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Review

Jatropha's Rapid Developments and Future Opportunities as a Renewable Source of Biofuel—A Review

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Abstract: Biofuel is an attractive alternative to fossil fuels since it is renewable and biodegradable—it is mainly made from edible and non-edible sources. Globally, the usage of renewable biofuels is expected to rise quickly. The rising production and use of biofuel has prompted an examination of its environmental impact. Biodiesel is a fatty acid methyl ester generated from sustainable lipid feedstock that substitutes petroleum-based diesel fuel. Non-food oils, such as Jatropha, waste cooking oil, and by-products of vegetable oil from refineries provide inexpensive feedstock for biodiesel manufacturing. Due to its increased oil yield, adequate fatty acid content, tolerance to various agro-climatic conditions, and short gestation period, Jatropha may be one of the most promoted oilseed crops worldwide. Furthermore, Jatropha can provide several economic and agronomic advantages because it is a biodegradable, renewable plant. This study examines whether Jatropha can be considered as the most preferable biofuel in the future. The study begins with an overview of current fuels, including their classifications, dynamic changes in consumption, advantages, and cross-examining the limitations to identify the significance of bringing an alternate fuel. Then we elaborate on the outlook of the Jatropha crop, followed by evaluating its availability, opportunity, and advantages over other biofuels. Subsequently, the extraction methods, including the transesterification process and integration methods for improving the efficiency of Jatropha fuel, are also reviewed in the paper. We also assess the current stage of Jatropha cultivation in different countries with its challenges. The review concludes with future perspectives and directions for research.

Keywords: biofuels; Jatropha; transesterification process

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1. Introduction

Fuel is one of the most frequently used energy sources today. Fuels generate energy and power engines. Additionally, the combustion provides heat to generate commercial electricity, power ships, cars, and aircraft, and provides electricity to homes and buildings. The life activities of humans depend on fuels. Fuels provide energy for enormous activities. They make man's job much more manageable. The distance covered by motors quickly and the space shift carrying tons of loads and flying airlines became possible through the energy obtained from burning fuels [1]. The world energy consumption is oil 39%, natural gas 21.2%, coal 23.9%, nuclear power 6.3%, and hydropower 2.7%. The primary energy source is oil, contributing about 40%. Transportation activities depend on oil 97–98% [2]. We must develop energy-saving technologies that can stretch oil reserves while modifying our energy-use patterns and infrastructure to become more sustainable over the next few decades, as the fuel sources are at a constant depletion rate [3,4]. It is both an ecological

necessity and a technological challenge to reduce dependence on oil from the current level of 98% consumption [5].

Fuels can be classified under various categories. The review mainly talks about the plant Jatropha curcas which can be converted into biofuel after specific chemical treatments. Jatropha is a versatile plant with a lot of promise. The plant can prevent or regulate erosion, recover land (as a live fence to contain or exclude farm animals), and improve income (as a commercial crop). Jatropha is a drought-tolerant, hardy plant that cultivates easily and grows fast. It is not browsed since the leaves and stems are poisonous to animals. However, the treated seeds or seed cake might be utilized as animal feed. The plant's bark contains tannin, the blooms attract bees to produce honey, and the wood and fruit are used for various purposes, including fuel. The fruit of the Jatropha plant contains viscous oil, which makes soap in the cosmetics sector, and as a diesel/kerosene replacement or extender [6].

Jatropha comes under second-generation biofuels. The properties of Jatropha include its oil content of 35–40%, the oil yield of 1892 L/ha/year, having a fatty acid composition of palmitic C16:0 14.2, Stearic C18:0 6.9, Oleic C18:1 43.1, and Linoleic C18:2 34.3 [7]. Moreover, some other properties make Jatropha a suitable biofuel: cetane number, cloud point, cold filter plugging point, flashpoint, Oxidation stability, kinematic viscosity, heating value, iodine number, and density [8–10]. Many experiments were carried out to test and compare the efficiency of Jatropha. Biswas et al. [11] examined the co-processing effects through vacuum residue, Jatropha oil, and high-density polyethylene. Experiments were carried out in a tubular batch reactor, with a fixed bed, with a flow rate of 120 mL/h of nitrogen. Liquid fuels and gases were among the products. The co-cracking response of the three combined oils exhibited synergy when they were processed together. However, in fractured liquid of vacuum residual high-density polyethylene (HDPE), the generated liquid primarily comprises diesel range hydrocarbons. There are 22 percent gasoline range hydrocarbons in a liquid from Jatropha oil, vacuum residue, and HDPE. The gases CH_4, n-butane, iso-butane, n-pentane, 2-methyl butane, and uncondensed components make up the gaseous product produced. They [11] finally found nickel, iron, vanadium, magnesium, and potassium in the solid remnants. The findings revealed interactive interactions between the reactive compounds produced during co-processing.

Jatropha curcas is the best triglyceride-based biomasses, owing to its agronomic characteristics among the many studied feedstocks [12]. Jatropha is well known for its growth in harsh environments, requiring less water than other crops. On the other hand, it can grow in different soil conditions, including non-arable and dry areas, with very little energy and water [13]. Hence Jatropha oil has gained profound attention in the energy sector, mainly being used as a primary fuel in both automotive and aviation sectors [14]. However, the Jatropha biofuel (JBF) manufacturer does not fully use the Jatropha crop. Experiments on the conversion of Jatropha oil to fuels ratio was 75% [15–17]. Jatropha fruit leftovers, 75% of the total weight of the fruit, have been shown to have a significant potential for conversion into a variety of energy intermediates, including syngas [18]. Gasification can be used to upgrade this to JBF. However, no attempts have been made to incorporate the total crop yield into energy, including the Jatropha fruit, in the synthesis of JBF. Jatropha is biodegraded up to four times quicker than petroleum fuel. Due to its greater flashpoint, it does not ignite spontaneously under typical conditions. According to stringent industrial criteria, biodiesel from Jatropha satisfies American Society for Testing and Materials (ASTM) D6751 standards and has a moderate, pleasant odor [19]. Even though there are lots of attractive opportunities that exist for the Jatropha curcas, it still undergoes particular challenges, including seed life, the continuous supply of seeds for extraction and esterification throughout the year, and the seed price offered to the farmers. Moreover, farmers' profit is not increasing at the same rate as the cost of inputs. Therefore, a financial gap has led to debt traps and suicides [20–22]. The protection techniques for the Jatropha plant from weeds are another challenge to be evaluated [23]. Many studies improved the production rate of the plant. However, large-scale plantation without plant evaluation, climate, and knowledge gaps causes failure. As a result, Jatropha production

as a biofuel encounters several problems, including production, oil extraction, conversion, and usage as a sustainable biofuel [24]. This paper discusses the obstacles and potential solutions for participation in the biofuel production of Jatropha.

This review deeply investigates the availability and opportunities of Jatropha as a biofuel and fuel production from various processes, including biodiesel production with homogeneous catalysts. Furthermore, it describes the transesterification process and identifies the energy efficaciousness of Jatropha curcas over other biofuels. Moreover, it discusses the opinion of researchers relating the integration techniques that make Jatropha a suitable source of fuel and jet fuel. Finally, the study evaluates the challenges in producing sustainable biodiesel from Jatropha in different areas and discusses the global bulk production of Jatropha.

2. Fuel Energy: An Overview

Different fuels are used worldwide. This area summarizes commonly used fuels from various sources. The commonly used fuels will be projected after the following subsection.

Most fuels are natural compounds, such as petro fuel, diesel, and natural gas, either taken directly from the ground or refined from petroleum. Fuels can be categorized according to various forms. They are classified as solid, liquid, and gaseous fuels based on their physical appearance. Primary and secondary sub-classifications categorize wood, coal, and peat as primary fuels and coke and charcoal as secondary solid fuels. Similarly, petroleum is a primary liquid fuel; diesel, gasoline, kerosene, LPG, ethanol, and biodiesel are secondary biofuels [25]. Finally, there is another category of fuels similar to gaseous fuels, in which natural gas is a perfect sample of primary gaseous fuel.

On the other hand, hydrogen, propane, methane, coal gas, and water gas are secondary gaseous fuels. In addition, petrol, gas oil, diesel fuel, fuel oils, aviation fuel, jet fuel, and marine fuel are typical forms of fuel [26–28]. Another classification is based on the purpose of fuel. For example, materials burnt to generate nuclear energy are called nuclear fuels, and those producing heat are called thermal fuels. The burning of plutonium produces nuclear energy [29]. When burning coal, wood, oil, or gases, they produce heat.

2.1. Classification of Fuels

Table 1 shows the general classification of fuels, and Figure 1 shows the detailed classification based on their physical state and occurrence.

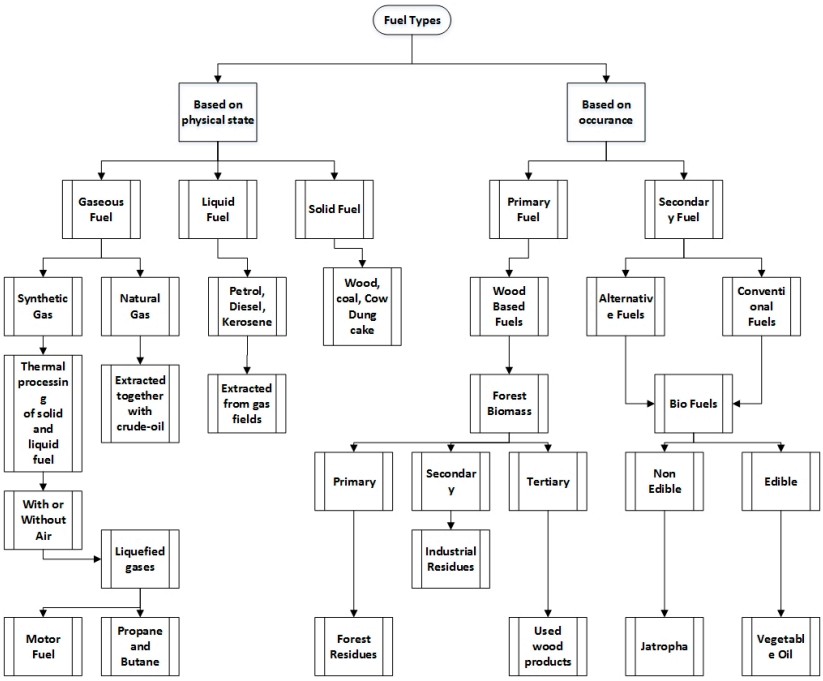


Figure 1. Classification of fuels based on their physical state and occurrence.

Table 1. General classification of fuels.

Fuel Type	Primary Fuels	Secondary Fuels
Solid Fuels	wood, coal, peat, dung, sugarcane, charcoal, etc.	coke, charcoal
Liquid fuels	Petroleum, Biodiesel, Bio alcohols, Vegetable oil	diesel, gasoline, kerosene, LPG, coal tar, naphtha, ethanol
Gaseous fuels	Natural gas, Biogas	hydrogen, propane, methane, coal gas, water gas, blast furnace gas, coke oven gas, CNG

2.2. Ongoing Sources of Energy

Petroleum fossil fuels are common fuels. Currently, the combustion of fossil fuels supplies about 80% of the world's energy requirements [30]. However, Fossil fuels are not a sustainable energy resource despite the rules to reduce the environmental effect of their burning. In certain countries like India, fossil fuels satisfy energy needs, and coal power plants generate 70% of the required electricity. As their resources are limited, we should think about alternate sources. The production rate of conventional oil will soon enter a phase of permanent decline [31]. Fossil fuel pollution puts the entire globe in trouble. Other analysts have projected 3 to 8% decline rates in world oil production [32]. Fossil fuel ruminants, non-renewable sources, are usually hazardous to the environment. The transportation of petroleum products is another challenging task. It may cause oil spills [33–35]. Moreover, fossil fuels take millions of years to produce. Petroleum fields that are formed after millions of years will not produce accordingly based on the current consumption.

The second most utilized fuel is biomass. Over 840 million people depend on traditional biomass to satisfy their energy necessities [36]. Around 2.4 billion people, or roughly 40% of the world's population, rely on biomass fuels (wood, charcoal, dung, and agricultural waste) to satisfy their cooking and heating needs [37]. On the other hand, fossil fuels provide about two-thirds of the world's energy demands [38]. As a result, many individuals work in the fossil fuel business worldwide. However, there is a growing recognition of the fossil fuel sector's apparent flaws, which have plagued the global economy in recent years [39].

Furthermore, some renewable energy sources are always available and can exist for a long time. These include solar energy from the sun, geothermal energy from the earth, wind energy, biomass from plants, and Hydropower from flowing water. Figure 2 shows the percentage energy consumption of different fuels.

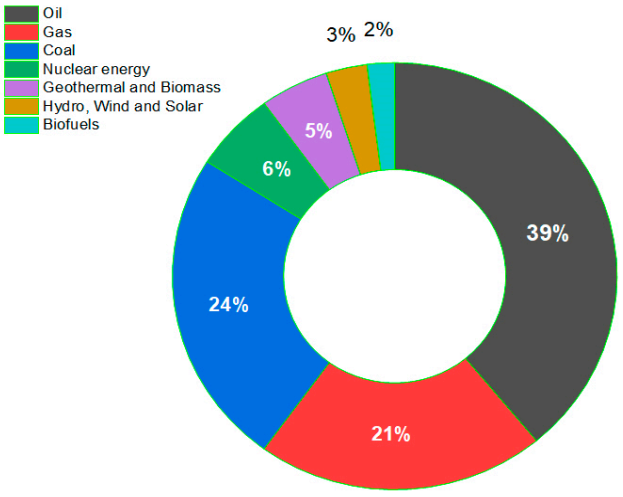


Figure 2. Percentage of energy consumption of fuels.

2.3. Dynamic Changes in Consumption of Fuels

The situation will likely change rapidly, and the difference between crude oil demand and supply will continue to increase. Nonrenewable fossil fuels are being depleted quicker than ever, putting the world's resources on the verge of depletion. For example, in 2000, India produced 32 million tons of oil and imported 90 million tons (73% of its total demand). The cost of imports in 2002–2003 was around INR 90,000 crores, which is expected to rise further due to rising oil prices and demand-pull prices. According to estimates, India will rely on imported oil for approximately 95% of its energy by 2030. As a result, the oil import bill will significantly impact the economy. This dangerous situation necessitates a significant increase in the usage of non-conventional energy sources. This condition applies to developing countries like India and many developed countries with low fossil fuel reserves [40]. Burning fuels causes hazardous environmental pollutants, but fossil fuels are widely used because no alternative solutions meet energy needs. Numerous energy sources are now being investigated as potential alternatives to gasoline to reduce the pollution rate and protect nature [41–45]. Due to the global depletion of conventional energy sources, especially fossil fuels, alternative energy sources have gotten much attention.

2.4. Advantages and Disadvantages of Biofuels

Biofuels are considered sustainable and ecologically acceptable energy sources since they are made from natural resources [46]. Biofuels are derived from plants and crops at earlier ages. They may be utilized in various energy-related areas, including electricity generation, power generation, and transportation. Different scenarios regarding the estimated biofuels from multiple sources in the future energy system are being developed [47]. The biofuel policy encourages the production and use of biomass-based fuels. Although biofuels have both good and negative consequences, global biofuel production has steadily increased [48–52]. Biofuels are made from sustainable sources, such as wheat, corn, soybeans, sugarcane, and Jatropha, which can be generated on demand [53–56]. Bioethanol, known as ethanol, is the most widely extracted and utilized biofuel. It is mixed with gasoline and can substitute gasoline in vehicles. Ethanol is an alcohol used as a blending agent with gasoline to increase octane and cut down carbon monoxide and other smog-causing emissions [57]. Fuels generated from plants are an ideal candidate since they are from renewable resources, which can be cultivated everywhere and emit less carbon than fossil fuels [58,59]. As crude oil prices remain highly uncertain, most applications are turning towards biofuels, which lessen their dependence on the commodity [59]. The advantages of biofuels over fossil fuels [60–68] are listed in Table 2.

Even though biofuels have many advantages, they also bear some disadvantages [69–72], including:

- Second-generation fuels are not commercially available due to high manufacturing costs and a lack of technical proof;
- Current harvesting, storage, and transportation technologies are insufficient for processing and distributing biomass on a wide scale;
- A clear and long-term policy framework is required to guarantee the industry and confidence in financiers;
- The changing needs of the agricultural/forestry industry for biomass feedstock from residues and crops need a substantial shift in the present business model. As a result, using edible oil fuels is connected with a higher risk of food crisis in developing countries or a negative impact on consumer prices in developed ones [73–77]. Hence, using non-edible oils is mostly preferred.

In addition, Table 3 lists the disadvantages of biofuels over fossil fuels [78–85].

Table 2. Advantages of biofuels over fossil fuels.

Advantages	Description
Efficient Fuel	Compared to fossil diesel, biofuel is generated from renewable resources and is less combustible. It has far superior lubricating qualities.
Cost-Benefit	They are producing high-value biomass products and lowering the cost of creating biopower.
Durability of machinery	Biofuels may be easily adapted to contemporary engine layouts and operate without hassles. Higher cetane number and greater lubrication advantages. In addition, biodiesel improves the engine's durability.
Easy to Source	Biofuels may be generated from various sources, including manure, agricultural waste, other wastes, algae, and plants cultivated expressly.
Renewable	Crops cultivation is cyclic.
Reduce Greenhouse Gases	Burning coal and oil contributes to global warming. People worldwide use biofuels to minimize the impact of greenhouse emissions.
Economic Security	The demand for appropriate biofuel crops rises due to biofuel production, giving the agriculture business a boost. Biofuels are less costly than fossil fuels for powering homes, businesses, and automobiles. With a rising biofuel business, more employment will be generated, ensuring the economy's stability.
Reduce reliance on imported oil	Alternate solution for fossil fuel.
Lower Levels of Pollution	Although carbon dioxide is produced as a byproduct of biofuel production, it helps plants with photosynthesis.

Table 3. Disadvantages of biofuels over fossil fuels.

Disadvantages	Description
High Cost of Production	Mass production is expensive
Monoculture	Monoculture might be economically attractive; however, the soil quality will be affected; hence there is a possibility of a decrease in the yield rates
Fertilizers	Chemicals from the fertilizers risk both soil and water pollution
Food Shortage	The use of feedstocks increases the food process
Industrial Pollution	Large-scale industries meant for churning out biofuel are known to emit large amounts of emissions and cause small-scale water pollution as well
Water Consumption	Irrigation of biofuel crops throughout the year is challenging owing to water scarcity. Water management is necessary to handle the water issue
Future Price Hike	Fluctuation of the commodity prices may risk the biodiesel production cost

Even though biofuels have certain disadvantages, biofuels can substitute fossil fuels in the future because of their advantages. As observed from Figure 1. the categories of biofuels are edible and non-edible oils. Humans consume edible oils from vegetable or plant sources. Additionally, animal fat is considered edible oil. Nowadays, the productions of edible oils are not up to the consumption rate. Therefore, food scarcity and deficiency will be the main challenge if we consider biofuels [86] more widely. Non-edible oils can be widely used as fuel because they are not food items. These are mainly obtained from plant sources and have higher calorific values and properties than edible oils. Popular non-edible oils include Jatropha oil, rice bran non-edible oil, soapstock, and wax. Non-edible oils are not rich in nutrition, and it does not usually require any chemical processing for their extraction from oilseeds, nut, or fruits. The main examples of non-edible oilseed crops are the Jatropha tree (Jatropha curcas), castor bean seed (Ricinus communis), and rubber seed tree (Hevea brasiliensis) [87]. Among these, Jatropha has a high oil content [20]. Compared

to edible oils, non-edible oils are cheaper and have instant availability. Hence, non-edible oils are mostly preferred as a biofuel by all means.

Non-edible oils are currently rising in popularity due to their widespread availability in many world regions, particularly in wastelands where food oil crops are not able to be grown. In addition, they minimize food competition, improve production efficiency, reduce deforestation, and are more cost-effective than edible oils [86,88–91].

The selection of oils for fatty acid alkyl esters (FAAE) synthesis is mainly based on the feedstocks' economic perspective and the oil content [90–97]. The feasibility of biodiesel production can be designed based on the content of FAAE. Sunflower and soybean edible oil are the key feedstocks currently used worldwide [92]. However, the non-edible oil Jatropha was a promising feedstock in developing countries with crop shortages and food scarcity [88,98–101].

According to the aforementioned publications, an alternate fuel source is essential to replace fossil fuels. Among different renewable sources, biofuels are one of the most satisfying fuels since early days. Studies are underway to make Jatropha one of the future common biofuel available. Hence, this review focuses on Jatropha as a promising source for future energy production. The next part of the review discusses the relevant studies involved in the production of Jatropha [102–104].

3. Relevant Studies on Jatropha

In this section, studies dealing with the Jatropha are reviewed. Most of the studies, such as those by Atabani et al. [105], and Lim et al. [106], discussed its manufacturing techniques. In contrast, a few studies, such as those by Mazumdar et al. [107], addressed the availability and opportunities of Jatropha. Integration methods for improving efficiency were mentioned in journals; for example, the study by Alherbawi et al. [108]. Relevant studies monitored Jatropha's advantages and challenges in producing sustainable biodiesel from Jatropha.

The following objective functions are reported in the current relevant literature:

Objective 1: Advantages of Jatropha over other biofuels;

Objective 2: Jatropha availability and opportunity;

Objective 3: Production and Extraction method of Jatropha;

Objective 4: Integration methods for improving the efficiency of Jatropha fuel;

Objective 5: Challenges in producing sustainable biodiesel from Jatropha;

Objective 6: Other studies related to Jatropha.

Table 4 chronologically lists the studies associated with Jatropha curcas for using it as a biofuel using this classification scheme.

Table 4. List of studies related to Jatropha for utilizing it as a fuel.

Reference No.	Reference Outcomes	Objectives						Year
		1	2	3	4	5	6	
[108]	A study on different integration techniques to improve the efficiency of Jatropha to utilize it as a biofuel	×	×			×		2021
[109]	Study the chemical composition of Jatropha oil, techniques for synthesis of biodiesel using a homogeneous catalyst, heterogeneous catalyst, enzymes (lipases), and non-catalytic supercritical process to obtain Jatropha-based biodiesel satisfying ASTM 6751, EN 14214, and IS 15607 specifications.	×	×		×			2013
[110]	Study the development of a Jatropha biofuels sector; Conflicts reflect opposing views and interests among parties about sustainability.			×			×	2009
[111]	A case study of Jatropha in Kenya showing climatic variations and effects	×		×	×			2010
[112]	Feedstock production and biofuel projects	×	×	×				2019
[113]	Lack of Jatropha seed cultivation to produce biodiesel. Advantages of Jatropha as the source.	×		×			×	2019
[114]	Implications of large-scale investments in biofuels for growth and income distribution. Its advantages and effects.	×			×			2010

Table 4. *Cont.*

Reference No.	Reference Outcomes	Objectives						Year
		1	2	3	4	5	6	
[115]	Problems experienced by the farmers, efforts needed to improve yield levels and stability through genetic improvements and drought tolerance	×					×	2012
[116]	Bio jet production using vegetable oils and non-edible oils		×			×		2019
[117]	Production of biodiesel from Jatropha via homogenous acid and alkaline catalyst	×			×	×		2013
[118]	Impact of alcohol on biodiesel production and properties	×				×		2016
[119]	Activities of homogenous and heterogeneous catalysts in the transesterification process				×	×		2012
[120]	Current technologies for the production of biodiesel		×		×			2014
[121]	A potential biofuel plant, Jatropha its properties	×		×		×	×	2012
[122]	Production of biofuel from Jatropha	×	×	×	×		×	2012
[123]	Jet biofuel production using non-edible oils				×	×		2017
[124]	Discussion about methods of cultivating Jatropha	×	×				×	2016
[106]	A mechanical process like harvesting and shelling for the production of Jatropha	×	×					2015
[125]	Sustainability of Jatropha biodiesel in India	×					×	2012
[126]	Status of molecular breeding for improving Jatropha curcas	×	×				×	2013
[127]	Human requirements in Jatropha oil production for rural electrification	×						2012
[128]	Factors affecting the potential of Jatropha for sustainable biodiesel production	×					×	2021
[129]	Biogas production from Jatropha seed cake	×	×	×	×			2012
[130]	Different platforms for Jatropha cultivation in the sub-Saharan African region			×				2012
[131]	Challenges in Jatropha cultivation						×	2018
[132]	Evaluation of genetic diversity of toxic and non-toxic Jatropha plant							2013
[133]	Integrated assessment of biofuel production in arid lands and Jatropha cultivation on islands							2015
[134]	Extraction of oil from Jatropha curcas seedbed combination of ultrasonication and aqueous enzymatic process				×			2005
[135]	The supercritical reactive extraction process for Jatropha		×		×			2013
[136]	Study regarding the influence of co-solvents in both supercritical extraction and transesterification	×	×		×			2013
[137]	CO_2 extraction from Jatropha oil		×		×		×	2018
[138]	Improving the oil yield by ethanolic extraction	×	×		×			2016
[139]	Study on seed propagation, plantation management, oil extraction, and biodiesel processing in China	×	×	×	×		×	2012

3.1. Advantages of Jatropha over Other Biofuels

From the authors' view, there is currently a high demand of biofuels, especially Jatropha fuels, in the world. Azam M. et al. [140] and Asif et al. [141] mentioned that, as compared with other plants, 30% or more oil can be generated through the Jatropha seeds. Therefore, they recommended Jatropha as the most appropriate plant for biodiesel production. Akubude et al. [142] and Rezania et al. [143] emphasized that transesterification or alcoholysis extracts biodiesel from Jatropha via the reaction of a triglyceride in oil. Moazeni et al. [144] mentioned that the above process can be carried out with or without the influence of a catalyst to form biodiesel Fatty Acid Methyl Esters (FAME) and glycerol. Properties such as calorific value, fatty acid composition, iodine value, and saponification number can forecast the quality of the FAME, which is high for Jatropha [145,146]. Hence, Jatropha is the best candidate for usage as biodiesel since it satisfies all requirements of the biodiesel standard [147]. According to Van Eijck et al. [148], initial investment requirements for plant cultivation could be relatively low. Najaf et al. [149] reported that Jatropha biodiesel has advantages of reducing SO_2, CO, and CO_2. The benefits of Jatropha

include the plant's ability to grow in harsh environments and water-scarce areas [150]. The investigations from Dyer et al. [151] found that the plant is drought resistant and needs little water.

3.2. Jatropha Availability and Opportunity

Although Jatropha production is easier than the production of other crops, the availability of the plant is rare [152]. Forson et al. [153] addressed that tropical and subtropical climates support the growth of Jatropha curcas. They noted that the plant can grow on almost any surface, including gravelly, sandy, and saline soils. It can also flourish in wastelands. Souza et al. [154] highlighted the opportunities for Jatropha to produce products such as fuels, lubricants, binders, candles, soaps, pesticides, and cosmetics. Tapanes et al. [155] mentioned that seeds of Jatropha curcas contain up to 60% of oil, which is high compared to other crops. According to Gui et al. [156] the Jatropha oil production cost is about 0.39 USD per kg, and the overall soybean oil production costs approximately 1.65 USD per kg. Therefore, Jatropha oil production is economical compared with other crops, and this plant has many opportunities.

3.3. Extraction Method of Jatropha

This section likely intimates the extraction method of Jatropha. Like most edible and non-edible seeds, Jatropha undergoes several processes for turning into biofuel. After harvesting crops, seeds containing oil and protein will undergo mechanical grinding, including processing the residue from pressing [157]. Rida et al. [158] mentioned that the conventional extraction method and transesterification process filter the plant oil to produce biodiesel. Figure 3 shows a simplified Jatropha bio refinery schematic diagram showing biodiesel production's stages, processes, and operational requirements.

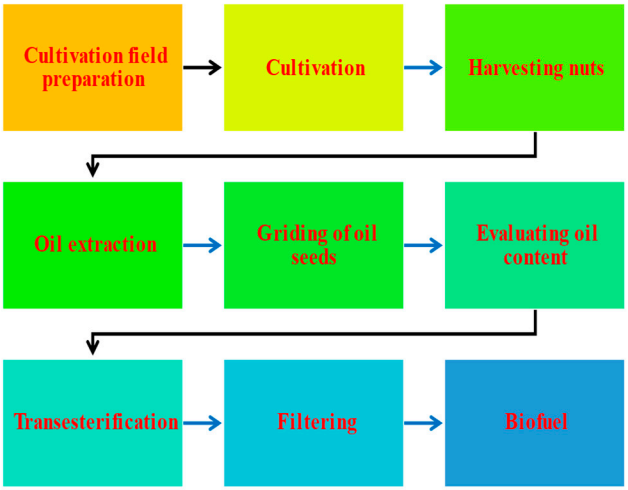


Figure 3. Schematic of a simplified Jatropha bio refinery showing the stages, processes, and operational requirements of biodiesel production methods.

On the other hand, by optimizing extraction techniques, oil production can be increased. Furthermore, Makkar et al. [159] mentioned that the quality of the feedstock also plays a vital role. They also suggested that the chemical extraction method, which uses n-hexane as a solvent, and the mechanical extraction method, which uses either a manual ram-press or an engine-driven expeller, are the two main techniques for extracting oil. The authors found that the mechanical ram-press is more accessible because of its availability. Initially, the brown ripe Jatropha fruits were collected and followed by the drying process that can be done by direct sunlight or a solar dryer. Then, all the portions of the husks were removed while segregating fruits from the seeds. Later, the seeds were crushed to extract black seed shells. Finally, the procured seed kernels were pressed using an extractor to

collect oil. They revealed that proper extraction techniques extract up to 20 kg of shelled fruits from 30 kg unshelled seeds. Warra et al. [160] intimated that 6 kg to 10 kg of oil could be produced by milling, and approximately 21.5 to 31.25% per kg of biomass is collected. However, Demirbas et al. [161] intimated that due to the poor viscosity of free fatty acid content (FFAC) and volatility during storage and burning, any raw oil used directly as fuel in diesel engines is not recommended.

Ayoob et al. [162] specified that transesterification is the most suitable method for turning edible and non-edible oils into biodiesel. They specified that transesterification or alcoholysis is a process by which triglyceride interacts with alcohol (with or without a catalyst) in fat or oil to produce biodiesel fatty acid methyl esters (FAME) and glycerol. The ideal transesterification reaction and its mechanism can be represented as Equations (1)–(4).

$$\text{Triglycerides} + \text{Metanol} \rightarrow \text{Glycerol} + \text{Fame} \quad (1)$$

$$\text{Triglyceride} + R^1OH \rightarrow \text{Diglyceride} + RCOOR^1 \quad (2)$$

$$\text{Diglyceride} + R^1OH \rightarrow \text{Monoglyceride} + RCOOR^1 \quad (3)$$

$$\text{Monoglyceride} + R^1OH \rightarrow \text{glycerol} + RCOOR^1 \quad (4)$$

The reaction takes place in the presence of a catalyst. Since this reaction is reversible, much alcohol is required to move the equilibrium reaction forward [163]. In the transesterification process, triglycerides are transformed into diglycerides into monoglycerides into glycerol. Therefore, one alkyl ester molecule results from each glyceride at each step [164]. Musa et al. [165] revealed that methanol and ethanol are the most prevalent and often utilized alcohols. They mentioned that ethanol is chosen over methanol for biodiesel because it is from agricultural feedstocks. However, methanol is frequently used because of its inexpensive cost and physical and chemical benefits. Methanol-derived biodiesel has somewhat greater cloud and pour points and slightly lower viscosities than ethanol-derived biodiesel. Furthermore, methanol does not form an azeotrope and is easily recycled, unlike ethanol [166,167]. Wang et al. [168] stated that the transesterification reaction will take place with or without a catalyst. Alkaline, acidic, or enzymatic catalysts can be employed. Moreover, the transesterification process can homogeneously or heterogeneously be catalyzed based on the solubility of the catalyst in the reactant [169]. Depending on their solubility in the reactants, acidic and alkaline catalysts can be homogeneous or heterogeneous. Depending on the oil's FFA concentration, reactions can occur in a single stage with an acid/basic catalyst or in two phases with acidic and basic catalysts [170]. Tiwari et al. [100] specified that the first stage is the esterification of FFA with alcohol in acidic catalysts, which produce biodiesel and water. Equation (5) represents the mechanism of the esterification reaction, which takes place in the presence of a catalyst.

$$\text{FFA (Carboxylic acid)} + \text{Alcohol} \rightarrow \text{Biodiesel} + \text{Water} \quad (5)$$

In the second stage, methanol transesterify triglycerides in the presence of an alkaline catalyst [171]. Enzymes catalyze both transesterification and esterification processes in feedstocks with high FFA concentrations. They generally have much activity in a water-short environment and produce very little effluent. The non-catalytic supercritical alcohol technique overcomes the initial mass transfer constraint caused by the low solubilities of the alcohol and oil phases. As there is no catalyst, this technique has a greater reaction rate, a shorter reaction time, a simpler separation and purification, and no waste production. However, owing to the extremely high temperature and pressure, this approach has an inherent drawback of expensive equipment costs. The bio-catalyzed transesterification process's effectiveness depends on the enzyme supply and operating parameters, as shown in Table 5, Adapted with permission from Ref. [172].

Table 5. Outline of Jatropha curcas oil enzymatic transesterification.

Lipase	Free Pseudomonas Cepacia	Pseudomonas Cepacia on Celite		Candida Antarctica Lipase (Novozym 435)	Thermomyces Lanuginosus (Lipozyme)	Rhizomucor Miehei (Lipozyme RMIM)	Enterobacter Aerogenes on Activated Silica 48 55 4:1 68 t	Rhizopus Oryzae on Polyurethane Foam	Candida Antarctica Lipase B (Novozym 435)
Reaction temp (oC)	40	50	40	45	45	45	55	30	30
Time (h)	24	8	24	24	24	24	48	60	90
Alcohol/oil molar ratio	4:1	4:1	4:1	5:1	5:1	5:1	4:1	3:1	3:1
Conv (%)	65	98	91	98	77	78	68	80	75
Remarks	No solvent	Addition of 50 g/kgof water	No solvent	A mixture of 25% pentanol and 75% iso-octane were used as a solvent			t-Butanol was used as solvent	No solvent	

Berchmans et al. [173] quoted that biodiesel from Jatropha is produced using homogeneous alkaline catalysts, and the used catalyst is KOH (Potassium Hydroxide) at 1–2% weight, 50–60 °C with alcohol: oil molar ratio of 6:1 to 7.5:1. It has a reaction time of about 1–2 h, having a yield conversion of about 90%. Gandhi et al. [174] mentioned that using both an alkaline catalyst and Jatropha oil containing 10.45% Free Fatty Acids (FFA), the fatty acid alkyl in (FAAE) yield is 42.7% for the single-step process and 96.4% for the two-step process. Ding et al. [175] revealed that although methanol is the preferred alcohol in both steps, ethanol is also used. A similar case is for Castor oil, converted into FAAE; the optimal ethanol to oil molar ratio is much higher, i.e., 40:1 in the first step and 20:1 in the second step [176].

The chemical route for Jatropha curcas oil conversion is depicted in Figure 4 [177,178]. Decarboxylation and decarbonylation are two possible processes. FFA is converted into saturated hydrocarbons, such as n-pentadecanes ($C_{15}H_{32}$) and n-heptadecanes ($C_{17}H_{36}$), as well as unsaturated n-heptadecenes during the decarboxylation process (monounsaturated and diunsaturated). The preferred process is decarboxylation, in which oxygen is eliminated as carbon dioxide (reaction b in Figure 4). Decarboxylation produces hydrocarbons that can be combined directly with diesel or even used as a substitute for petro-diesel. The decarbonylation process is shown by reaction 'c' in Figure 4.

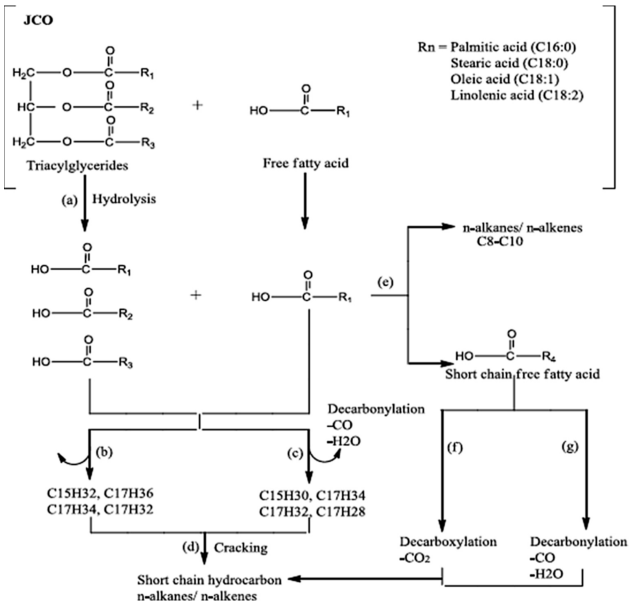


Figure 4. Deoxygenation reaction route for diesel production. Adapted with permission from Ref. [177].

During the decarbonylation process ($C_{17}H_{28}$), FFA is altered to unsaturated n-heptadecene and n-pentadecane. This transformation includes monounsaturated ($C_{15}H_{30}$, $C_{17}H_{34}$), diunsaturated ($C_{17}H_{32}$), and polyunsaturated ($C_{17}H_{32}$) n-pentadecanes and n-heptadecene. The generated hydrocarbons undergo a cracking process to produce shorter chain hydrocarbons by breaking CAC bond. The cracking process may directly utilize raw FFA in reaction 'e' to create hydrocarbons C_8–C_{10} shorter chain. The feeds of reactions 'd' and 'e' are biofuels that can be used instead of traditional jet fuel.

Many researchers have trans esterified the non-edible oil Jatropha because of its appealing physiochemical characteristics, which are shown in Table 6. As in the case of edible oil transesterification, the percent yield may be maximized by adjusting the different parameters [179].

Table 6. Physio-chemical properties of Jatropha oil.

Sl. No.	Reference	Properties			
		Free Fatty Acid (as Oleic, %)	Iodine Value (gI2/100 g)	Saponification Value (mgKOH/g)	Unsaponifiable Matter (%)
1	[180]	22.6	100.1	208.27	–
2	[181]	2.67	96–105	196–200	–
3	[182]	2.23	103.62	193.55	–
4	[183]	1.5–19	93–107	188–196	0.4–1.1
5	[184]	0.62	102	197	0.4
6	[109]	5.1–6.3	103.6	193.0	–
7	[139]	55.9	–	191.7	–

The main parameter for hydrotreatment of Jatropha oil is Kerosene 54.30% under the following reaction conditions: temperature of about 4100 °C, the pressure of 50 bar, H_2/oil—1500 NL/L, and Space velocity—2 h-1(2 reactor volumes are fed per hour) having NiMo/HZSM-5 as catalyst [185]. Heterogeneous catalysts for transesterification of Jatropha seeds are carried out by using calcium oxide as a catalyst with a MeOH/oil ratio of 9:1. The reaction time for the process is about 2.5 h under 70 °C having a percentage yield of 93% [186]. The oil content of Jatropha seeds varies according to different sites. Oil extraction methods also influence the percentage of oil yield. The oil content of Jatropha seeds obtained from various sites is shown in Table 7.

Table 7. The oil content of Jatropha seeds obtained from a variety of sites.

SI No	Reference	Located Sites	Oil Extraction Methods	Estimated Oil Yield (wt%) (Range)
1	[10,129,134,137]	India	Supercritical CO_2 extraction, Aqueous enzymatic extractions, Solvent extraction, Mechanical extraction	13.7–60
2	[187–189]	China	Solvent extraction, Supercritical CO_2 extraction	38.9–40.3
3	[190]	Tanzania	Mechanical extraction, Traditional extraction	22.02–26.15
4	[138,191–194]	Others (Ghana, Mexico, Brazil, Indonesia, Iranian)	Ultra-sound-assisted solvent extraction, Solvent extraction, Supercritical CO_2 extraction	31.6–59.3

Zhou et al. [195] investigated the transesterification process for Jatropha curcas utilizing nano-La_2O_3 as a solid catalyst. The produced catalyst demonstrated outstanding activity because of its high alkaline nature and large surface area. Under ideal circumstances, the yield reached 98%: 180 °C, 2 h of reaction, and a catalyst/oil weight ratio of 10%. Different Ni/Co catalysts were developed by Asikin-Mijan et al. [177] with multi-walled carbon nanotubes (MWCNTs). They deoxygenated Jatropha curcas oil in a hydrogen-free atmosphere using the developed catalyst. Ni/MWCNT, Co/MWCNT, and Ni-Co/MWCNT are the three developed catalysts. The Ni-Co/MWCNT catalyst has the best selectivity for C_{15}–C_{17} hydrocarbons. The ideal Ni-Co/MWCNT mixture of both Ni and Co was 20 wt%

and 10 wt%. The maintained catalyst yields a conversion rate of 76% and a green biodiesel selectivity of >60% for four trials.

It has been proven that oil extraction may be combined with simultaneous esterification/transesterification (reactive extraction) [135,136,196]. Lim et al. [196] took Jatropha oil seeds and deposited them in a reactor. The seeds were dried, crushed, sieved, and combined with methanol and n-hexane as co-solvents. At temperatures not exceeding 300 °C, pressures not exceeding 240 MPa, and without a catalyst, 100% oil extraction and 100% FAME production were recorded. Despite the remarkable outcomes, these circumstances were deemed to be excessive. Further research was carried out to see if alternative solvents could produce the same results at lower temperatures and pressures. Pentane, heptane, toluene, CO_2, and N_2 were co-solvents for the experiments. The results showed that a co-solvent substantially influenced the rate of extraction and conversion. A CO_2 co-solvent allowed the process to be carried out at 280 °C and 4 L/kg of methanol instead of 300 °C and 5 L/kg. As a result, reactive biodiesel extraction from oil seeds has many potentials. The following section discusses the integration methods for improving the efficiency of Jatropha fuel.

3.4. Integration Methods for Improving the Efficiency of Jatropha Fuel

Jatropha oil is used in different integrated techniques, including baseline scenarios [197]. The waste and by-products, water, and heat-power integration are the standard methods. The primary goal of every method is to understand the technical, economic, and environmental relations and their effects on various conditions. Lahijani et al. [198] revealed that the gasification-Fischer-Tropsch pathway, biofuel generation, and hydroprocessing were used in the integrated technology to produce high-performance fuel. Additionally, it converts Jatropha wastes into practical syngas.

The model also considers the generation of biofuels and their hydroprocessing into oil [199]. Another stage is waste and by-product integration. It has different stages, including mixing deoxygenation off-gas (CO, CO_2, H_2O, and excess H_2) into the crude syngas stream to improve the H_2: CO ratio and waste carbon monoxide. In this stage, incorporating wax and tar into the hydrotreatment and cracking processes is also carried out [200]. Moreover, the surplus water is recovered after the process. Finally, the heat and power integration method involves exothermic and endothermic reaction processes. Furthermore, about 5% of the gas stream exits the reforming reactor to establish necessary pressure in the system. Gas combustion occurs in a gas turbine unit for power generation only in fractionation. In other situations, streams are heated with natural gas shells and tube heaters [201–203].

M. Alherbawi et al. [108] developed a flow sheet that contains all integration techniques. In Figure 5, the upstream process is initiated by presenting the Jatropha fruit into a dehuller shell remover. The fruit's shell is removed through mechanical extraction force [204]. Before the gasification step, the oil is pumped to the hydroprocessing portion, and the fruit shells and seedcake are processed into a drier. An "RYield" reactor block replicates the drying step at 120 °C and atmospheric pressure, whereas the product yield is found by proximate analysis. The moisture outflow is sent to the water tank to produce synthetic gas dominated by hydrogen and carbon monoxide. This process is further subclassified as pyrolysis, oxidation, and reduction [205,206]. The gasifiers used in the process are classified as follows:

(1) Gasifying agent—steam gasifiers, air-blown and O_2 [207,208];
(2) Operating pressureatmospheric and pressurized [209];
(3) Fluid dynamics—updraft, downdraft, and fluidized-bed flow gasifiers [205].

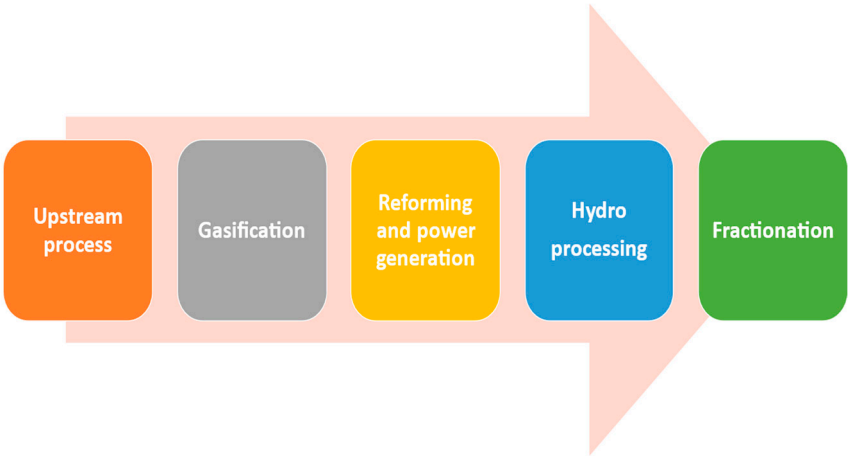


Figure 5. Flowsheet of an integrated system.

Compared to other processes, steam gasification has a higher energy efficiency and an optimum H_2:CO ratio for Fischer-Tropsch (FT) reaction [210]. An entrained gasifier is used under 1000 °C and atmospheric pressure with a steam-to-biomass ratio of 0.5 [211]. Before further processes, decomposition breaks down Jatropha solid leftovers into simpler components using two blocks: "RYield" and "RGibbs". In the "RYield" block, non-conventional components are converted to conventional components, such as sulfur, carbon, hydrogen, nitrogen, and oxygen. In the "RGibbs" block, all volatile carbons are converted to carbon monoxide and carbon dioxide; nitrogen and sulfur contents are converted to NH_3 and H_2S, with tar's help [212].

The overall system of the operating parameters is represented in Figure 5 and is an integrated flow sheet. The sub-systems are hydroprocessing, gasification, and gas to liquid. Corresponding unit operations for those subsystems are hydrogenation, deoxygenation, hydrocracking, and Isomerization. The different physical parameters related to the subsystems are mentioned in Table 8.

Table 8. Physical parameters for the sub-systems.

Process	Temperature (°C)	Pressure (Bar)	Hydrogen Load (wt% of Feed)	Catalyst	Liquid Hourly Velocity (LHSV) kg/hr.kg Catalyst
Deoxygenation	300	45	1	Ni/Al_2O_3	2
Hydrocracking	350	80	1	Ni/ZSM-5	1.84
Isomerization	180	20	-	$Pt/\gamma Al_2O_3$	1.2
Hydro process (Decomposition, Oxidation, and Reduction)	1000	1	-	-	-
Fischer-Tropsch	240	25	-	Co/Al_2O_3	-
Reforming	900	15	-	Ni/Al_2O_3	-

The main gasification reactions involved in the process are mentioned in [213] and is briefly shown in Table 9.

Table 9. The gasification reaction and process involved.

Gasification Reactions	Process
Biomass → Char + Tar + NH_3 + H_2S + H_2 + CO + CO_2	Pyrolysis
CO + $\frac{1}{2}$ O_2 ←→ CO_2	Oxidation
CH_4 + H_2O ←→ CO + $3H_2$	Methane reforming
C + $2H_2$ ←→ CH_4	Methanation
H_2 + $\frac{1}{2}$ O_2 ←→ H_2O	Production of stream
C + H_2O ←→ CO + H_2	Gasification of steam
C + CO_2 ←→ 2CO	Boudouard reaction
C + O_2 ←→ CO_2	Char combustion (Complete)
C + $\frac{1}{2}$ O_2 ←→ CO	Char combustion (Incomplete)
CO + H_2O ←→ CO_2 + H_2	Water-gas shift reaction

Next is the FT process. Here, reasonable to high temperature and pressure breaks the feed into monomers and then polymerizes them to produce long hydrocarbons. The chemical reactions in FT reactors are represented in Table 10 as follows:

Table 10. The chemical reaction and involved process.

Chemical Reactions	Process
nCO + (2n + 1)H_2 ←→ CnH(2n + 2) + nH_2O	Paraffin synthesis
nCO + (2n)H_2 ←→ CnH(2n) + nH_2O	Olefins synthesis
nCO + (2n)H_2 ←→ CnH(2n + 1)OH + (n − 1)H_2O	Alcohol synthesis

After completing the upstream and gasification process, reforming and power generation is the third main process. In the above process, the system includes a gas reforming unit to maximize liquid fuel output. Two reactors, operating in parallel, model the process at 900 °C and 15 bar, with a Ni/Al_2O_3 catalyst present and having a steam-to-carbon ratio of 1:4 [214]. The reaction is shown in Equations (6) and (7) as follows:

$$C_nH(2n+2) \rightarrow nCO + (2n+1)H_2 \quad (6)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (7)$$

The other process involved is hydroprocessing, which has three main parts: Hydrotreatment, Hydrocracking, and Isomerisation. The three essential steps of triglyceride hydrotreatment (deoxygenation) are the breakdown of triglycerides into three distinct features: fatty acids and propane, hydrogenation, and the removal of oxygen. The hydrotreatment is frequently carried out at high temperatures (300–4000 °C) with hydrogen gas at working pressures ranging from 30 to 90 bar. About 196 mL of hydrogen was required to convert 1 mL of Jatropha oil into paraffin. However, more hydrogen is necessary to keep the catalytic activity [215,216]. Propane, H_2O, CO_2, CO, and excess H_2 were processed along with the syngas stream and reformed. The chemical reaction of JFA (Jatropha fatty acid) saturation and deoxygenation is shown in Table 11 as follows:

Table 11. The chemical reaction of Jatropha's fatty acid saturation and deoxygenation.

(a) Hydrogenation	(b) Deoxygenation	(C) Decarboxylation	(d) Decarbonylation
$C_{18}H_{32}O_2 + H_2 \rightarrow C_{18}H_{34}O_2$	$C_{18}H_{36}O_2 + 3\ H_2 \rightarrow C_{18}H_{38} + 2\ H_2O$	$C_{18}H_{36}O_2 \rightarrow C_{17}H_{36} + CO_2$	$C_{18}H_{36}O_2 + H_2 \rightarrow C_{17}H_{36} + CO + H_2O$
$C_{18}H_{32}O_2 + 2\ H_2 \rightarrow C_{18}H_{36}O_2$	$C_{16}H_{32}O_2 + 3\ H_2 \rightarrow C_{16}H_{34} + 2\ H_2O$	$C_{16}H_{32}O_2 \rightarrow C_{15}H_{32} + CO_2$	$C_{16}H_{32}O_2 + H_2 \rightarrow C_{15}H_{32} + CO + H_2O$
$C_{18}H_{34}O_2 + H_2 \rightarrow C_{18}H_{36}O_2$	$C_{18}H_{34}O_2 + 3\ H_2 \rightarrow C_{18}H_{36} + 2\ H_2O$	$C_{18}H_{34}O_2 \rightarrow C_{17}H_{34} + CO_2$	$C_{18}H_{34}O_2 + H_2 \rightarrow C_{17}H_{34} + CO + H_2O$

The following process is hydrocracking and isomerizing. Since the catalyst acid activity is triggered at high temperatures, hydrocracking frequently necessitates more pressure and temperature than hydrotreatment. While fuel selectivity improves as operating pressure

rises. Moreover, several catalyst systems for the hydrocracking process have been tried previously, including transition metals [217]. The basic materials used are SAPO-11, ZSM-5 and MCM-41. Because of its excellent stability and low cost, ZSM-5 is utilized industrial level for the hydrocracking process; isomerization is required [215,217]. The process is simulated using an "RStoic" reactor [218]. At 180 °C and 20 bar, a Pt/Al_2O_3 catalyst system is employed, considering an LHSV of 1.2 kg/hr.kg of catalyst. Paraffin with a carbon number of 6–8 has been transformed into a branching structure; the other paraffin has had minimal isomerization and is not specified in the model. The downstream process is the final process. Initially, the stream passed over the three stages of the flash unit at the conditions of 60 °C and 20 bar to distinct the gaseous phase and moisture residue presence. Then the procured liquid hydrocarbons were processed by18-stage distillation column to generate the fuels such as gasoline, diesel, aviation fuel, and gases.

Model and experimental works are validated in the literature using similar operating conditions and input characteristics from Doherty et al. [219]. The impact of the most important operational factors (full integration), such as hydrogen load and pressure conditions of the major stages, was investigated. In addition to that, steam to biomass ratio and temperature role were also analyzed. The overall hydrogen load varied by varying the biomass weight by 0–4%, while the steam-to-biomass ratio varies by (0–1.5). In addition, the temperature for the hydroprocessing and gasification phases was adjusted. Furthermore, the pressure in the hydroprocessing steps was adjusted (10–90 bars). It improved the overall efficiency of the fuel.

Jatropha will be the upcoming jet fuel [108]. According to the model, 49% of Jatropha biomass can be turned into liquid fuels; 64.5% of liquid fuel is generated for jet biofuel, and 31.5% is biomass feed. Compared to processing Jatropha oil alone, these statistics imply a roughly 88% increase in Jet biofuel output. In addition, 7% wt transformed into a usable fuel gas from Jatropha. While the produced electricity in their study can almost entirely meet the system's power requirements (97.6%).

Furthermore, according to Alherbawi et al. [108], the system is a water-independent operation with a substantial water surcharge. The proposed innovative integrated route is a viable option for JBF production because it uses Jatropha as a feedstock and can accept a variety of additional oil-bearing energy crops and oil-solid waste integrated refineries. Different oil-bearing crops can be tested to better understand the best feedstock for JBF production in integrated systems.

The energy efficiencies claimed in the literature for the various JBF production paths varied owing to the various quantification methodologies and efficiency criteria. This analysis employs methods that account for direct and indirect energy inputs and outputs throughout the lifespan of JBF manufacturing [220]. Direct energy streams are quantified using the lower heating value (LHV), whereas indirect energy streams (i.e., fertilizers) are estimated using all resources input during the production's lifespan. The energy efficiency of a production system is a ratio of the total energy demand to the energy output of Jet Biofuel (MJ/MJ JBF) [221]. The oil has a high percentage of mono-unsaturation in fatty acid composition. Therefore, it is an excellent non-edible feedstock for biodiesel production. The mono-unsaturation values of non-edible Jatropha oil [120,182] are shown in Table 12. The next section, followed by Table 12, discusses the challenges in producing sustainable biodiesel from Jatropha in different countries.

Table 12. Mono-unsaturation values of non-edible Jatropha oil.

Fatty Acid	Jatropha Curcas Oil (*Jatropha curcas*)
Oleic 18:1	44.70
Monounsaturated	45.40
Saturated	21.60
Polyunsaturated	33.00
Margaric 17:0	0.10
Heptadecenoic 17:1	-
Stearic 18:0	7.00
Linoleic 18:2	32.80
Acid values (g/kgKOH)	35.80
Palmitic 16:0	14.20
Myristic 14:0	0.10
Linolenic 18:3	0.20
Arachidic 20:0	0.20
Palmitoleic 16:1	0.70

3.5. Challenges in Producing Sustainable Biodiesel from Jatropha

Even though Jatropha has many advantages, it has some challenges, which stunt the growth of Jatropha cultivation. This section discusses the challenges in producing Jatropha in different regions worldwide. Balat et al. [222] investigated the main problems of Jatropha cultivation in the Nicaragua region and found that there was a lack of enthusiasm from farmers, inadequate project promotion, a lack of skilled technical advisors, and a lack of market for oil and byproduct sales. Castro Gonzales et al. [124] focused their study on Brazil and found that the country has inadequate agronomic practices, such as improper seedling management, excessive weed development, and a lack of pruning. In Costa Rican areas, seed yield is meager and has many financial and organizational problems for Jatropha production, whereas Guatemala has limited genetic improvement, poor seed estimation, and market problems for seed and oil selling; this was reported by Balat et al. [222]. They also studied the challenges in El Salvador, where inadequate plantation management, having lower seed yield, absence of risk share between farmers and investors, poor technical advisor for Jatropha farming, and no information about estimated oil and seed yields were all reported. Mischler et al. [223] conducted their studies in Bolivia; they found that shifting the Jatropha cultivator to other areas was a primary problem. The absence of local biodiesel producers for commercial use of locally harvested seeds is another challenge. Ghana region has Limited cultivation and management experience, poor business planning, institutional barriers, limited community participation, unfair compensation practices, obstacles posed by civil society, and unconstructive involvement of chiefs, and these were addressed by Sushma et al. [224]. In Kenya, Ahmed et al. [225] mentioned that monoculture and intercropping were not sustainable due to conflict with food supply, but Jatropha planted as a hedge was found to be successful. The biggest challenges in the Senegal region were found by Openshaw et al. [226], and that was its technical and economic factors. Inadequate information on the management and growth of Jatropha and a limited marketing opportunity for Jatropha products was also an issue. South African regions have intensive labor to harvest (regular cultivation of Jatropha was not profitable), rainfall was the primary determinant for Jatropha seed yield, and lack of knowledge about the plant among stockholders was another challenge [226]. The problems in Tanzania were the absence of governmental promotion; structural, infrastructural, and logistic problems; lower seed and oil price; technical skill and knowledge gaps, and limited local research and cultural barriers [227]. Abdullah et al. [228] studied the Togo region and found several problems involved in the slow growth of Jatropha: political pressure, poor microeconomic environment, lower price of seed and oil, and poor agronomic practices. Nygaard et al. [229] found that China, in 2008, had high volume seed requirements, high capital needs, market risks, limited learning levels, inadequate knowledge sharing between Jatropha actors, weak public support and development, and reduced access to technical and managerial information, resulting in decline production of the crop. The main problems in

India were the conflict between cultivators and farmers, bigger expectations from farmers than the reality, landholding issues, limited water accessibility for irrigation, and lower seed yield in the selected wasteland [222,230,231]. The Ethiopia region has a land resource conflict, lower seed production on moisture stressed and degraded land, technical and knowledge gaps, limited follow-up and support from the government, absence of clear policy on Jatropha investment, little participation of stockholders, ambitious biodiesel production plan, limited research on the performance and genetic improvement of Jatropha varieties, poor agronomic practices, weak management system, allocation of improper land for Jatropha cultivation, and computation between food and fuel [232,233]. In Rwanda, there are a lack of improved seeds, land shortage, poor soil quality, poor seed yields, high seed production cost, lower seed selling price due to lack of reliable markets, and a low level of sensitization among stockholders [234,235]. The challenges faced during Jatropha cultivation in Mexico was investigated by Soto et al. [131]. The country faced deterioration in the perception of Jatropha profitability, on-payment of expected subsidies, and the wealth position of the household. Moreover, the pest and disease damage played a significant role in abandoning Jatropha cultivation. The other related studies and discussions are discussed in the next section.

3.6. Other Studies Related to Jatropha

Shahinuzzaman et al. [236] discussed Jatropha's medical and cosmetic soap production. Non-edible Jatropha oil can produce many oil products and soap to reduce edible oil consumption. Jatropha's antibacterial properties could be used to make soap for both medicinal and cosmetic purposes. Basically, the detoxification process for hazardous Jatropha oil uses adsorption. As a result, 99% of phorbol esters can be eliminated. In other words, the amount of phorbol found in seed oil was 2.70 mg/g, which was higher than the 0.09 mg/g permitted limit. The Jatropha soap meets Bureau of Indian Standards for quality. The chemical composition of the Jatropha plant and the underutilized Jatropha seed oil is studied [237]. The plant's physiochemical properties for soap and cosmetic production were investigated [238]. Many authors like Becker et al. [239], Verma et al. [240], and Verma et al. [241] mentioned the possibility of utilizing Jatropha as a cosmetic product and for the making of soaps.

Abobatta et al. [242] discuss using Jatropha to produce biogas and organic fertilizers [242]. Vega-Quirós et al. [243] studied the plant's toxicity utilizing the single nucleotide polymorphism (SNP) mechanism of Jatropha curcas associated with the phorbol ester content. They ended up giving multiple uses of the plant. For example, the plant can obtain biofuel, and the remnants can be utilized as animal feed by reducing its toxicity [243]. Alqahtani et al. [244] found that Jatropha pelargoniifolia (JP), a medicinal plant, is widely used in traditional medicine owing to its broad range of therapeutic activities. They conducted experiments, including the preparation, characterization, and in vitro-in silico biological activities of Jatropha extract loaded with chitosan nanoparticles [244].

4. Conclusions

The review of Jatropha's rapid developments and future opportunities as a renewable source of biofuel can be summarized as follows:

- According to the general agreement on the results, Jatropha will be a successful alternate biofuel for fossil fuels in the future. The oil content of Jatropha is high, and the production time is less than other non-edible crops. The unique integrated system, including Fischer-Tropsch, hydro-processing, gasification, and reforming, will help the fuel to improve its efficiency.
- From the major observations of the researchers, a variety of Jatropha production scenarios utilizing various integration approaches such as technology integration, wastes and byproducts integration, and water, heat, and electricity integration will increase the productivity of the fuel.

- Biofuel can even be considered jet fuel as it meets the criteria. The integrated pathway mentioned in this review is believed to be an alternative for the production of JBF. Implementing this integrated approach can improve traditional process efficiency and contribute to long-term feedstock use.
- This review reveals that the properly integrated system uses whole Jatropha fruit to generate a cost-competitive, high-yielding, and performance biofuel.
- Methods like mechanical pressing are conventional and have to be modified. An introduction of suitable catalysts and enzymes to improve the reaction rate is essential.
- However, the current failure is due to the lack of excellent commercial varieties of Jatropha plant, poor yield, disease-resistant crops, lack of basic research, and general theoretical assumptions without scientific and technical support. Efficient oil extraction methods and solvent elimination must be introduced to obtain a better result.
- Methods like mechanical pressing are conventional and have to be modified. An introduction of suitable catalysts and enzymes to improve the reaction rate has to be introduced.
- By-products like seed oil cake and glycerin provide a new commercial opening to improve the profit. It will attract more people to the field.
- Genetic engineering and biotechnology are the two main aspects of crop development in the future, and they can offer improved immunity and weed resistance.

From the analysis, it can be concluded that Jatropha holds brilliant promise in the field of biofuels, particularly regarding process efficiency and product quality. There are few works on Jatropha, but it is far behind when compared with other crops' research. As a result, researchers have to concentrate more on developing female flowers with a reduced toxin rate and higher immunity for better yield. Therefore, an extensive study is required to understand the ability to produce high-quality fuels from the Jatropha crop and will be performed in future research.

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