viscosity @ 40 °C, Cst	49.93	35.8	36.43	–	34.7	65.48
Acidity, mg. KOH/g	–	3.2	–	1.16	42.6	63.05
Calorific value, MJ/kg	39.77	37.8	38.79	39.22	38.7	37.16
Flash point, °C	240	330	219	326.5	210-240	-
Cetane number	40-45	–	44			-
References	[87]	[88]	[83]	[89]	[22]	[90]

Table 2. Fuel properties of jatropha biodiesel and diesel

Properties	***ASTM D6751***	Jatropha Biodiesel						Diesel		
Density, g/ml	880	880	876.2	881.1	891	883.3	872	846.1	833.1	870
Kinematic viscosity @ 40 °C, Cst	1.9–6.0	5.65	4.57	4.71	4.452	4.805	4.34	2.96	3.556	3.21
Calorific value, MJ/kg	–	38.45	39.46	39.07	37.74	39.84	39.61	45.36	44.66	42.23
Flash point, °C	100–170	170	125.5	161.5	–	202.5	163	75.5	77.5	65
Cetane number	47	50-55	59	–	–	51	48.21	49.6	47	47.2
References	[19]	[87]	[88]	[91]	[92]	[93]	[83]	[87]	[93]	[83]

5. Technology Insentification for Jatropha Based Biodiesel

The biodiesel price shows decreasing trends in this decade with increasing concern to environmental sustainability. The recent prices of Biodiesel in US for B20 and B99-B100 is $2.35/gallon and $ 3.15/gallon, respectively. Meanwhile, the diesel prices is at $2.48/gallon. In Malaysia, the price of biodiesel from Jatropha is $0.68/L and $ 0.41/L for diesel [94]. Conventional biodiesel production consists of several steps such as oil extraction, oil refining, and transesterification. Kartika et al. [95] introduced simultaneous solvent extraction and transesterification. From their study, there are two main parameters to obtain high biodiesel yield namely ratio of n-hexane to seed and methanol to oil ratio. The highest biodiesel yield (92%) was achieved at 2:1 n-hexane to seed and 10.6:1 methanol to oil ratio. The presence of n-hexane was crucial in this study to improve the mass transfer of oil to methanol, thus faster the reaction. Non-catalytic biodiesel production attracted some researchers recently. The approach includes supercritical methanol transesterification which requires high temperature and pressure. Samniang et al. [96] compared two non-edible oil consist of Krating and Jatropha. They observed that FAME yield depends on FFA and unsaturated fatty acid contents. The most influential parameter in Jatropha was the temperature, while Krating oil depends to pressure. At almost similar pressure (15 MPa), the biodiesel yield for Jatropha (320 °C) and Krating (260 °C) were 85% and 91%, respectively. Additionally, the Jatropha's FAME quality still did not meet the biodiesel standard which requires degumming as pre-treatment. From an economic perspective, the supercritical methanol process seems feasible for Jatropha. This process yielded a high purity of FAME (99.96%) and glycerol (96.49%) with an estimated cost of USD 0.78/kg [94]. A study by Araujo et al. [97] developed two methods for the degumming process which comprises water and phosphoric acid (H_3PO_4). Degumming was conducted by adding little hot water (60 °C) to oil, while the alternating process utilized a low ratio of H_3PO_4 (0.1% of oil) to preheated water. They proved that degumming with H_3PO_4 exhibited higher oil conversion. This may be ascribed to more phospholipid transformation in *Jatropha* oil to insoluble lipids which ease separation, thus enhanced the biodiesel yield. Kamel et al. [98] initiated a smart method to use *Jatropha* seeds as a heterogeneous catalyst. The remaining dregs after oil extraction could not be used as animal feed due to the existence of hazardous components. Thus, the utilization of this agricultural waste was beneficial to both the economy and ecology. The dregs proceeded to two different routes namely calcination and activation with KOH catalyst. From their study, they concluded that calcination is better than activation with higher biodiesel yield and also lower production cost. This may be assigned to excessive surface basicity of the catalyst after soaking with KOH. Microwave heating is one popular method to accelerate the reagents' movement at the atomic level. Sodium amide ($NaNH_2$) with microwave irradiation yielded 96% of FAME within 7 min. The total amount of energy was less than 10 times of the conventional heating process [99]. Then, Lin et al. [100] have successfully produced biodiesel from Jatropha oil within 10 s with a conversion of 90% in its optimum condition. Additionally, they also developed a CSTR-like continuous reactor which able to produce 17 tons/day of biodiesel with energy consumption of 9.5 kJ. A comparison between ultrasonic irradiation with conventional stirring was reported recently by Tan et al. [101]. The ultrasonic irradiation produced higher biodiesel yield (85% vs 76%) and higher FAME purity (99% vs 92%) compared magnetic stirring. Kumar [99] reported a detailed parameter in ultrasonic irradiation. The optimum conversion was achieved at amplitude 50% with 0.3 s cycle and seed size of 1-2 mm. Then, the continuous production of Jatropha biodiesel was reported using three tank reactors assisted with ultrasonic. This reactor used FAME as a solvent for methanol and Jatropha oil. This FAME displays intermediate polarity to methanol and oil which eases miscibility between these two phases. Meanwhile, ultrasonication was beneficial to generate small bubbles in concentrated places with high temperature and pressure. Additionally, ultrasonic also assists in decreasing the catalyst consumption. The optimum biodiesel yield was achieved at amplitude 60% and cycles of 0.7 s with a biodiesel conversion of 98.75% [102]. Poor oxidation stability is one hindrance in biodiesel commercialization, especially for non-edible oil which contains many polyunsaturated fatty acids. Thus, some antioxidants may be added to FAME to enhance their stability. Agarwal et al [103] investigated five low-cost and commercially available antioxidants to some non-edible oil such as Karanja, Neem, and *Jatropha*. The antioxidants were 2,6-di-tert butyl-4-methyl phenol (BHT), 2-tert butyl-4-methoxy phenol (BHA), 2-tert butyl hydroquinone (TBHQ), 1,2,3 tri-hydroxy benzene (PY) and 3,4,5-tri hydroxy benzoic acid (PG). They confirmed that PY and PG were the most efficient at low concentrations, namely in the range of 100-1000 ppm. Meanwhile, other antioxidants required high concentration to work effectively such as TBHQ.

6. Engine Performance and Emission of Using Jatropha Based Biodiesel

Non-edible (*Jatropha curcas*), Karanja (*Pongamia pinnata*) and Polanga (*Calophyllum inophyllum*) based methyl esters were produced and blended with conventional diesel having sulphur content less than 10 mg/kg [104]. Ten fuel blends (Diesel, B20, B50, and B100) were tested for their use as a substitute fuel for a water-cooled three-cylinder tractor engine. Test data were generated under full/part throttle position for different engine speeds (1200, 1800, and 2200 rev/min). Changes in exhaust emissions (Smoke, CO, HC, NO_x, and PM) were also analysed to determine the optimum test fuel at various operating conditions. The maximum increase in power is observed for 50% *Jatropha* based biodiesel and diesel blend. Reduction in smoke was observed for all the biodiesel and their blends when compared to diesel. Smoke emission was also observed to reduce with blends and speeds during the full-throttle performance test.

Ong et al. [5] conducted an experimental study to investigate the engine performance and emissions using Jatropha curcas, Ceiba pentandra, and Calophyllum inophyllum biodiesel in a CI diesel engine. In order to analyze the engine performance, the authors measured the (i) engine torque, (ii) brake power, (iii) brake specific fuel consumption, (iv) brake thermal efficiency, and (v) exhaust gas temperature. The authors also analyzed the emissions by measuring the (i) oxides of nitrogen (NOx), (ii) hydrocarbon emission (HC), (iii) carbon dioxides (CO_2), (iv) carbon monoxide (CO), and smoke opacity. The authors found that 10% blends produce the best engine performance and can reduce exhaust emissions, except NOx, compared to diesel fuel. The lower concentration of biodiesel-diesel blends indicates complete combustion and reduces brake specific fuel consumption. There was a reduction in brake specific fuel consumption for JCB10, CPB10, and CIB10 but an increase in NOx emissions for biodiesel-diesel blends. A review of the engine performance and emissions by using Jatropha based biodiesel is presented in **Table 3**.

Table 3. Summary of the review of engine performance and emissions by using Jatropha based biodiesel

Ref.	Scope of the study	Findings
[104]	Experimentally compare the performance and emission of using biodiesel (B20, B50, and B100) compared to diesel.	• 50% *Jatropha* based biodiesel and diesel blend produced the maximum increase in power. • A reduction in smoke was observed by using biodiesel compared to diesel. • A reduction of smoke emission was observed during full throttle performance test. • Limitation: a) Experimental design performed in a systematic way such as B20 B50 and B100; b)Need to engage mathematical model in engine performance and emission characteristic.
[50]	Experimentally investigate the engine performance, and emissions using *Jatropha curcas*, *Ceiba pentandra,* and *Calophyllum inophyllum.*	• 10% blends produced the best engine performance which could reduce exhaust emissions, except NO_x, compared to diesel fuel. • Complete combustion and brake specific fuel consumption were reduced by using a lower concentration of biodiesel-diesel blends. • A reduction of brake specific fuel consumption was observed for JCB10, CPB10, and CIB10. • An increase in NO_x emissions for biodiesel-diesel blends was observed.
[105]	Study the effects of *Jatropha* based biodiesel on the engine hardware reliability, emission, and performance.	• Abnormal viscosity decrease is observed by using both types of *Jatropha* based biodiesel, i.e., B10 and B30. • Pollutants emissions are found to be higher for B10 but lower for B30 compared to conventional diesel fuel. • Limitation: Carbon deposit was found on throttle body, EGR Ejector, piston, intake valve, and injector. • Untypical jelly built up on thrust bearing.
[106]	Study the effect of blending *Jatropha* oil with diesel to the performance, emission and combustion characteristics.	• *Jatropha* oil as a substitute for diesel for CI engine caused lower brake thermal efficiency and higher specific fuel consumption compared to diesel fuel operation. • Hydrocarbon, carbon dioxide, and NO_x emissions are found to be higher. • The smoke level is found to be lower than the dual-fuel operation with diesel.
[107]	Performance and emission of preheated *Jatropha* oil on a medium-capacity diesel engine.	• Preheated *Jatropha* oil is recommended to be a good substitute fuel for the diesel engine. • The optimal fuel inlet temperature was found to be 80^0C considering the BTE (brake thermal efficiency), BSEC (brake specific energy consumption), and gaseous emissions. • BTE of the engine was lower and BSEC was higher when the engine was fuelled with Jatropha oil as compared to diesel fuel. • Limitation: Need to engage mathematical model in engine performance and emission characteristic.

Table 4. (continued) Summary of the review of engine performance and emissions by using Jatropha based biodiesel

Ref.	Scope of the study	Findings
[108]	Performance and emission characteristics of a diesel engine fuelled with different blends of *Jatropha* oil and diesel (10-50%).	• The specific fuel consumption is found to be slightly higher than diesel for B20 but closer to diesel among all the blends. • Blends up to 20% substantially reduced CO$_2$ emissions with a marginal decrease in brake thermal efficiency. • Since the engine was air-cooled, the exhaust gas temperatures were higher, which in turn increased the NO$_x$ emissions. • The smoke opacity was found to be higher than diesel for all blends due to their higher viscosity and density which led to poor atomization during combustion. • A maximum brake thermal efficiency of 29.4% was achieved for B20 while for diesel it was 30.9% for the same power output. • Experimental investigations showed that the blending of *Jatropha* methyl esters up to 20 % with diesel for use in an unmodified diesel engine is viable.
[109]	Performance of a single-cylinder C.I. engine using blends of diesel and *Jatropha* oil.	• The specific fuel consumption and the exhaust gas temperature were reduced by using the blend of *Jatropha* oil with diesel. • Acceptable thermal efficiencies of the engine were obtained with blends containing up to 50% volume of *Jatropha* oil. • About 40 - 50% of *Jatropha* oil can be substituted for diesel without any engine modification and preheating of the blends. • Limitation: They use jatropha oil and mix with diesel to produce the jatropha-diesel and called it biodiesel. Hence there is no chemical process in conversion oil to biodiesel.
[110]	The effect of fuel inlet temperature on the performance of a diesel engine by using neat *Jatropha* oil as fuel.	• The engine performance parameters with neat *Jatropha* oil were found to be comparable to the performance obtained with mineral diesel and *Jatropha* methyl ester. • The exhaust gas temperature was observed to be lower at all fuel inlet temperature except for fuel inlet temperature of 110°C, compared to the diesel fuel operation. • The brake specific fuel consumption (BSFC) of neat *Jatropha* oil was found to vary with fuel inlet temperature. • Acceptable thermal efficiencies of the engine were obtained. • The fuel inlet temperature of 90°C was found to be an optimal preheating temperature for neat *Jatropha* oil and can be substituted for diesel without any engine modification. • For the higher value of fuel inlet temperature above 90°C, the performance was observed to be marginally inferior. • Limitation: They use jatropha oil and mix with diesel to produce the jatropha-diesel. Preheating the oil up to 90 °C was to achieve required viscosity.
[111]	*Jatropha* biodiesel, *Jatropha* oil & Diesel are used as fuels in compression ignition engine, and their performance and emission characteristics are analysed.	• Engine efficiency, BSFC, BTE & mechanical efficiency were found to increase at 80% load and nearly the same as diesel at 100 % load. • CO$_2$, HC, and smoke opacity were observed to be less when the load was increased, however, CO was found to be nearly the same and NO$_x$ was found to increase slightly.
[112]	Assessment of diesel engine performance, emissions and combustion characteristics burning biodiesel blends from jatropha seeds	• Biodiesel was blended with diesel oil in volumetric ratios of B100. • The increase of biodiesel percentage in biodiesel blends led to the mean effective pressure decrease because of the lower heating values decreases for biodiesel mixtures. The higher viscosity and density of biodiesel resulted in the fuel atomization and vaporization problems. B100 showed the maximum decreases in brake mean effective pressure of 27 %. • CO emission was increased with the increase of biodiesel percentage due to the higher carbon to hydrogen ratio compared to diesel oil. The maximum increases of CO emissions for B100 is 16 % at 75 % of engine load
[113]	Performance, energy, emission and cost analysis *Jatropha Curcas*) oil as a biofuel for compression ignition engine	• B100 have thermal efficiency of 19.2% • CO emission of B100 fuel is found to be 24.5% lesser than diesel fuel. While for HC emission B100 fuel is 27.9% lesser than diesel fuel

It can be noted that jatropha biodiesel blends can work as a substitute for diesel in compression engines. It shows good engine performance and lower emission, but slightly higher NO_x emission. A higher concentration of NOx was found in biodiesel compared to diesel due to the high exhaust gas temperature and heat release rate. Both these are responsible for the longer effective reaction between nitrogen and oxygen, causing higher concentrations of NO_X production. Blended Jatropha biodiesel will help to achieve environmental protection and improve the energy economy. Hence, jatropha biodiesel can be predicted to be a potential fuel in the near future.

7. Economic Feasibility

Jatropha is one of the potential biodiesel feedstocks in the near future. The biological life cycle of the Jatropha species and procedures for biodiesel production are shown in **Figure 8**. The economic feasibility of Jatropha depends on various factors, including the cost of cultivation, oil extraction, refining, and distribution, also depending on the market price of conventional diesel. Jatropha is introduced as a promising feedstock due to its high oil content, ability to grow in marginal lands and low competition with food crops for arable lands. Hence, the following discusses the several challenges and uncertainties that will affect the economic viability. The integration of Jatropha biodiesel fired plants seem promising to substitute natural gas in Nigeria. The electricity cost of this biodiesel is in the range of $0.203-0.252/kWh which is still cheaper than a self-electricity generation ($0.45-0.70/kWh) [114]. Cultivation of Jatropha oils on a large scale has become one of the crucial issues for the commercialization of biodiesel. The actual oil yield per hectare can vary significantly based on factors such as soil quality, climate, agricultural practices, and plant genetics. Lower than expected yields will affect the overall economics of cultivation. Recently, the systematic selection and evaluation of Jatropha germplasm worldwide have been reported by Kumar et al [115]. From this study, the oil contents are at less than 30%, 30-40%, and more than 40%. The superior genotypes are in sub-mountain with high rainfall (800-1500 mm) which is planted in sandy-lam soil. Researchers stated that the capital and the operating cost to produce every litre of biodiesel are presented in **Figure 9**. The cost of feedstock, which includes the cultivation of Jatropha, harvesting and logistics supply to the factory for further process and these costs of feedstock is compromising almost 68% of the selling price of the Jatropha oil. This cost also includes the initial investment in land preparation, planting jatropha trees, irrigation, fertilizers, and labour cost. These costs need to be balanced against potential returns from biodiesel sales. The oil extraction and processing cost of extracting the jatropha oil from the seed such as pressing and extraction. These cost compromise approximately 3% of the total cost. The processing cost for a conversion of oil to biodiesel depends on the cost of methanol, catalyst, and the efficiency of the processes and associated cost that impact the overall cost of conversion. Moreover, heating material also contributes to the high material cost of biodiesel production. There is large fixed operating cost which included the maintenance of equipment, labour cost and overheads especially for oil extraction, transesterification, biodiesel recovery and onsite energy generation part. From all the costs, they confirmed that to achieve a competitive biodiesel market, the oil yield should be 50 wt.% with a selling price of $1/L with seed yield in the average of 4.45 t/ha [116]. Meanwhile, another study in Rwanda, East Africa claimed that Jatropha cultivation could be feasible from an economic perspective with a minimum seed yield of 5400 kg/ha. They also suggest using compost manure and genetically modified species to reduce overall cost [117]. Regarding the production cost, Ntaribi et al [117] recommended that small scale farmers could plant Jatropha as fences around their farms or alongside the road. Additionally, farmers should replace labour workers with mechanics at a reasonable cost during weddings, pruning, disease control, and Jatropha harvesting to reduce the production cost. Aside from the cost of production, the market price of biodiesel is also influenced by a few factors, such as government policies, subsidies, competition from fossil fuels and consumer demand. The price fluctuations in biodiesel will determine the feasibility and profitability of the Jatropha biodiesel production. Besides producing demanded biodiesel, their cultivation produces by-products such as seed cakes, which can be used as animal feed or organic fertiliser. Utilizing these by-products can effectively improve the overall economic feasibility of Jatropha cultivations. Besides, government policy support, tax incentives, and mandates that promote renewable fuels will significantly impact the economic feasibility of Jatropha biodiesel production. Supportive renewable energy policies will attract more investors to develop renewable energy in particular countries. Hence, ongoing research and technological advancements may improve the economic viability of Jatropha biodiesel in the future.

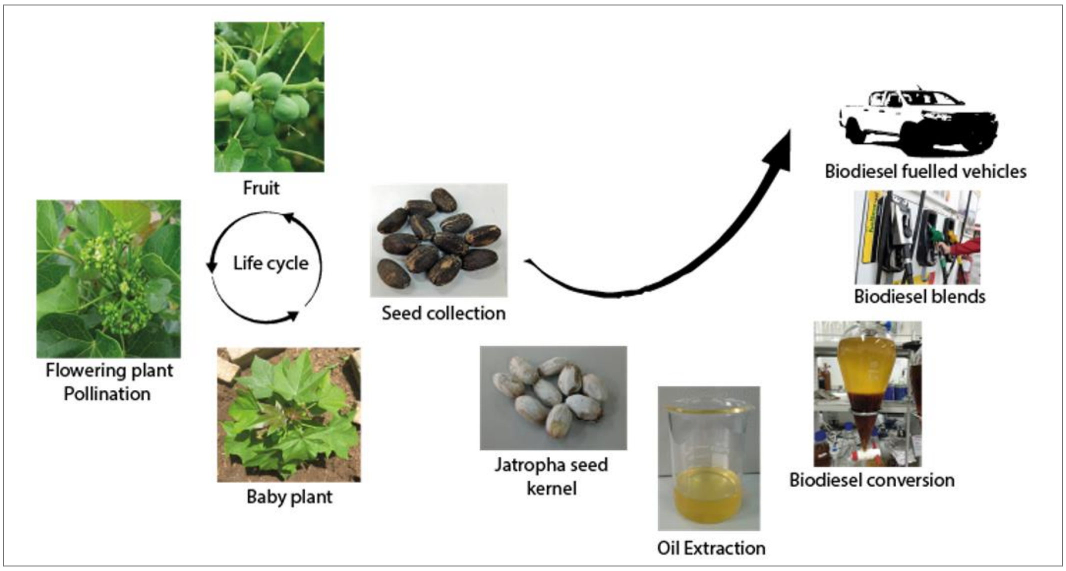

Figure 8. The life cycle of the Jatropha and biodiesel production cycle

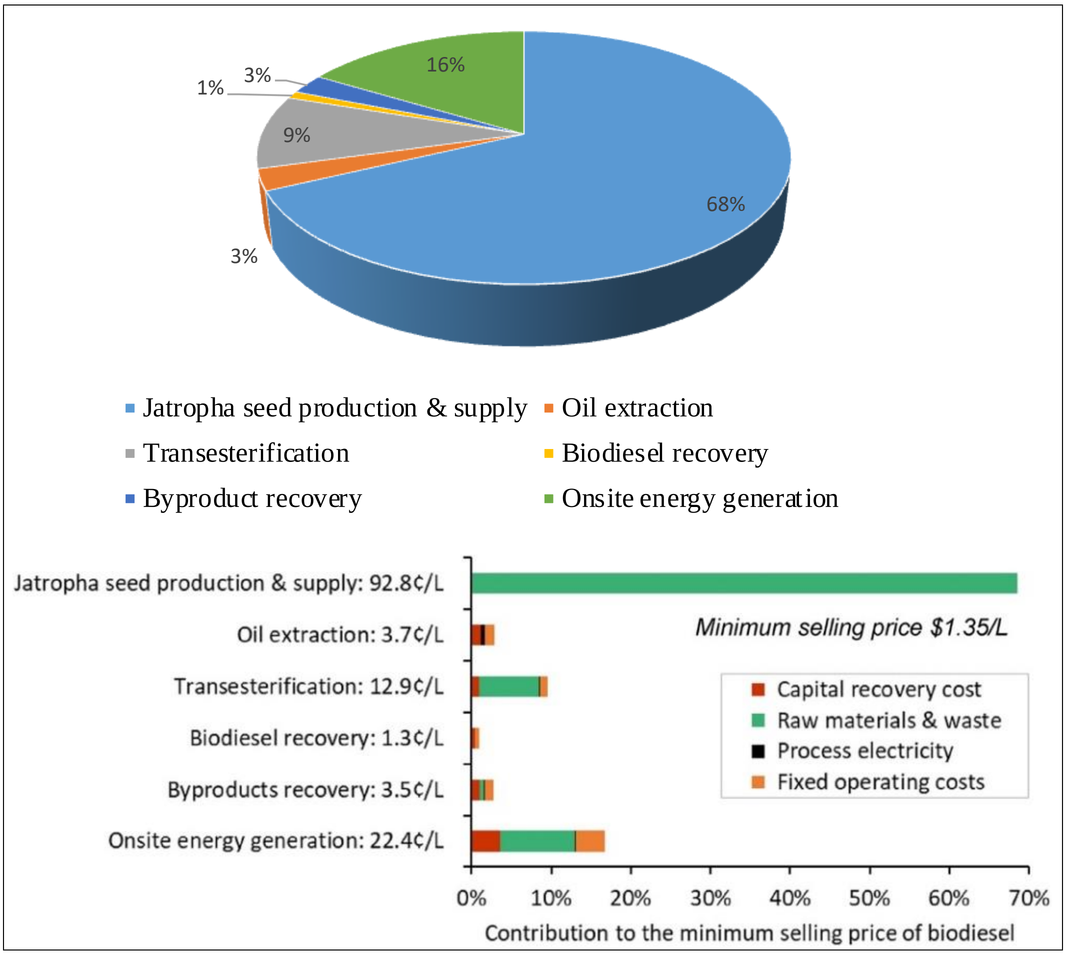

Figure 9. Capital and operating cost of Jatropha biodiesel production [98]

8. Conclusion

After reviewing the characteristics and performance of jatropha-based biodiesel based on global studies and literature, it is evident that this renewable fuel source offers distinct advantages. Unlike biodiesel derived from crops intended for human consumption, Jatropha-based biodiesel utilizes raw materials that do not compete with food production. Additionally, Jatropha plants thrive in marginal lands and do not require fertile soils, distinguishing them from traditional edible crops or through agroforestry approaches that promote biodiversity and carbon sequestration. Continued research and development efforts aimed at improving Jatropha cultivation practices, increasing oil extraction efficiency, and optimizing biodiesel production processes could enhance the economic viability of Jatropha biodiesel. Moreover, the use of Jatropha-based biodiesel demonstrates environmental benefits, as it generates fewer pollutants when utilized in internal combustion engines compared to conventional diesel. Importantly, engine performance remains comparable between Jatropha-based biodiesel and petroleum-based diesel, ensuring reliable operation. Shifts in global energy markets, geopolitical factors, and changes in consumer preferences towards cleaner and renewable energy sources could influence the demand for biodiesel. Considering the long-term sustainability and environmental concerns associated with fossil fuels, including their depletion and price volatility, Jatropha-based biodiesel emerges as a viable alternative. Its renewable nature and stable performance underscore its potential to mitigate dependence on finite fossil fuel resources and provide a reliable solution amidst fluctuating petroleum-based diesel prices. Collaboration between governments, industry stakeholders, research institutions, and non-governmental organizations (NGOs) can foster knowledge sharing, technology transfer, capacity building, and investment mobilization to drive sustainable development of the Jatropha biodiesel industry.

Acknowledgments

The authors would like to acknowledge the researchers supporting to the Universiti Tenaga Nasional, Malaysia (J510050002-IC-6 BOLDREFRESH2025 - CENTRE OF EXCELLENCE) and the AAIBE Chair of Renewable grant no: 201801 KETTHA. The authors wish to thank University of Technology Sydney, Sydney, Australia (Strategy Research Support Funding 2023; 324100.2200035) and Politeknik Negeri Medan, Medan Indonesia (DIPA POLMED 2023).

Authors’ Declaration

Authors’ contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Funding – has been explained in the Acknowledgments.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

References

[1] M. A. Abdullah, A. U. Rahmah, and Z. Man, “Physicochemical and sorption characteristics of Malaysian Ceiba pentandra (L.) Gaertn. as a natural oil sorbent,” *Journal of hazardous materials*, vol. 177, no. 1–3, pp. 683–691, 2010, doi: 10.1016/j.jhazmat.2009.12.085.

[2] A. K. Agarwal, “Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines,” *Progress in energy and combustion science*, vol. 33, no. 3, pp. 233–271, 2007, doi: 10.1016/j.pecs.2006.08.003.

[3] T. M. I. Mahlia *et al.*, “Patent landscape review on biodiesel production: Technology updates,” *Renewable and Sustainable Energy Reviews*, vol. 118, p. 109526, 2020, doi: 10.1016/j.rser.2019.109526.

[4] X. J. Lee, H. C. Ong, Y. Y. Gan, W.-H. Chen, and T. M. I. Mahlia, “State of art review on conventional and advanced pyrolysis of macroalgae and microalgae for biochar, bio-oil and bio-syngas production,” *Energy Conversion and Management*, vol. 210, p. 112707, 2020, doi: 10.1016/j.enconman.2020.112707.

[5] H. C. Ong, H. H. Masjuki, T. M. I. Mahlia, A. S. Silitonga, W. T. Chong, and T. Yusaf, “Engine performance and emissions using Jatropha curcas, Ceiba pentandra and Calophyllum inophyllum biodiesel in a CI diesel engine,” *Energy*, vol. 69, pp. 427–445, May 2014, doi: 10.1016/j.energy.2014.03.035.

[6] A. S. Silitonga *et al.*, “Intensification of Reutealis trisperma biodiesel production using infrared radiation: Simulation, optimisation and validation,” *Renewable Energy*, vol. 133, pp. 520–527, 2019, doi: 10.1016/j.renene.2018.10.023.

[7] N. Hossain, J. Zaini, T. M. I. Mahlia, and A. K. Azad, “Elemental, morphological and thermal analysis of mixed microalgae species from drain water,” *Renewable Energy*, vol. 131, pp. 617–624, 2019, doi: 10.1016/j.renene.2018.07.082.

[8] A. S. Silitonga *et al.*, “Evaluation of the engine performance and exhaust emissions of biodiesel-bioethanol-diesel blends using kernel-based extreme learning machine,” *Energy*, vol. 159, pp. 1075–1087, 2018, doi: 10.1016/j.energy.2018.06.202.

[9] R. Sarin, M. Sharma, S. Sinharay, and R. K. Malhotra, “Jatropha–palm biodiesel blends: an optimum mix for Asia,” *Fuel*, vol. 86, no. 10–11, pp. 1365–1371, 2007, doi: 10.1016/j.fuel.2006.11.040.

[10] M. Mofijur, H. H. Masjuki, M. A. Kalam, and M. Shahabuddin, “Experimental study of additive added palm biodiesel in a compression ignition engine,” *Energy Educ Sci Technol Part A: Energy Sci Res*, vol. 30, p. 737e48, 2012.

[11] J.-H. Ng, H. K. Ng, and S. Gan, “Characterisation of engine-out responses from a light-duty diesel engine fuelled with palm methyl ester (PME),” *Applied Energy*, vol. 90, no. 1, pp. 58–67, 2012, doi: 10.1016/j.apenergy.2011.01.028.

[12] H. G. How, Y. H. Teoh, H. H. Masjuki, and M. A. Kalam, “Impact of coconut oil blends on particulate-phase PAHs and regulated emissions from a light duty diesel engine,” *Energy*, vol. 48, no. 1, pp. 500–509, 2012, doi: 10.1016/j.energy.2012.10.009.

[13] H. C. Ong *et al.*, “Biodiesel production from Calophyllum inophyllum-Ceiba pentandra oil mixture: Optimization and characterization,” *Journal of Cleaner Production*, vol. 219, pp. 183–198, May 2019, doi: 10.1016/j.jclepro.2019.02.048.

[14] A. S. Silitonga *et al.*, “Biodiesel synthesis from Ceiba pentandra oil by microwave irradiation-assisted transesterification: ELM modeling and optimization,” *Renewable Energy*, vol. 146, pp. 1278–1291, 2020, doi: 10.1016/j.renene.2019.07.065.

[15] A. S. Silitonga, H. H. Masjuki, T. M. I. Mahlia, H. C. Ong, W. T. Chong, and M. H. Boosroh, “Overview properties of biodiesel diesel blends from edible and non-edible feedstock,” *Renewable and Sustainable Energy Reviews*, vol. 22, pp. 346–360, 2013, doi: 10.1016/j.rser.2013.01.055.

[16] D. Ramesh, A. Samapathrajan, and P. Venkatachalam, “Production of biodiesel from Jatropha curcas oil by using pilot biodiesel plant,” *The Jatropha Journal*, vol. 18, no. 9, pp. 1–6, 2006.

[17] N. M. Prabu, S. Nallusamy, and K. T. Rasu, “Experimental Analysis of Jatropha Curcas Bio-Diesel for Optimum Blend Characteristics,” *Bonfring International Journal of Industrial Engineering and Management Science*, vol. 3, no. 2, p. 63, 2013, doi: 10.9756/BIJIEMS.4667.

[18] R. K. Singh and S. K. Padhi, “Characterization of jatropha oil for the preparation of biodiesel,” *Natural Product Radiance*, vol. 3, no. 2, pp. 63–69, 2009.

[19] J. Milano *et al.*, “Physicochemical property enhancement of biodiesel synthesis from hybrid feedstocks of waste cooking vegetable oil and Beauty leaf oil through optimized alkaline-catalysed transesterification,” *Waste Management*, vol. 80, pp. 435–449, 2018, doi: 10.1016/j.wasman.2018.09.005.

[20] A. Demirbaş, “Biodiesel from vegetable oils via transesterification in supercritical methanol,” *Energy conversion and management*, vol. 43, no. 17, pp. 2349–2356, 2002, doi: 10.1016/S0196-8904(01)00170-4.

[21] M. Ahmad, M. A. Khan, M. Zafar, and S. Sultana, “Biodiesel from non edible oil seeds: a renewable source of bioenergy,” *Economic effects of biofuel production*, pp. 259–280, 2011, doi: 10.5772/24687.

[22] B. H. H. Goh, C. T. Chong, H. C. Ong, J. Milano, X. J. Lee, and J.-H. Ng, “Strategies for fuel property enhancement for second-generation multi-feedstock biodiesel,” *Fuel*, vol. 315, p. 123178, 2022, doi: 10.1016/j.fuel.2022.123178.

[23] A. K. Das, A. S. Chavan, D. C. Shill, and S. Chatterjee, “Jatropha Curcas oil for distribution transformer–A comparative review,” *Sustainable Energy Technologies and Assessments*, vol. 46, p. 101259, 2021, doi: 10.1016/j.seta.2021.101259.

[24] C. A. Andrade-Tacca, C.-C. Chang, Y.-H. Chen, D.-V. Manh, and C.-Y. Chang, “Esterification of jatropha oil by sequential ultrasonic irradiation with auto-induced temperature rise and dosing of methanol and sulfuric acid catalyst,” *Journal of the Taiwan Institute of Chemical Engineers*, vol. 45, no. 4, pp. 1523–1531, 2014, doi: 10.1016/j.jtice.2014.03.001.

[25] C. A. Andrade-Tacca *et al.*, “Esterification of jatropha oil via ultrasonic irradiation with auto-induced temperature-rise effect,” *Energy*, vol. 71, pp. 346–354, 2014, doi: 10.1016/j.energy.2014.04.066.

[26] A. Chang *et al.*, “Efficient simultaneous esterification/transesterification of non-edible Jatropha oil for biodiesel fuel production by template-free synthesized nanoporous titanosilicates,” *Catalysis Today*, vol. 356, pp. 56–63, 2020, doi:

10.1016/j.cattod.2019.10.006.

[27] G. Corro, F. Bañuelos, E. Vidal, and S. Cebada, "Measurements of surface acidity of solid catalysts for free fatty acids esterification in Jatropha curcas crude oil for biodiesel production," *Fuel*, vol. 115, pp. 625–628, 2014, doi: 10.1016/j.fuel.2013.07.060.

[28] G. Corro, U. Pal, and N. Tellez, "Biodiesel production from Jatropha curcas crude oil using ZnO/SiO2 photocatalyst for free fatty acids esterification," *Applied Catalysis B: Environmental*, vol. 129, pp. 39–47, 2013, doi: 10.1016/j.apcatb.2012.09.004.

[29] S. Ban, R. Shrestha, Y. Chaudhary, J.-K. Jeon, R. Joshi, and B. Uprety, "Process simulation and economic analysis of dolomite catalyst based biodiesel production from Nepalese Jatropha Curcas," *Cleaner Chemical Engineering*, vol. 2, p. 100029, 2022, doi: 10.1016/j.clce.2022.100029.

[30] R. Z. Raia, L. S. da Silva, S. M. P. Marcucci, and P. A. Arroyo, "Biodiesel production from Jatropha curcas L. oil by simultaneous esterification and transesterification using sulphated zirconia," *Catalysis Today*, vol. 289, pp. 105–114, 2017, doi: 10.1016/j.cattod.2016.09.013.

[31] L. Díaz, D. Escalante, K. E. Rodríguez, Y. Kuzmina, and L. A. González, "Response surface methodology for continuous biodiesel production from Jatropha curcas oil using Li/pumice as catalyst in a packed-bed reactor assisted with diethyl ether as cosolvent," *Chemical Engineering and Processing - Process Intensification*, vol. 179, no. May, 2022, doi: 10.1016/j.cep.2022.109065.

[32] A. Kolakoti and G. Satish, "Biodiesel production from low-grade oil using heterogeneous catalyst: an optimisation and ANN modelling," *Australian Journal of Mechanical Engineering*, vol. 21, no. 1, pp. 316–328, 2023, doi: 10.1080/14484846.2020.1842298.

[33] S. B. Chavan, R. R. Kumbhar, D. Madhu, B. Singh, and Y. C. Sharma, "Synthesis of biodiesel from Jatropha curcas oil using waste eggshell and study of its fuel properties," *RSC advances*, vol. 5, no. 78, pp. 63596–63604, 2015, doi: 10.1039/C5RA06937H.

[34] J. Nisar *et al.*, "Enhanced biodiesel production from Jatropha oil using calcined waste animal bones as catalyst," *Renewable Energy*, vol. 101, pp. 111–119, 2017, doi: 10.1016/j.renene.2016.08.048.

[35] Y. H. Taufiq-Yap, S. H. Teo, U. Rashid, A. Islam, M. Z. Hussien, and K. T. Lee, "Transesterification of Jatropha curcas crude oil to biodiesel on calcium lanthanum mixed oxide catalyst: Effect of stoichiometric composition," *Energy Conversion and Management*, vol. 88, pp. 1290–1296, 2014, doi: 10.1016/j.enconman.2013.12.075.

[36] K. Sudsakorn, S. Saiwuttikul, S. Palitsakun, A. Seubsai, and J. Limtrakul, "Biodiesel production from Jatropha Curcas oil using strontium-doped CaO/MgO catalyst," *Journal of environmental chemical engineering*, vol. 5, no. 3, pp. 2845–2852, 2017, doi: 10.1016/j.jece.2017.05.033.

[37] A. Kolakoti and V. S. R. Chandramouli, "Waste to Energy Conversion from Orange Peel: Heterogeneous Catalyst Preparation and Biodiesel Production," *Ethiopian Journal of Applied Science and Technology*, pp. 9–15, 2023, [Online]. Available: https://journals.ju.edu.et/index.php/ejast/article/view/4542

[38] H. H. Mardhiah, H. C. Ong, H. H. Masjuki, S. Lim, and Y. L. Pang, "Investigation of carbon-based solid acid catalyst from Jatropha curcas biomass in biodiesel production," *Energy conversion and management*, vol. 144, pp. 10–17, 2017, doi: 10.1016/j.enconman.2017.04.038.

[39] V. Mutreja, S. Singh, T. K. Minhas, and A. Ali, "Nanocrystalline potassium impregnated SiO 2 as heterogeneous catalysts for the transesterification of karanja and jatropha oil," *RSC Advances*, vol. 5, no. 58, pp. 46890–46896, 2015, doi: 10.1039/C5RA01446H.

[40] N. A. Negm, G. H. Sayed, F. Z. Yehia, O. I. Habib, and E. A. Mohamed, "Biodiesel production from one-step heterogeneous catalyzed process of Castor oil and Jatropha oil using novel sulphonated phenyl silane montmorillonite catalyst," *Journal of Molecular Liquids*, vol. 234, pp. 157–163, 2017, doi: 10.1016/j.molliq.2017.03.043.

[41] Z. Helwani, N. Aziz, M. Z. A. Bakar, H. Mukhtar, J. Kim, and M. R. Othman, "Conversion of Jatropha curcas oil into biodiesel using re-crystallized hydrotalcite," *Energy Conversion and Management*, vol. 73, pp. 128–134, 2013, doi: 10.1016/j.enconman.2013.04.004.

[42] D. A. Torres-Rodríguez, I. C. Romero-Ibarra, I. A. Ibarra, and H. Pfeiffer, "Biodiesel production from soybean and Jatropha oils using cesium impregnated sodium zirconate as a heterogeneous base catalyst," *Renewable Energy*, vol. 93, pp. 323–331, 2016, doi: 10.1016/j.renene.2016.02.061.

[43] B. Xue, J. Luo, F. Zhang, and Z. Fang, "Biodiesel production from soybean and Jatropha oils

by magnetic CaFe2O4–Ca2Fe2O5-based catalyst," *Energy*, vol. 68, pp. 584–591, 2014, doi: 10.1016/j.energy.2014.02.082.

[44] S. H. Teo *et al.*, "Efficient biodiesel production from Jatropha curcus using CaSO4/Fe2O3-SiO2 core-shell magnetic nanoparticles," *Journal of cleaner production*, vol. 208, pp. 816–826, 2019, doi: 10.1016/j.jclepro.2018.10.107.

[45] F. Zhang *et al.*, "Catalytic production of Jatropha biodiesel and hydrogen with magnetic carbonaceous acid and base synthesized from Jatropha hulls," *Energy conversion and management*, vol. 142, pp. 107–116, 2017, doi: 10.1016/j.enconman.2017.03.026.

[46] Y.-T. Wang *et al.*, "One-step production of biodiesel from Jatropha oils with high acid value at low temperature by magnetic acid-base amphoteric nanoparticles," *Chemical Engineering Journal*, vol. 348, pp. 929–939, 2018, doi: 10.1016/j.cej.2018.05.039.

[47] J. Rodrigues *et al.*, "Biodiesel production from crude Jatropha oil catalyzed by non-commercial immobilized heterologous Rhizopus oryzae and Carica papaya lipases," *Bioresource technology*, vol. 213, pp. 88–95, 2016, doi: 10.1016/j.biortech.2016.03.011.

[48] F. Al Basir, S. Datta, and P. K. Roy, "Studies on biodiesel production from Jatropha curcas oil using chemical and biochemical methods–A mathematical approach," *Fuel*, vol. 158, pp. 503–511, 2015, doi: 10.1016/j.fuel.2015.05.048.

[49] R. Abdulla and P. Ravindra, "Immobilized Burkholderia cepacia lipase for biodiesel production from crude Jatropha curcas L. oil," *Biomass and Bioenergy*, vol. 56, pp. 8–13, 2013, doi: 10.1016/j.biombioe.2013.04.010.

[50] A. S. Silitonga, A. E. Atabani, T. M. I. Mahlia, H. H. Masjuki, I. A. Badruddin, and S. Mekhilef, "A review on prospect of Jatropha curcas for biodiesel in Indonesia," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 8, pp. 3733–3756, 2011, doi: 10.1016/j.rser.2011.07.011.

[51] N. Carels, "Jatropha curcas: a review," *Advances in botanical research*, vol. 50, pp. 39–86, 2009.

[52] X.-R. Wang and G.-J. Ding, "Reproductive biology characteristic of Jatropha curcas (Euphorbiaceae)," *Revista de Biología Tropical*, vol. 60, no. 4, pp. 1525–1533, 2012, doi: 10.15517/rbt.v60i4.2070.

[53] S. Dharma *et al.*, "Optimization of biodiesel production process for mixed Jatropha curcas–Ceiba pentandra biodiesel using response surface methodology," *Energy conversion and management*, vol. 115, pp. 178–190, 2016, doi: 10.1016/j.enconman.2016.02.034.

[54] A. Kumar and S. Sharma, "An evaluation of multipurpose oil seed crop for industrial uses (Jatropha curcas L.): A review," *Industrial crops and products*, vol. 28, no. 1, pp. 1–10, 2008, doi: 10.1016/j.indcrop.2008.01.001.

[55] M. Y. Koh and T. I. M. Ghazi, "A review of biodiesel production from Jatropha curcas L. oil," *Renewable and sustainable energy reviews*, vol. 15, no. 5, pp. 2240–2251, 2011, doi: 10.1016/j.rser.2011.02.013.

[56] B. R. Moser, "Biodiesel production, properties, and feedstocks," *In Vitro Cellular & Developmental Biology-Plant*, vol. 45, pp. 229–266, 2009, doi: 10.1007/s11627-009-9204-z.

[57] D. K. Garnayak, R. C. Pradhan, S. N. Naik, and N. Bhatnagar, "Moisture-dependent physical properties of jatropha seed (Jatropha curcas L.)," *Industrial crops and products*, vol. 27, no. 1, pp. 123–129, 2008, doi: 10.1016/j.indcrop.2007.09.001.

[58] J. Heller, *Physic nut, Jatropha curcas L.*, vol. 1. Bioversity International, 1996.

[59] A. Kumar and S. Sharma, "Potential non-edible oil resources as biodiesel feedstock: an Indian perspective," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 4, pp. 1791–1800, 2011, doi: 10.1016/j.rser.2010.11.020.

[60] B. N. Divakara, H. D. Upadhyaya, S. P. Wani, and C. L. L. Gowda, "Biology and genetic improvement of Jatropha curcas L.: a review," *Applied Energy*, vol. 87, no. 3, pp. 732–742, 2010, doi: 10.1016/j.apenergy.2009.07.013.

[61] R. P. S. Katwal and P. L. Soni, "Biofuels: an opportunity for socio-economic development and cleaner environment.," *Indian Forester*, vol. 129, no. 8, pp. 939–949, 2003.

[62] K. Openshaw, "A review of Jatropha curcas: an oil plant of unfulfilled promise," *Biomass and bioenergy*, vol. 19, no. 1, pp. 1–15, 2000, doi: 10.1016/S0961-9534(00)00019-2.

[63] S. Perumal and V. Sanmugam, "Fabrication and Categorization of Bioplant Methyl Ester," *SSRG Int. J. Mater. Sci. Eng.(Ssrg-ijmse)*, vol. 1, pp. 5–8, 2015, doi: 10.14445/23948884/IJMSE-V1I1P102.

[64] R. L. Evangelista and S. C. Cermak, "Full-press oil extraction of cuphea (PSR23) seeds," *Journal of the American Oil Chemists' Society*, vol. 84, pp. 1169–1175, 2007, doi:

10.1007/s11746-007-1142-5.

[65] P. V. Rao and G. S. Rao, "Production and characterization of Jatropha oil methyl Ester," *International Journal of Engineering Research*, vol. 2, no. 2, pp. 141–145, 2013.

[66] K. Becker and H. P. Makkar, "Effects of phorbol esters in carp (Cyprinus carpio L).," *Veterinary and Human Toxicology*, vol. 40, no. 2, pp. 82–86, 1998.

[67] W. M. J. Achten *et al.*, "Towards domestication of Jatropha curcas," *Biofuels*, vol. 1, no. 1, pp. 91–107, 2010, doi: 10.4155/bfs.09.4.

[68] H. A. Abdelgadir and J. Van Staden, "Ethnobotany, ethnopharmacology and toxicity of Jatropha curcas L.(Euphorbiaceae): A review," *South African Journal of Botany*, vol. 88, pp. 204–218, 2013, doi: 10.1016/j.sajb.2013.07.021.

[69] S. Kamal, S. Manmohan, and S. Birendra, "A review on chemical and medicobiological applications of Jatropha curcas," *International research journal of pharmacy*, vol. 2, no. 4, pp. 61–66, 2011, [Online]. Available: https://irjponline.com/details.php?article=364

[70] B. S. Nayak and K. N. Patel, "Pharmacognostic studies of the Jatropha curcas leaves.," *International Journal of PharmTech Research*, vol. 2, no. 1, pp. 140–143, 2010.

[71] H. A. Abdelgadir, S. D. Johnson, and J. Van Staden, "Pollinator effectiveness, breeding system, and tests for inbreeding depression in the biofuel seed crop, Jatropha curcas," *The Journal of Horticultural Science and Biotechnology*, vol. 84, no. 3, pp. 319–324, 2009, doi: 10.1080/14620316.2009.11512524.

[72] A. J. S. Raju and V. Ezradanam, "Pollination ecology and fruiting behaviour in a monoecious species, Jatropha curcas L.(Euphorbiaceae)," *Current science*, pp. 1395–1398, 2002, [Online]. Available: https://www.jstor.org/stable/24106968%0A

[73] D. K. Vyas and R. N. Singh, "Feasibility study of Jatropha seed husk as an open core gasifier feedstock," *Renewable energy*, vol. 32, no. 3, pp. 512–517, 2007, doi: 10.1016/j.renene.2006.06.006.

[74] M. M. Gui, K. T. Lee, and S. Bhatia, "Feasibility of edible oil vs. non-edible oil vs. waste edible oil as biodiesel feedstock," *Energy*, vol. 33, no. 11, pp. 1646–1653, 2008, doi: 10.1016/j.energy.2008.06.002.

[75] J. Janaun and N. Ellis, "Perspectives on biodiesel as a sustainable fuel," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 4, pp. 1312–1320, 2010, doi: 10.1016/j.rser.2009.12.011.

[76] B. Dehgan, *Jatropha (Euphorbiaceae)*. New York Botanical Garden Press, 2012.

[77] C. M. Herrera, M. C. Castellanos, and M. Medrano, "Geographical context of floral evolution: towards an improved research programme in floral diversification," *Ecology and evolution of flowers*, pp. 278–294, 2006.

[78] H. P. S. Makkar, K. Becker, F. Sporer, and M. Wink, "Studies on nutritive potential and toxic constituents of different provenances of Jatropha curcas," *Journal of Agricultural and Food Chemistry*, vol. 45, no. 8, pp. 3152–3157, 1997, doi: 10.1021/jf970036j.

[79] R. Banerji, A. R. Chowdhury, G. Misra, G. Sudarsanan, S. C. Verma, and G. S. Srivastava, "Jatropha seed oils for energy," *Biomass*, vol. 8, no. 4, pp. 277–282, 1985, doi: 10.1016/0144-4565(85)90060-5.

[80] N. Foidl, G. Foidl, M. Sanchez, M. Mittelbach, and S. Hackel, "Jatropha curcas L. as a source for the production of biofuel in Nicaragua," *Bioresource technology*, vol. 58, no. 1, pp. 77–82, 1996, doi: 10.1016/S0960-8524(96)00111-3.

[81] G. M. Gübitz, M. Mittelbach, and M. Trabi, "Exploitation of the tropical oil seed plant Jatropha curcas L.," *Bioresource technology*, vol. 67, no. 1, pp. 73–82, 1999, doi: 10.1016/S0960-8524(99)00069-3.

[82] M. K. A. Nasir, G. M. Memon, M. U. Valhari, and L. M. Khatri, "Studies on fixed oil of Jatropha curcas seeds.," *Pakistan Journal of Scientific and Industrial Research*, vol. 31, no. 8, pp. 566–568, 1988.

[83] P. S. Yadav, Z. Said, R. Gautam, R. Raman, and H. Caliskan, "Novel investigation on atomization, performance, and emission characteristics of preheated jatropha oil methyl ester and ethyl ester," *Energy*, vol. 270, p. 126870, 2023, doi: 10.1016/j.energy.2023.126870.

[84] A. E. Atabani, T. M. I. Mahlia, I. A. Badruddin, H. H. Masjuki, W. T. Chong, and K. T. Lee, "Investigation of physical and chemical properties of potential edible and non-edible feedstocks for biodiesel production, a comparative analysis," *Renewable and Sustainable Energy Reviews*, vol. 21, pp. 749–755, 2013, doi: 10.1016/j.rser.2013.01.027.

[85] S. Pinzi, I. L. Garcia, F. J. Lopez-Gimenez, M. D. Luque de Castro, G. Dorado, and M. P.

Dorado, "The ideal vegetable oil-based biodiesel composition: a review of social, economical and technical implications," *Energy & Fuels*, vol. 23, no. 5, pp. 2325–2341, 2009, doi: 10.1021/ef801098a.

[86] E. G. Giakoumis, "A statistical investigation of biodiesel physical and chemical properties, and their correlation with the degree of unsaturation," *Renewable Energy*, vol. 50, pp. 858–878, 2013, doi: 10.1016/j.renene.2012.07.040.

[87] A. Sharma and S. Murugan, "Investigation on the behaviour of a DI diesel engine fueled with Jatropha Methyl Ester (JME) and Tyre Pyrolysis Oil (TPO) blends," *Fuel*, vol. 108, pp. 699–708, 2013, doi: 10.1016/j.fuel.2012.12.042.

[88] S. Dharma *et al.*, "Experimental study and prediction of the performance and exhaust emissions of mixed Jatropha curcas-Ceiba pentandra biodiesel blends in diesel engine using artificial neural networks," *Journal of cleaner production*, vol. 164, pp. 618–633, 2017, doi: 10.1016/j.jclepro.2017.06.065.

[89] A. V Yate, P. C. Narváez, A. Orjuela, A. Hernández, and H. Acevedo, "A systematic evaluation of the mechanical extraction of Jatropha curcas L. oil for biofuels production," *Food and Bioproducts Processing*, vol. 122, pp. 72–81, 2020, doi: 10.1016/j.fbp.2020.04.001.

[90] J. Milano *et al.*, "Optimization of biodiesel production by microwave irradiation-assisted transesterification for waste cooking oil-Calophyllum inophyllum oil via response surface methodology," *Energy conversion and management*, vol. 158, pp. 400–415, 2018, doi: 10.1016/j.enconman.2017.12.027.

[91] B. Y. Lamba, G. Joshi, A. K. Tiwari, D. S. Rawat, and S. Mallick, "Effect of antioxidants on physico-chemical properties of EURO-III HSD (high speed diesel) and Jatropha biodiesel blends," *Energy*, vol. 60, pp. 222–229, 2013, doi: 10.1016/j.energy.2013.08.005.

[92] Z. Ni, F. Li, H. Wang, and H. Xiao, "Prediction of physical parameters of Jatropha biodiesel-ethanol dual fuel based on topological indices," *Applied Energy*, vol. 328, p. 120202, 2022, doi: 10.1016/j.apenergy.2022.120202.

[93] M. A. Iqbal, M. Varman, M. H. Hassan, M. A. Kalam, S. Hossain, and I. Sayeed, "Tailoring fuel properties using jatropha, palm and coconut biodiesel to improve CI engine performance and emission characteristics," *Journal of Cleaner Production*, vol. 101, pp. 262–270, 2015, doi: 10.1016/j.jclepro.2015.04.011.

[94] N. Yusuf and S. K. Kamarudin, "Techno-economic analysis of biodiesel production from Jatropha curcas via a supercritical methanol process," *Energy conversion and management*, vol. 75, pp. 710–717, 2013, doi: 10.1016/j.enconman.2013.08.017.

[95] I. A. Kartika *et al.*, "Simultaneous solvent extraction and transesterification of jatropha oil for biodiesel production, and potential application of the obtained cakes for binderless particleboard," *Fuel*, vol. 181, pp. 870–877, 2016, doi: 10.1016/j.fuel.2016.05.038.

[96] A. Samniang, C. Tipachan, and S. Kajorncheappun-Ngam, "Comparison of biodiesel production from crude Jatropha oil and Krating oil by supercritical methanol transesterification," *Renewable energy*, vol. 68, pp. 351–355, 2014, doi: 10.1016/j.renene.2014.01.039.

[97] F. D. da Silva Araújo, I. C. Araújo, I. C. G. Costa, C. V. R. de Moura, M. H. Chaves, and E. C. E. Araújo, "Study of degumming process and evaluation of oxidative stability of methyl and ethyl biodiesel of Jatropha curcas L. oil from three different Brazilian states," *Renewable Energy*, vol. 71, pp. 495–501, 2014, doi: 10.1016/j.renene.2014.06.001.

[98] D. A. Kamel, H. A. Farag, N. K. Amin, A. A. Zatout, and R. M. Ali, "Smart utilization of jatropha (Jatropha curcas Linnaeus) seeds for biodiesel production: Optimization and mechanism," *Industrial Crops and Products*, vol. 111, pp. 407–413, Jan. 2018, doi: 10.1016/j.indcrop.2017.10.029.

[99] G. Kumar, "Ultrasonic-assisted reactive-extraction is a fast and easy method for biodiesel production from Jatropha curcas oilseeds," *Ultrasonics sonochemistry*, vol. 37, pp. 634–639, 2017, doi: 10.1016/j.ultsonch.2017.02.018.

[100] J.-J. Lin and Y.-W. Chen, "Production of biodiesel by transesterification of Jatropha oil with microwave heating," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 75, pp. 43–50, 2017, doi: 10.1016/j.jtice.2017.03.034.

[101] S. X. Tan *et al.*, "Two-step catalytic reactive extraction and transesterification process via ultrasonic irradiation for biodiesel production from solid Jatropha oil seeds," *Chemical Engineering and Processing-Process Intensification*, vol. 146, p. 107687, 2019, doi: 10.1016/j.cep.2019.107687.

[102] G. Kumar, V. Singh, and D. Kumar, "Ultrasonic-assisted continuous methanolysis of Jatropha

curcas oil in the appearance of biodiesel used as an intermediate solvent," *Ultrasonics Sonochemistry*, vol. 39, pp. 384–391, 2017, doi: 10.1016/j.ultsonch.2017.05.002.

[103] A. K. Agarwal, D. Khurana, and A. Dhar, "Improving oxidation stability of biodiesels derived from Karanja, Neem and Jatropha: step forward in the direction of commercialisation," *Journal of Cleaner Production*, vol. 107, pp. 646–652, 2015, doi: 10.1016/j.jclepro.2015.05.055.

[104] P. K. Sahoo *et al.*, "Comparative evaluation of performance and emission characteristics of jatropha, karanja and polanga based biodiesel as fuel in a tractor engine," *Fuel*, vol. 88, no. 9, pp. 1698–1707, 2009, doi: 10.1016/j.fuel.2009.02.015.

[105] C. Ciaravino, "Effect of Jatropha based Biodiesel , on engine hardware reliability , emission and performance," 2010.

[106] S.-Y. No, "Inedible vegetable oils and their derivatives for alternative diesel fuels in CI engines: A review," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 131–149, 2011, doi: 10.1016/j.rser.2010.08.012.

[107] B. S. Chauhan, N. Kumar, Y. Du Jun, and K. B. Lee, "Performance and emission study of preheated Jatropha oil on medium capacity diesel engine," *Energy*, vol. 35, no. 6, pp. 2484–2492, 2010, doi: 10.1016/j.energy.2010.02.043.

[108] T. Elango and T. Senthilkumar, "Performance and emission characteristics of CI engine fuelled with non edible vegetable oil and diesel blends," *Journal of Engineering Science and Technology*, vol. 6, no. 2, pp. 240–250, 2011.

[109] K. Pramanik, "Properties and use of Jatropha curcas oil and diesel fuel blends in compression ignition engine," *Renewable energy*, vol. 28, no. 2, pp. 239–248, 2003, doi: 10.1016/S0960-1481(02)00027-7.

[110] M. N. Nasim, R. B. Yarasu, and R. H. Sarda, "Experimental investigation on compression ignition engine powered by preheated neat jatropha oil," *Journal of Petroleum Technology and Alternative Fuels*, vol. 4, no. 7, pp. 119–124, 2013.

[111] M. Singh, E. V. Chaudhary, M. Kumar, and N. Saraswat, "Analysis of biodiesel from Jatropha fuel properties," *Ratio*, vol. 2, no. 4, 2013, doi: 10.1016/j.eti.2017.12.003.

[112] M. S. Gad, A. S. El-Shafay, and H. M. A. Hashish, "Assessment of diesel engine performance, emissions and combustion characteristics burning biodiesel blends from jatropha seeds," *Process Safety and Environmental Protection*, vol. 147, pp. 518–526, 2021, doi: 10.1016/j.psep.2020.11.034.

[113] K. S. Mehra, S. Singh, A. K. Singh, H. Kharkwal, and S. Avikal, "Performance, energy, emission and cost analysis of Jatropha (Jatropha Curcas) oil as a biofuel for compression ignition engine," *Materials Today: Proceedings*, vol. 43, pp. 348–354, 2021, doi: 10.1016/j.matpr.2020.11.675.

[114] T. O. Somorin and A. J. Kolios, "Prospects of deployment of Jatropha biodiesel-fired plants in Nigeria's power sector," *Energy*, vol. 135, pp. 726–739, 2017, doi: 10.1016/j.energy.2017.06.152.

[115] R. Kumar and N. Das, "Survey and selection of Jatropha curcas L. germplasm: Assessment of genetic variability and divergence studies on the seed traits and oil content," *Industrial crops and products*, vol. 118, pp. 125–130, 2018, doi: 10.1016/j.indcrop.2018.03.032.

[116] N. R. Baral, P. Neupane, B. B. Ale, C. Quiroz-Arita, S. Manandhar, and T. H. Bradley, "Stochastic economic and environmental footprints of biodiesel production from Jatropha curcas Linnaeus in the different federal states of Nepal," *Renewable and Sustainable Energy Reviews*, vol. 120, p. 109619, 2020, doi: 10.1016/j.rser.2019.109619.

[117] T. Ntaribi and D. I. Paul, "The economic feasibility of Jatropha cultivation for biodiesel production in Rwanda: A case study of Kirehe district," *Energy for sustainable development*, vol. 50, pp. 27–37, 2019, doi: 10.1016/j.esd.2019.03.001.