Chapter 23
Production of Biodiesel and Nontoxic *Jatropha* Seedcakes from *Jatropha curcas*

Novizar Nazir, Djumali Mangunwidjaja, and M.A. Yarmo

Abstract Different processes for transesterification of *Jatropha* biodiesel production are currently available. Among them are homogeneous catalysis, heterogeneous catalysis or enzyme catalysis alcohol treatment, supercritical alcohols, lipase-catalyzed in situ reactive extraction, and homogenous-catalyzed in situ transesterification. High cost of biodiesel production is the major impediment to its large-scale commercialization. Methods to reduce the production cost of biodiesel must be developed. One way to reduce production costs is to increase the added value of protein-rich *Jatropha* seedcakes, the by-product of oil extraction, through detoxification process. Development of integrated biodiesel production process and detoxification process results in two products, namely biodiesel and protein-rich seedcakes that can be used for animal feed. This chapter provides information concerning *Jatropha* potential, current development of biodiesel and nontoxic seedcakes production from *Jatropha curcas* and implication of biodiesel production on global warming, environmental impact, and energy efficiency.

N. Nazir (✉)
Faculty of Agricultural Technology, Andalas University, Padang, West Sumatra 25163, Indonesia
e-mail: nazir_novizar@yahoo.com

D. Mangunwidjaja
Department of Agroindustrial Technology, Bogor Agricultural University,
Bogor, West Java, Indonesia

M.A. Yarmo
School of Chemical Science and Food Technology,
Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia

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1 Introduction

Biodiesel, an alternative diesel fuel, is made from renewable biological sources such as vegetable oils and animal fats. It is a clean combustion, biodegradable, nontoxic fuel and has low emission of carbon monoxide. These conditions give environmental benefits. Research found that the use of biodiesel has potential to reduce pollution levels and possible carcinogens ([12, 20, 22, 70, 92, 97]). In addition, practically biodiesel contains no sulfur and has good lubrication properties [38, 50, 70].

One source of vegetable oils which has good prospects to be developed as a raw material of biodiesel is *Jatropha curcas.* The oil which is produced from *Jatropha* has potential as an alternative fuel and not derived from food crops like corn, palm, soybean, etc. Thus, it is not competitive with food consumption.

The genus *Jatropha* belongs to the Euphorbiaceae family, consisting of about 170 species. Linnaeus [47] is the one who firstly gave the name *Jatropha* L. to the *Jatropha* in "Species Plantarum" and this is still acknowledged today. The genus name *Jatropha* is derived from the Greek word *jatr'os* (physician) and *troph'e* (food), which indicates its use as being edible or medicinally useful [35].

Jatropha was originated from tropical America, but now it grows well in many parts of tropic and subtropic regions in Africa and Asia. These small trees can grow to 20 ft high under favorable conditions in areas with low to high rainfall (200–1,500 mm/year). In low rainfall areas and in prolonged rainless periods, the plant let its leaves fall as a response to drought [64].

The fruit of *Jatropha* can be used for various purposes including fuel. The seeds *contain* viscous oil, which can be used as a diesel. In addition to being a source of oil, *Jatropha* also provides seedcake, by-product of oil extraction process, that serves as a highly nutritious and economic protein supplement in animal feed, if the toxins are removed [13]. The purpose of this review is to provide information concerning its potential and current development in the field of production of biodiesel and nontoxic seedcakes from *J. curcas* and the implication of biodiesel production on global warming, environmental impact, and energy efficiency.

2 Chemical and Physical Aspects of *Jatropha curcas*

2.1 Chemical Composition of Jatropha Kernel

The dry fruit husk of *Jatropha* represents around 35% of the fruit and host 1–4 seeds. Individual seeds of *Jatropha* have an average weight of 0.40 g to over 1 g. The seeds have hard, black outer shell containing a white kernel. The proportion of shell and kernel range from 350 to 400 g/kg and from 600 to 650 g/kg, respectively. The seeds contain about 300–350 g/kg oil which can be used directly as fuel or, in its transesterified form, as a substitute for diesel [54]. Figure 1 illustrates the whole plant of *J. curcas*, its parts, and its average proportion on dry weight basis starting with 1,000 kg of fruit.

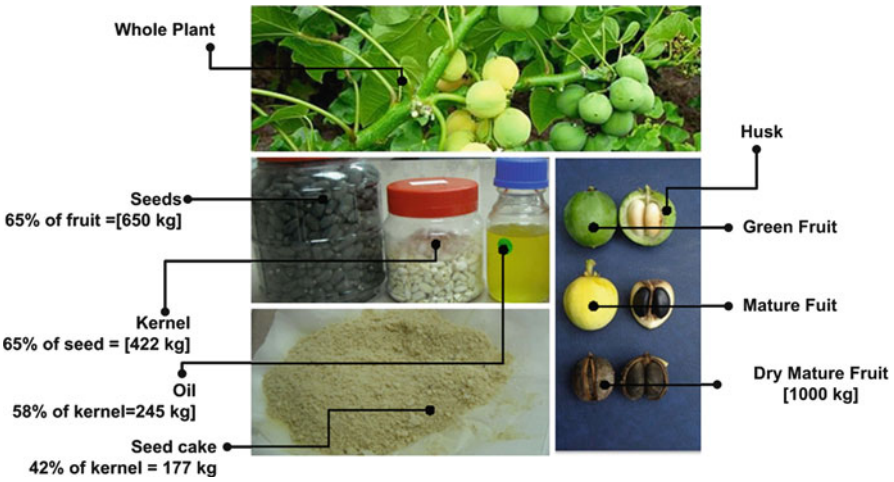

Fig. 1 Whole plant of *Jatropha curcas*, its parts, and the average proportion on dry weight basis starting with 1,000 kg of fruit

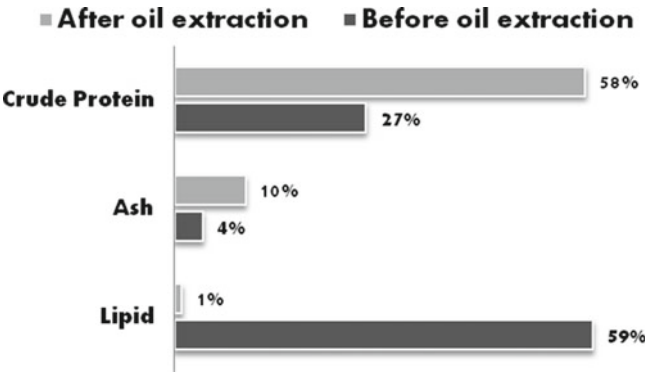

Fig. 2 Chemical composition of *Jatropha* kernel before oil extraction and after oil extraction

Assuming that 1 ha of land consisting of 2,500 *Jatropha* plants and each tree has 40 branches, and each branch has 3 bunches of fruit/year, and each cluster could produce 10–15 fruits/bunch (30–45 seeds), then the number of seeds that would be generated from area of 1 ha is 2,500 × 40 branch × 3 bunches × (10–15) fruits × 3 seed = 9,000,000 – 13,500,500 seeds. If 1 kg consists of 2,000 dry seeds, the production of *Jatropha* per hectare per year would be 4.5–6.75 tons of dry seeds/ha. Assuming that an average seed yield of 5 tons/ha (2 tons/acre) could be achieved, estimated theoretical yield of biodiesel is 750 kg/acre and its seedcake product is 500 kg/acre.

Kernel of *Jatropha* contains 27–32% of protein, 58–60% of oil, and 3.6–5.0% of ash content. After the oil extraction of kernel (fully defatted), *Jatropha* seedcake will have a protein content of 55–60%, lipid content of 0.6–1.5%, and ash content of 9.6–12.1% (Fig. 2), with high essential amino acid composition (Table 1)

Table 1 Amino acid composition (g/16 g nitrogen) of kernel meal from toxic, nontoxic genotypes, and protein concentrate obtained from *Jatropha* seedcake

Amino acid	Protein concentrate[a]	Toxic variety [55]	Nontoxic variety [55]	Soybean meal [55]
Essential amino acids				
Methionine	1.66	1.91	1.76	1.22
Cystine	1.34	2.24	1.58	1.70
Valine	5.18	5.19	5.30	4.59
Isoleucine	4.47	4.53	4.85	4.62
Leucine	7.08	6.94	7.50	7.72
Phenylalanine	5.42	4.34	4.89	4.84
Tyrosine	3.20	2.99	3.78	3.39
Histidine	3.51	3.30	3.08	2.50
Lysine	3.00	4.28	3.40	6.08
Arginine	14.16	11.80	12.90	7.13
Threonin	3.56	3.96	3.59	3.76
Tryptophan	1.21	1.31	ND	1.24
Nonessential amino acids				
Serine	5.23	4.80	4.82	5.67
Glutamic acid		14.68	15.91	16.90
Aspartic acid	12.50	9.49	9.92	11.30
Proline	5.45	4.96	3.80	4.86
Glycine	5.10	4.92	4.61	4.01
Alanine	5.47	5.21	4.94	4.23

ND not determined

[a]Proteins from the seed cakes were solubilized at pH 11 for 1 h at 60°C and the precipitation of these proteins was done by lowering the pH to 4 [54]

[53, 55, 56]. Composition of the essential amino acid of *Jatropha* (except lysine) confirms identical pattern with the existing amino acids in soybean [91].

2.2 *Fatty Acid Composition and Physicochemical Properties of Jatropha Oil*

Table 2 shows the fatty acid composition of *Jatropha* oil containing of 23.6% of saturated fatty acids mainly from palmitic, stearic, and myristic acid and 76.4% of unsaturated fatty acids which consist of mainly oleic, linoleic acid, and palmitoleic. The physicochemical properties of *Jatropha* oil which is extracted from the seeds of different origin viz., Malaysia, Indonesia, Thailand, Nigeria, Brazil, are given in Table 3.

The ability of fluid to pump and flow within an engine is determined by its viscosity. The desired viscosity of diesel fuel ranges from 1.9 to 4.1 cSt. Transesterification is one of the recognized and efficient methods to reduce the viscosity of the vegetable oil to make it suitable as a biodiesel [25].

Table 2 Fatty acids exist in *J. curcas* oil

			wt.%					
Generic name	Formula	Structure[a]	Foidl et al. [26][b]	Foidl et al. [26][c]	Gubitz et al. [29]	Haas and Mittelbach [31]	Azam et al. [11]	Average
Capric	$C_{10}H_{20}O_2$	C10:0	0.1	0.1				
Lauric	$C_{12}H_{24}O_2$	C12:0						
Miristic	$C_{14}H_{28}O_2$	C14:0	0.1	0.1	0–0.1		1.4	
Palmitic	$C_{16}H_{32}O_2$	C16:0	15.1	13.6	14.1–15.3	14.2	15.6	
Stearic	$C_{18}H_{36}O_2$	C18:0	7.1	7.4	3.7–9.8	6.9	9.7	
Arachidic	$C_{20}H_{40}O_2$	C20:0	0.2	0.3	0–0.3	–	0.4	
Behenic	$C_{22}H_{44}O_2$	C22:0	0.2	–	0–0.3	–	–	
Miristoleic	$C_{14}H_{20}O_2$	C14:1						
Palmitoleic	$C_{16}H_{30}O_2$	C16:1	0.9	0.8	0–1.3	1.4	–	
Oleic	$C_{18}H_{34}O_2$	C18:1	44.7	34.3	34.3–45.8	43.1	40.8	
Linoleic	$C_{18}H_{32}O_2$	C18:2	31.4	43.2	29.0–44.2	34.4	32.1	
Linolenic	$C_{18}H_{30}O_2$	C18:3	0.2	–	0–0.3	–		
Saturated			22.8	21.7	22.6	23.7	27.1	23.6
Unsaturated			77.2	78.3	77.4	76.3	78.9	76.4

[a]Number of carbon chain:number of double bond
[b]Variety of Caboverde
[c]Variety of Nicaragua

Table 3 Physicochemical properties of tropical *J. curcas* oil from different origin

Properties	Malaysia [73]	Indonesia [61]	Thailand [25]	Nigeria [8]	Brazil [21]
Density	0.90	0.90	0.90		0.92
Viscosity(cSt)	47.50	53.94	39.20		30.69
Iodine value	193.55	200.66	216.09	105.20	
Peroxide value	1.90				
Acid value	2.38	9.91		3.50	8.45
Free fatty acids (FFA) (%)	2.23			1.76	
Saponification value	197.8	183.2		198.85	

The iodine value is a measurement for the unsaturation level in fats and oils; a high iodine value is an indication of the presence of high unsaturation levels in the oils [43]. The high iodine value of *Jatropha* oil is due to the presence of high amounts of unsaturated fatty acids such as oleic and linoleic acid (Table 3).

The peroxide value determines the formation of hydro peroxides (primary oxidation products) [30]. This can be associated with the presence of higher amounts of polyunsaturated fatty acids such as linoleic acid (Table 3). The instability of any oil is directly related to the level of unsaturation.

Acid value ("acid number" or "acidity") is the mass of potassium hydroxide (KOH) in milligrams that is required to neutralize 1 g of chemical substance.

The acid value of edible oils or their corresponding esters indicates the quantity of free fatty acids (FFA) and mineral acids (negligible) present in the sample.

Fatty acids can be bound or attached to other molecules such as triglycerides or phospholipids. When they are not attached to other molecules, they are known as "free" fatty acids (FFA). FFA is detrimental to the biodiesel-making process. For biodiesel production purposes, FFA content of *Jatropha* oil indicates two types of *Jatropha* oil: low FFA oil (FFA<2.5%) and high FFA oil (FFA>2.5%) [61]. A high saponification value indicates that *Jatropha* oil possesses normal triglycerides and may be useful in the production of liquid soap and shampoo [30].

2.3 Jatropha Seeds and Its Toxicity

Even though the *Jatropha* seeds are rich in oil and crude protein, they are highly toxic and unsuitable for human or animal consumption. The toxic nature of oil and *Jatropha* seedcake has been demonstrated in several studies [1, 2, 5, 6, 46]. The toxic or irritant compounds found in *Jatropha* seedcake are phorbol ester (2.43 mg/g kernel in toxic varieties and 0.11 mg/g kernel of nontoxic varieties), lectin (102 mg/g kernel in toxic varieties and 51 mg/g kernel on nontoxic varieties), trypsin inhibitor activity (21.2 mg inhibitory/g meal in toxic varieties and inhibition of 26.5 mg/g meal in nontoxic varieties), phytate (9.7% in the *Jatropha* seedcake of toxic varieties and 8.9% in nontoxic varieties), and Saponin (equivalent to 2.3% diosgenin in *Jatropha* seedcake of toxic varieties and 3.4% in nontoxic varieties).

Curcin, a toxic protein isolated from the seeds, was found to inhibit protein synthesis in in vitro studies. The high concentration of phorbol esters in *Jatropha* seed has been identified as the main toxic agent of *Jatropha* which is responsible for the toxicity ([52, 4]. Several cases of poisoning *J. curcas* in humans after consumption of seeds by chance have been reported with symptoms of dizziness, vomiting, and diarrhea and in extreme conditions has been noted even cause death [13].

Lectin is also predicted to cause toxicity in *J. curcas* [16]. However, Aderibigbe et al. [3] and Aregheore et al. [9] show that the lectin is not the main toxic compounds in *Jatropha* seedcakes. Successful utilization of *Jatropha* seedcakes cannot be achieved without the removal of all of toxic and antinutritional compounds. Toxic-removal processes for seedcakes of low FFA *Jatropha* can be done directly by in situ transesterification [61] and through detoxification process using heat and chemical treatments for seedcakes of high FFA [9, 68].

3 *Jatropha* Oil as Feedstock of Biodiesel Production

The growing demand for lower-cost, nonfood, nonrainforest-based feedstock for biodiesel provides new opportunities and stimulate fresh investment in the production of lower-cost, alternative feedstock such as *Jatropha*. The governments in South Asia and Africa have identified between 20 and 50 million ha of suitable land

for *Jatropha* cultivation. Indonesia has identified nearly 23 million ha of *Jatropha* land potential. One hectare of *Jatropha* can produce between 1.5 and 2.5 tons of seed oil. *Jatropha* is now becoming one of the prime contenders for biodiesel feedstock supply in the near future [87]. This is due to the expansion of commercial-scale *Jatropha* production from India to Africa, Southeast Asia, and Latin America and to pilot programs and larger-scale ventures in China, Central Asia, South/Central America, and southern parts of the USA.

A variety of equipment is available to obtain oil from the seeds. The oil can be extracted mechanically using a press (ram, hydraulic, or screw) or chemically using organic solvents or water [12, 26, 65], three phase partitioning (TPP) extraction method [76], and supercritical extraction method [97].

The objective of oil preparation is to find an efficient and effective method in extracting oil from *Jatropha* seed. Technique of TPP with enzyme pretreatment and sonication constitutes an efficient procedure to obtain oil from *Jatropha* seed kernels. This technique can extract 97% oil within 2 h [77]. Extraction using ethyl acetate and methyl acetate is better than using hexane [83]. It was found that Gas-Assisted Mechanical Expression (GAME) process in *Jatropha* oil extraction is capable of reaching yields up to 30 wt.% higher than conventional expression under the same conditions [96].

3.1 Mechanical Press Extraction

In Indonesia, *Jatropha* oil is usually extracted by hydraulic press and screw press at 60°C heat treatment. The yield of *Jatropha* oil using hydraulic press method at maximum pressure of 20 tons is 47.2% and the oil extraction is done twice [84, 85].

In Tanzania presently, the *Jatropha* oil is obtained only mechanically with a ram press or a screw press, that is a small hand-press [89]. With the ram press method, the seeds are poured by giving a pressure on the seeds. About 5 kg of seed is needed to obtain 1 L of oil. The oil is extracted and then dripped into a container. The extraction rate of this press is quite low as the seedcake, which is left after the pressing, still contains part of the oil.

Larger expellers and screw presses which are run by an engine can also be used. The screw which turns continuously transports the seeds from one side of the press to the other while squeezing out the oil. The extraction rate of this press is higher because more oil is extracted from the seeds; the cake residue is also much dryer. The capacity of this screw is higher than that of the ram press. For example, the Sayari oil expeller, which is used in Tanzania, has a capacity of about 20 L/h (60 kg/h) and can extract 1 L of oil from 3 kg of seeds. The larger screw expellers, like Chinese expellers, can extract about 50 L/h (150 kg/h). After the oil is expelled, it is filtered by letting it stand for some times or pouring it through a cloth [89].

3.2 Aqueous and Solvent Extraction

Aqueous oil extraction (AOE) is a method in which *Jatropha* seeds are cracked and the shells are carefully removed. Shah et al. [78] used *Jatropha* kernels for oil extraction. The suspension was prepared with powdered (obtained by using a homogenizer) *Jatropha* kernels in distilled water, and then was incubated at desired temperature with constant shaking at 100 rpm for specified time period. The upper oil phase was collected after a centrifugation at 10,000 × *g* for 20 min. Enzyme-assisted AOE was performed similar to AOE. The difference is that the preparations, i.e., Protizymee, Cellulase, Pectinex Ultra SP-L, Promozyme, as well as mixture of all these enzymes, were added after the pH of the suspension was adjusted. The amounts of oil obtained were calculated as the percentage of total oil present in *Jatropha* kernels.

It is found that the use of ultrasonication as a pretreatment before aqueous oil extraction and aqueous enzymatic oil extraction is useful in the case of extraction of oil from the seeds of *J. curcas* L. [78]. The use of ultrasonication for a period of 10 min at pH 9.0 followed by AOE resulted in a yield of 67% of available oil. The maximum yield of 74% was obtained by ultrasonication for 5 min followed by aqueous enzymatic oil extraction using an alkaline protease at pH 9.0 (44 g oil/100 g *Jatropha* kernels was taken as 100% recovery). Use of ultrasonication can also reduce the process time from 18 to 6 h [78].

To obtain an optimized condition for an extraction using microwave is by using petroleum ether as the solvent, with the ratio of seed powder to solvent is at 1:3. It is done under a microwave power of 810 W for a total radiation time of 5 min [97]. The extraction rate was 31.49% with the oil product containing 5.22 mg/g of acid number and 8.78 meq/g of peroxide value. For the ultrasonic method, hexane was used as the solvent and the ratio of seed powder to solvent was 1:7; the soaking time applied is 18 h and the sonication is 0.5 h. The extraction rate was 37.37% containing 5.91 mg/g of acid number and 8.37 meq/g of peroxide value in the final oil product [97].

Alkyl acetates, especially methyl acetate and ethyl acetate, are important chemicals and suitable solvents for seed oil extraction which are assisted by Novozym 435 [83]. The results were compared to those obtained by extraction with *n*-hexane. Ground seeds were mixed with methyl acetate or ethyl acetate in screw-caped glass vials. And, 30% (w/w) of Novozym 435 based on theoretical oil content was added. The reactions were carried out at 50°C and 180 rpm for 6 h in a shaker which was fitted with a thermostat. After filtration, the ground seed mixture was mixed with another solvent and then extracted at the same condition for another 2 h. The two filtrates were pooled and centrifuged at 17,400 × *g* for 10 min; the supernatant was collected into a round bottom flask and the solvent was evaporated using a rotary evaporator. The oil content in g/100 g was 54.90% (*n*-Hexane), 55.92% (Methyl acetate), and 56.65% (Ethyl acetate) [83].

3.3 Three Phase Partitioning Extraction Method

TPP is a method which is carried out by cracking the *Jatropha* seeds and removing the shells; the kernels obtained are used for slurry preparation [76]. The slurry, with pH adjusted to the desired value with 0.1 N NaOH or 0.1 N HCl, was prepared by grinding the seed kernels in distilled water. Ammonium sulfate in an appropriate amount was added and vortexed gently; an appropriate amount of *tert*-butanol was added. Then, the slurry was incubated at 25°C for 1 h for the three phase formation. The three phases were then separated by centrifugation at 2,000 × *g* for 10 min. To obtain the oil, the upper organic layer was collected and evaporated on rotary evaporator (under reduced pressure at 50°C, for 5 min) [76].

Combining a recently developed technique of TPP with enzyme pretreatment and sonication may constitute an economical or efficient procedure for obtaining oil from *Jatropha* kernels [74]. This method only takes about 2 h. TPP has been evaluated for extraction of oil from *Jatropha* seeds. This process consisted of simultaneous addition of *t*-butanol (1:1, v/v) and 30% (w/v) ammonium sulfate to the slurry prepared from *Jatropha* seed kernels. Combination of sonication and enzyme treatment with a commercial preparation of fungal proteases at pH 9 resulted in 97% oil yield within 2 h [74].

3.4 Supercritical Carbondioxide Extraction Method

Supercritical Carbondioxide Extraction (SCE) is a process for the production of oil with high yields that do not use organic solvents. In this process, the oil is dissolved in CO_2 and extracted from the plant material [95]. SCE method developed by Yan et al. [96] resulted in the actual extraction rate 37.45%; the final oil product contained 0.79 mg/g of KOH and 3.63 meq/g of peroxide value. Here, seeds of *J. curcas* were collected and powdered. The extraction pressure was 43 MPa, temperature for the extraction was 45°C, the flow rate of CO_2 was 20 kg/h, and the extraction time was 80 min. Even though the cost of supercritical extraction methods was higher, the oil quality was the best and refining was not needed [96].

3.5 Gas-Assisted Mechanical Expression

GAME is another potential alternative process for the production of oil with high yields which do not use organic solvents. In this process, CO_2 is dissolved in the oil contained in the seeds before pressing the seeds [93]. It was found that at the same effective mechanical pressure (absolute mechanical pressure minus the actual CO_2-pressure), the liquid content was the same in both conventional and GAME press cakes. The liquid in the GAME press cake was saturated with CO_2 (typically

20–50 wt.%), reducing the oil content compared to the conventional cake by the same amount. The contribution of this effect increased with increasing solubility of the CO_2 in the oil. Furthermore, the dissolved CO_2 reduced the viscosity of oil by about an order of magnitude [93], which could increase oil extraction. Some additional oil was removed by entrainment in the gas flow during depressurization of the cake.

GAME has some advantages compared with conventional pressing. The first advantage of GAME is the increased yield at lower mechanical pressure. Compared with supercritical extraction, the amount of CO_2 that has to be recycled is reduced by two orders of magnitude from typically 1 kg of CO_2/kg of seeds [93] to 100 kg of CO_2/kg of seeds [69]. Therefore, the energy and equipment cost for the solvent recycle can be reduced. Compared with SCE, the second advantage of GAME is CO_2-pressure required is low, which is approximately 10 MPa. In contrast, for SCE extraction, pressures of 40–70 MPa are not unusual ([69]; Rosa et al. 2005). These two effects provide a significant reduction in the energy requirements for recycling and repressurising the CO_2. Additionally, some reports in literature suggest that the use of CO_2 at 7–20 MPa has a sterilizing effect on the substrates [80, 94]; this may be a beneficial side-effect of the GAME process.

The general applicability of the GAME process to enhance the oil recovery from oilseeds was shown by pressing experiments for sesame, linseed, rapeseed, *Jatropha,* and palm kernel by Willems et al. [95]. It was proved that GAME was capable of reaching yields that were up to 30 wt.% higher than conventional expression under the same conditions. Despite the lower yields for hulled seeds in conventional expression, GAME yields for hulled and dehulled seeds were very similar. The oil yields obtained for GAME increased with increasing effective mechanical pressure; the yields were the highest at a temperature of 100°C. These effects were similar to conventional expression. With CO_2-pressure up to 10 MPa, the oil yield increased significantly. However, increasing the CO_2-pressure above 10 MPa did not significantly increase the oil yield.

4 Production of Biodiesel

The method commonly used for production of biodiesel is the transesterification of vegetable oils with methanol, using alkali, acid, or enzyme catalyst. Transesterification, also called alcoholysis, is the reaction of triglycerides with alcohols to generate, for example, methyl or ethyl esters and glycerol as a by-product. Usually a catalyst is used to improve the reaction rate and yield. The reaction requires excess of alcohols to improve the efficiency of the transesterification process [54].

There are important variables that affect the yield of biodiesel from transesterification; they are: reaction temperature, molar ratio of alcohol and oil, catalyst, reaction time, presence of moisture and FFA, and mixing intensity [15, 77, 81]. The rate of reaction is strongly determined by the reaction temperature. However, given enough time will help the reaction proceed to near completion even

at room temperature. The reaction is commonly conducted close to the boiling point of alcohol at atmospheric pressure [77].

It is observed that the stoichiometry of the transesterification reaction needs 3 mol of alcohol/mol of triglyceride to yield 3 mol of fatty esters and 1 mol of glycerol. To shift the transesterification reaction to the right, it is necessary to use a large excess of alcohol or remove one of the products from the reaction mixture continuously. Wherever feasible, the second option is preferential because it can drive the reaction toward the completion. The reaction rate is at its highest if 100% excess methanol is used. In industrial processes, a molar ratio of 6:1 is normally used to obtain methyl ester yields higher than 98% by weight [77].

Catalysts are categorized as alkali, acid, enzymes, or heterogeneous catalyst. Among these, alkali catalysts such as sodium hydroxide, sodium methoxide, potassium hydroxide, and potassium methoxide are more effective [15]. It is found that alkali-catalyzed transesterification is much faster than acid-catalyzed reaction. However, acid-catalyzed transesterification reaction is more suitable if a vegetable oil has high FFA and water content. Most commercial transesterification reactions are conducted with alkaline catalysts. This is partly due to faster esterification and partly to alkaline catalysts which are less corrosive to industrial equipment than acidic catalysts. It is observed that sodium methoxide is more effective than sodium hydroxide. Sodium alkoxides are among the most efficient catalysts used for this purpose. However, due to its low cost, NaOH has been used widely in large-scale transesterification [15].

Different processes for transesterification of vegetable oils for the production of *J. curcas* biodiesel are currently available. Among them are homogenous catalysis treatment [14, 17, 26, 72, 83, 84, 88, 90], heterogeneous catalyst [34, 58] or enzyme catalysis alcohol treatment [55, 56, 73], supercritical alcohols treatments and subcritical methanol ([68, 86]) and Lipase-catalyzed in situ reactive extraction [82], and homogenous-catalyzed in situ transesterification [58].

4.1 Biodiesel Production Using Homogeneous Chemical Catalyst

Foidl et al. [26] reported a technical process for processing seed oil and production of methyl ester and ethyl ester from the oil of *Jatropha* seeds. The fuel properties were also determined. Production of biodiesel used two-step transesterification: alkali–alkali transesterification for methyl ester and alkali–acid transesterification for ethyl ester.

Chitra et al. [17] found that methyl ester yield of 98% was obtained using 20 wt.% methanol and 1.0% NaOH at 60°C. The maximum reaction time needed for a maximum ester yield was 90 min. Total biodiesel of 96% was obtained from experimental studies on large-scale production (reactor capacity of 75 kg). Esterification–transesterification reaction for *Jatropha* biodiesel was done by Sudradjat et al. [83, 84], but methyl ester yield was not reported.

Tiwari et al. [88] and Berchmans and Hirata [14] have developed a technique to produce biodiesel from *Jatropha* with high FFA contents (15% FFA). They selected two-stage transesterification processes to improve methyl ester yield. The first stage involved the acid pretreatment process to reduce the FFA level of crude *Jatropha* seed oil to less than 1%. The second was the alkali base-catalyzed transesterification process resulting in 90% methyl ester yield. Tiwari et al. [88] found that the optimum combination to reduce the FFA of *Jatropha* oil from 14% to less than 1% was 1.43% v/v H_2SO_4 acid catalyst, 0.28 v/v methanol-to-oil ratio, and 88-min reaction time at a reaction temperature of 60°C. This process produced yield of biodiesel of more than 99%.

Berchmans and Hirata [14] reduced the high FFA level of *Jatropha* oil to less than 1% by a two-step process. The first step was carried out with 0.60 w/w methanol-to-oil ratio in the presence of 1% w/w H_2SO_4 as an acid catalyst in 1 h reaction at 50°C. The second step was transesterified using 0.24 w/w methanol to oil and 1.4% w/w NaOH to oil as alkaline catalyst to produce biodiesel at 65°C. The final yield for methyl esters was achieved ca. 90% in 2 h.

4.2 Biodiesel Production Using Heterogeneous Solid Super Base Catalyst

An environmentally kind process was developed for the production of biodiesel from *Jatropha* oil using a heterogeneous solid super base catalyst and calcium oxide. The results revealed that under the optimum conditions of catalyst calcinations, temperature of 900°C, reaction temperature of 70°C, reaction time of 2.5 h, catalyst dosage of 1.5%, and methanol/oil molar ratio of 9:1, the oil conversion was 93% [34]. Nazir [58] found that the yield of JCO FAME could reach up to 94.35% using the following reaction conditions: 79.33 min reaction time, 10.41:1 methanol:oil molar ratio, and 0.99% of CaO catalyst at reaction temperature 65°C.

4.3 Biodiesel Production Using Heterogeneous Enzyme Catalyst

Interest in using lipases as enzymatic catalyst for the production of alkyl fatty acid esters continuously grows. Some people work on the triglyceride by converting them to methyl esters, while some work on fatty acids. One of the main obstacles to the biocatalytic production of biodiesel is high cost of the enzyme; enzyme recycling might be the solution to this problem.

It was found that *Pseudomonas fluorescens* lipase immobilized on kaolinite lost one third of its activity when it is used for the second time, but no further decrease was observed in successive applications. The initial decrease in activity was put down to enzyme desorption from the solid support that was not observed after repeated (ten times) use [36]. Repeated batch reactions revealed that *Rhizomucor miehei*

lipase had high stability, which retained about 70% of its initial conversion after 8 cycles (24 h each cycle). Meanwhile, under the same experimental conditions, *Thermomyces lanuginosa* retained only 35% of the initial conversion. This difference was credited to factors such as inactivation of the biocatalyst in the oil phase, the type of carrier which is used for the immobilization, or enzyme sensitivity to long-term methanol exposure [79].

It is observed that various substances can slow down lipase activity (methanol, glycerol, phospholipids); however, a number of ways have been proposed to overcome these problems [71]. Commonly, biocatalytic process does not produce soaps or other by-products. If the reaction completes, only esters and glycerol are produced. This makes purification steps much simpler and consequentially lowers plant costs. Once immobilized, lipases can be used many times or even in continuous processes. This resolves the major disadvantage related to high cost. In conclusion, if obtained by biocatalysis, biodiesel is an environmentally friendly fuel which will contribute to reducing negative impacts to the environment.

Modi et al. [56] used Propan-2-ol as an acyl acceptor for immobilized lipase-catalyzed preparation of biodiesel. The optimum conditions set for transesterification of crude *Jatropha* oil were 10% Novozym 435 (immobilized *Candida antarctica* lipase B) based on oil weight and alcohol to oil molar ratio of 4:1 at 50°C for 8 h. The maximum conversion reached using propan-2-ol was 92.8% from crude *Jatropha* oil. Reusability of the lipase was preserved over 12 repeated cycles with propan-2-ol as it reached to zero by the seventh cycle when methanol was utilized as an acyl acceptor, under standard reaction condition [55].

Modi et al. [55, 57] explored ethyl acetate as an acyl acceptor for immobilized lipase-catalyzed preparation of biodiesel from the crude oil of *J. curcas*. The optimum reaction conditions set for interesterification of the oils with ethyl acetate were 10% of Novozym 435 (immobilized *C. antarctica* lipase B) which is based on oil weight, ethylacetate to oil molar ratio of 11:1, and the reaction period of 12 h at 50°C. Under the above optimum conditions, the maximum result of ethyl esters was 91.3% of purity. Reusability of the lipase over repeated cycles in interesterification and ethanolysis was also examined under standard reaction conditions. The relative activity of lipase could be well preserved over 12 repeated cycles with ethyl acetate as it reached to zero by the sixth cycle when ethanol was used as an acyl acceptor.

Shah and Gupta [73] conducted a process of optimization of monoethyl esters of the long chain fatty acids (biodiesel) by alcoholysis of *Jatropha* oil using lipase. The process includes (a) screening of various commercial lipase preparations, (b) pH tuning, (c) immobilization, (d) varying water content in the reaction media, (e) varying amount of enzyme used, and (f) varying temperature of the reaction. The best yield 98% (w/w) was obtained by using *Pseudomonas cepacia* lipase which was immobilized on celite at 50°C in the presence of 4–5% (w/w) water in 8 h. The yield was not affected if analytical grade alcohol was replaced by commercial grade alcohol. This biocatalyst could be applied four times without loss of any activity.

In order to lower the cost of biodiesel fuel production from *Jatropha*, Tamalampudi et al. [85] used lipase producing whole cells of *Rhizopus oryzae* which was immobilized onto biomass support particles. The activity of *R. oryzae*

was compared to Novozym 435, the most effective lipase. Methanolysis of *Jatropha* oil progresses faster than other alcoholysis regardless of any lipase used. The maximum methyl ester content in the reaction mixture reached 80 wt.% after 60 h using *R. oryzae*, but 76% after 90 h using Novozym 435. Both lipases could be used for repeated batches. They also exhibited more than 90% of their initial activities after 5 cycles. Whole-cell immobilized *R. oryzae* is a promising biocatalyst for producing biodiesel from oil [85].

4.4 Biodiesel Production Using Supercritical Alcohols

The synthesis of biodiesel from *Jatropha* oil has been investigated in supercritical methanol and ethanol, without using any catalysts, from 200 to 400°C at 200 bar [68]. It is found that for the synthesis of biodiesel in supercritical alcohols with an optimum molar methanol oil ratio of 50:1, very high conversions (>80%) were obtained within 10 min and nearly complete conversions within 40 min. The conversion into ethyl esters is higher than that of methyl esters [68].

Tang et al. [86] studied transesterification of the crude *Jatropha* oil which was catalyzed by micro-NaOH (0.2 to 0.5 to 0.8 wt-‰) in supercritical methanol. When the catalyst content, reaction temperature, and molar ratio of methanol to oil were developed at 0.8 wt-‰ NaOH, 534 K, 7.0 MPa, and 24:1, respectively, the methyl ester yield reached 90.5% within 28 min.

4.5 Biodiesel Production Using Lipase-Catalyzed In Situ Reactive Extraction

According to Su et al. [82], extraction and lipase-catalyzed transesterification with methyl acetate and ethyl acetate can be done under the same conditions. They can be simply combined to a two-step-onepot in situ reactive extraction. First, the alkyl acetates were performed as the extraction solvent and afterwards as the transesterification agent. Then, by removing the catalyst, defatted plant material (by filtration), and the solvent (by evaporation), the methyl/ethyl esters were obtained.

The negative effects of glycerol and alcohol on lipase can be reduced by substituting short-chained alkyl acetates for short-chained alcohols as acyl acceptors for fatty acid esters production. Short-chained alkyl acetates are also appropriate solvents for seed oil extraction. Therefore, Su et al. [82] adopted methyl acetate and ethyl acetate as extraction solvents and transesterification reagents at the same time for in situ reactive extraction of *J. curcas* L seed. Fatty acid methyl esters and ethyl esters were respectively obtained with higher yields than those resulted in by conventional two-step extraction/transesterification. The improvement varied from 5.3 to 22%. The key parameters such as solvent/seed ratio and water content were

further examined to find their effects on the in situ reactive extraction. The highest *J. curcas* ethyl/ethyl esters could achieve 86.1 and 87.2%, respectively, under the optimized conditions [82].

This transesterification method reduces the risk of deactivation of enzyme by short-chained alcohol and glycerol because in the reaction short-chained alcohol is substituted with short-chained alkyl acetate and no glycerol is produced. Furthermore, such a route to fatty acid esters can decrease the expense associated with solvent extraction and oil cleanup. Due to its low cost production, in situ reactive extraction would be very promising for fatty acid esters production [82].

4.6 Biodiesel Production by In Situ Transesterification

In situ transesterification [32, 33, 39, 78], a biodiesel production method that utilizes the original agricultural products instead of purified oil as the source of triglycerides for direct transesterification, eliminates the costly hexane extraction process and works with virtually any lipid-bearing material. It could reduce the long production system associated with preextracted oil and maximize alkyl ester yield. The use of reagents and solvents is reduced, and the concern about waste disposal is avoided.

The experimental results showed that the amount of *J. curcas* seed oil dissolved in methanol was approximately 83% of the total oil and the conversion of this oil could achieve 98% under the following conditions: less than 2% moisture content in *J. curcas* seed flours, 0.3–0.335 mm particle size, 0.08 mol/L NaOH concentration in methanol, 171:1 methanol/oil molar ratio, 45.66°C reaction temperature, and 3.02 h reaction time. The use of alkaline methanol as extraction and reaction solvent, which would be useful for extraction oil and phorbol esters, would reduce the phorbol esters content in the *Jatropha* seedcake. The seedcakes after in situ transesterification is rich in protein and is a potential source of livestock feed [58].

5 Postreaction Processing of Biodiesel Production

Post reaction processing comprises ester/glycerol separation, ester washing, ester drying, alcohol recovery, and glycerol refining. These steps are very important in producing fuel-grade biodiesel and in decreasing biodiesel oil cost through alcohol recovery and glycerol refining.

For best economy and pollution prevention, alcohol must be fully recycled. Glycerol is an economically coproduct that should be fully refined [7]. As by-product, 1 mol of glycerol produces every 3 mol of methyl esters, which is equivalent to approximately 10 wt.% of the total product. Glycerol markets have reacted strongly to the increasing availability of glycerol. Although the global production of biodiesel is still limited, the market price of glycerol has dropped rapidly [37]. Therefore,

new uses for glycerol need to be developed and economical ways of the low-grade glycerol utilization should be further explored.

As *Jatropha* oil possesses a significant amount of fatty acids with double bonds, oxidative stability is of concern, especially when storing biodiesel over an extended period of time. The storage problem is worsening by storage conditions such as exposure to air and/or light, temperature above ambient, and the presence of extraneous materials (contaminants) with catalytic effect on oxidation [43]. The presence of air or oxygen will hydrolyze the oil to alcohol and acid. The presence of alcohol will lead to reduction in flash point and the presence of acid will increase the total acid number. All these conditions make methyl ester relatively unstable on storage and cause damage to engine parts [23]. That is why oxidation stability is an important criterion for biodiesel production.

The stability of biodiesel is very critical. Various strategies for the improvement of biodiesel fuel quality have been suggested. Biodiesel requires antioxidant to meet storage requirements and to ensure fuel quality at all points along the distribution chain. In order to meet EN 14112 specification, around 200 ppm concentration of antioxidant is required, except for palm biodiesel, which is much higher than those required for petroleum diesel. To minimize the dosage of antioxidant, appropriate blends of *Jatropha* and palm biodiesel are made. Antioxidant dosage could be reduced by 80–90% if palm oil biodiesel is blended with *Jatropha* biodiesel at around 20–40% concentration [72].

6 Nontoxic *Jatropha* Seedcake Production from *J. curcas*

Although *Jatropha* seeds are rich in oil and protein, they are very toxic and not good for human or animal consumption [40]. LD^{1}_{50} for phorbol ester consumption for male rat was 27.34 mg/kg body weight, and LD_5 and LD_{95} were 18.87 and 39.62 mg/kg body weight, respectively [44]. Utilization of *Jatropha* seedcakes cannot be achieved without the removal of antinutritional compounds [27]. Martinez-Herrera et al. [53] studied the nutritional quality and effects of various treatments (hydrothermal processing techniques, solvent extraction, solvent extraction plus $NaHCO_3$, and treatment with ionizing radiation) to disable antinutrient factor. Trypsin inhibitor can easily be removed using steam with a temperature of 121°C for 25 min. Phytate can be lowered slightly by irradiation at 10 kGy. The content of saponins can be reduced through extraction with ethanol and irradiation. Extraction with ethanol followed by 0.07% $NaHCO_3$ decreases phorbolester and lectin activity by 97.9% in seeds, while in vitro digestibility will increase between 78.6 and 80.6%. Heat treatment will increase in vitro digestibility to 86%.

[1] LD is lethal dose. The LD_{50} is the dose that kills half (50%) of the animals tested. The animals are usually rats or mice, although rabbits, guinea pigs, hamsters, and so on are sometimes used.

Jatropha seedcakes obtained from 4.0% NaOH treatment at a temperature of 121°C for 30 min followed either by washing two times with 92% methanol or four times with distilled water showed good results of detoxification. Phorbol ester content of seedcakes after detoxification with this treatment cannot be detected. However, the seedcakes which are only washed with water still have strong smell of NaOH. This has a negative revenue impact on the food intake. Washing with methanol looks promising for the detoxification of seedcakes as long as methanol used can be recycled [10]. Research by Chivandi et al. [18] demonstrated that *Jatropha* seedcakes detoxification using hexane and ethanol solvent treatment followed by hot steam 121°C for 30 min has not been able to eliminate the whole lectin and trypsin and still leaves phorbol ester residue (1.90 mg/g pulp). This figure is higher than the content of phorbol ester on nontoxic *Jatropha* (0.11 mg/g pulp).

Rakshit et al. [66] investigated the influence of heat and chemical detoxification of seedcakes and evaluated the growth and histology of rat. Research results indicated that the treatment of 2% NaOH or 2% $Ca(OH)_2$ followed by hot steam from the autoclave at a temperature of 131°C for 30 min and wash with water (1:5 w/v) reduce the phorbol ester content very significantly. However, the test diet on male rats showed the weight loss and the death of the rat on the day 9. According to Goel et al. [28], heat treatment followed by chemical extraction can eliminate phorbol ester and lower antinutrient and toxic substances in a meaningful way. *Jatropha* seedcakes treated in this way can be harmful to rats [48] and fish [28].

Makkar et al. [51] conducted a study to obtain the protein concentrate from the seedcakes. The highest protein concentrate was obtained when the seedcakes were first dissolved with NaOH so that the pH increased to 11 for 1 h and the temperature of 60°C, after which the protein was precipitated by lowering the pH to 4 using HCl. Concentrated protein produced by this treatment still contains phorbol ester from 0.86 to 1.48 mg/g and trypsin inhibitor which is estimated tenfold in the protein concentrate compared with that in seedcakes. Meanwhile, lectin and phytate also exist at a high level. These results indicate that the protein concentrates must be detoxified by removing the phorbol ester and disabling the lectin and trypsin inhibitors by heat treatment [51].

Nontoxic seedcakes can also be produced through in situ transesterification. The use of alkaline methanol as extraction and reaction solvent, which would be useful for extraction oil and phorbol esters, would reduce the phorbol esters content in the *Jatropha* seedcakes. The seedcakes, after in situ transesterification, are rich in protein and are potential sources for livestock feed. Experimental results showed that the amount of *Jatropha* seed oil dissolved in methanol was approximately 83% of the total oil. The conversion of this oil could achieve 98% under the following conditions: less than 2% moisture content in *Jatropha* seed flours, 0.3–0.335 mm particle size, 0.08 mol/L NaOH concentration in methanol, 171:1 methanol/oil mole ratio, 45.66°C reaction temperature, and 3.02 h reaction time [58].

7 Process Control of Integrated *Jatropha* Biodiesel Processing and Detoxification Process

There are three critical processes of production and three outputs that have to be considered; they are: (1) oil preparation, (2) transesterification reaction, and (3) post-reaction processing. In process control, we must ensure that both quantitative and qualitative product specification and economic performance meet health, safety, and environmental regulations. The tasks of control system are to ensure the stability of process, to minimize the influence of disturbance and perturbation, and to optimize the overall performance [19]. Figure 3 shows a schematic diagram of process control approach of integrated *Jatropha* biodiesel processing and detoxification process.

The following is a sequence of steps that could be employed to develop process control for a cost-effective and environmentally friendly *Jatropha* biodiesel production [60]:

1. Constructing a process flow diagram which identifies the major process operation.
2. Developing a strategy to improve the quality of *Jatropha* seed input. This strategy involves preharvest treatments and postharvest handling and technology.
3. Identifying the output characteristics that will be achieved.

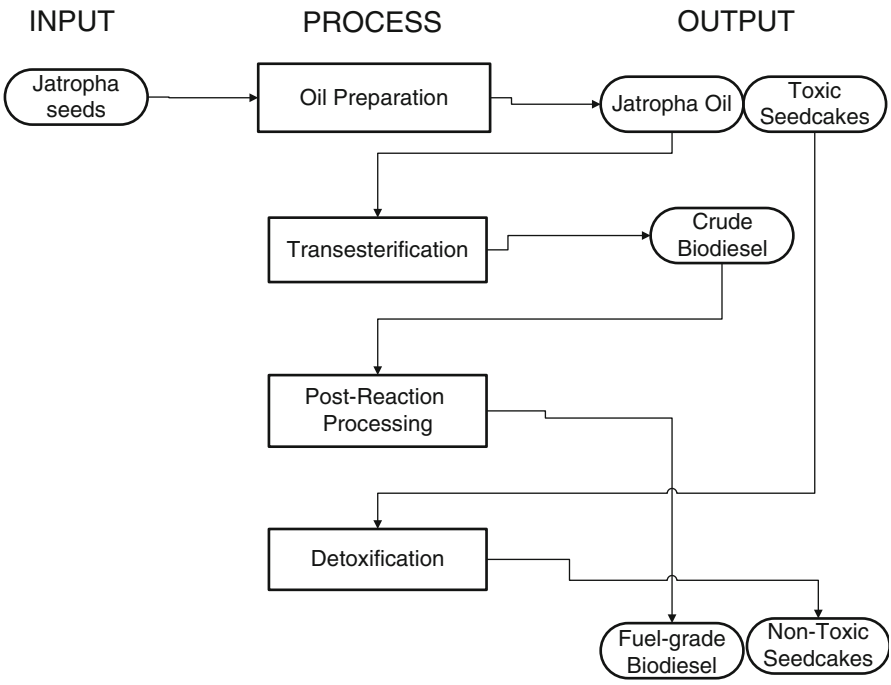

Fig. 3 Schematic diagram of the process control approach for integrated *Jatropha* biodiesel processing and detoxification process

4. Determining the principle process that will be applied for every output characteristics.
5. Identifying detection methods used to detect production problems and to prevent causes in the determined process.
6. Evaluating and analyzing cost feasibility of the process while always fulfilling health, safety, and environmental regulations.
7. Reviewing various possible actions for production system improvements.

8 Implication of Biodiesel Production on Global Warming, Environmental Impact Potential, and Energy

Since the cost and efficiency of the selected process will be tied up with the biodiesel production for a long time and affect the capital and operating costs and the environmental load of the product, selecting an appropriate process for the biodiesel production is a critical decision. Issues on capital and operating cost are relatively straightforward though issues on environmental load of the product are quite complicated [41]. One of the tools that can be employed to help answer the last issues is the life cycle assessment (LCA). The LCA is used to evaluate the environmental impact and other potential factors that a product (or service) has on the environment over the entire period of its life—from the extraction of the raw materials from which it is made, through the manufacturing, packaging, and marketing processes, and the use, reuse, and maintenance of the product, on to its eventual recycling or disposal as waste at the end of its useful life [41].

From the life cycle aspect, the growth of energy crops has raised concerns due to their high consumption of conventional fuels, fertilizers and pesticides for land preparation and biomass production, the materials and energy for oil extraction and biodiesel production, and the emissions and wastes which have been released to the environment. Figure 4 illustrates the system boundary for a LCA study of biodiesel production.

Nazir and Setyaningsih [59] developed a well-to-tank (WTT) life cycle inventory database of palm oil and *Jatropha* biodiesel and analyzed the environmental impacts of *Jatropha* and palm oil biodiesel by using the concept of life cycle thinking. The life cycle environmental impacts of *Jatropha* and palm oil biodiesel were compared and discussed. Table 4 shows the information related to materials and energy uses to produce 1 L biodiesel from *Jatropha* and palm oil.

8.1 Global Warming Potential of Biodiesel Production

The proportion of greenhouse gas (CHG) emissions from each material and energy used is shown in Fig. 5. The main contribution came from transesterification reaction for *J. curcas* and oil extraction for oil palm.

Biodiesel production from palm oil has bigger GHG emission than that from *Jatropha* oil.

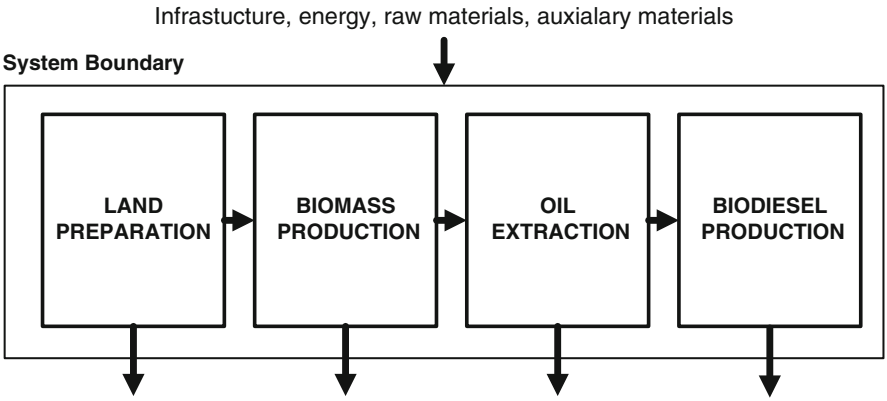

Fig. 4 The system boundary of *Jatropha* biodiesel production

Table 4 Materials and energy used in cultivation, oil extraction, and production of 1 L biodiesel from *J. curcas* oil and palm oil [59]

Input types	Input names	Unit	*J. curcas*	Oil palm
Cultivation				
Fertilizer	Urea	kg	0.135	0.265797
	KCl	kg	0.0675	0.399267
	DAP	kg	0.0336	0.072647
	Boron	kg	–	0.074327
Chemical	Herbicide	kg	0.0015	1.57232E−7
	Pesticide	kg	–	4.8224E−7
Fertilizing	Broadcaster	ha	3.59175E−6	0.000142
Plant protection	Field sprayer	ha	–	0.000142
Wood chopping	Mobile chopper	kg	–	4.53299
Transportation	Tractor/trailer	tkm	–	0.053299
	Lorry >16 ft	tkm	–	0.032132
	Freight	tkm	0.06708	0.111197
Land preparation	Diesel used	kg	0.0105	–
Provision	Stubble land	m^2	–	0.067579
Harvesting	Labor	MJ	0.007	0.004
Oil extraction				
Transportation	Tractor/trailer	tkm	–	0.00196
	Lorry >16 ft	tkm	–	0.37686
	Freight	tkm	0.002156	0.003267
	Electricity	MJ	0.0814	0.072
	Diesel	MJ	–	0.089
	Power and steam	MJ	–	4.967
Biodiesel production				
Chemical	Methanol	kg	0.14	0.09892
	Sulfuric acid	kg	0.0217	–
	NaOH	kg	0.00879	0.00998
Energy	Electricity	kWh	0.0852	0.036826
	Steam	kg	0.294	0.180

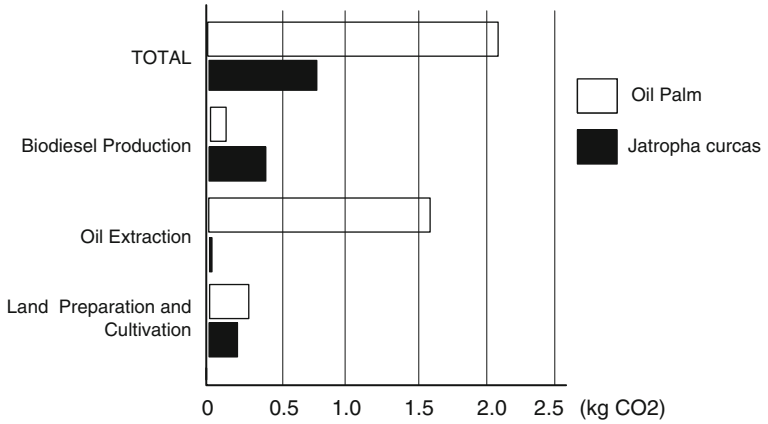

Fig. 5 Comparison of life cycle GHG emissions of biodiesel production from palm oil and *Jatropha* oil based on material and energy used in each steps of life cycle [59]

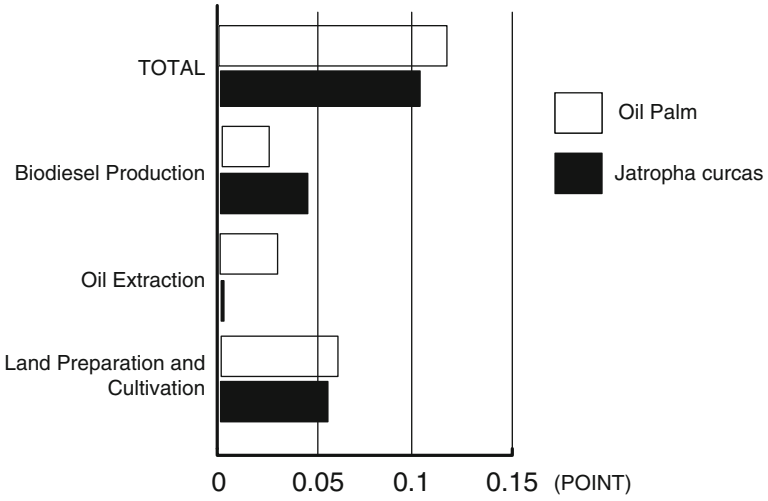

Fig. 6 Comparison of environmental impact of biodiesel production from palm oil and *Jatropha* oil based on material and energy used in each steps of life cycle [59]

8.2 Environmental Impact Potential of Biodiesel Production

Figure 6 shows the comparison of environmental impact of biodiesel production in each step of life cycle. Biodiesel production from palm oil has bigger total environmental impact than that of *Jatropha* oil. Cultivation contributes to the highest environmental impacts compared with other stages in the life cycle impact.

Table 5 The results of energy analysis biodiesel production

Fuel	Net energy value (NEV) (MJ/kg)	Net energy ratio (NER)	Net energy gain (%)	References
JCME	11.5	1.42	42.0	Prueksakorn and Gheewala [64]
POME	24.03	2.48	59.8	Papong et al. [63]

8.3 Net Energy Results of Life Cycle Impact Assessment

The life cycle energy analysis of *Jatropha* biodiesel production was conducted by evaluating direct energy input (such as electricity, diesel, gasoline, fuel oil, palm fiber, palm shell, etc.) and indirect energy input (energy accumulated in fertilizers, agrochemicals, and chemical production, excluding equipment and machinery used in the processes). The net energy value (NEV) and the net energy ratio (NER) can be estimated. The NEV is a measure of the energy gain or loss from the biodiesel used, which is defined as the energy content of the biodiesel minus the nonrenewable energy used in the life cycle of the biodiesel production [63]. The NER is a ratio of energy output to total energy input for the life cycle of the product [64].

Prueksakorn and Gheewala [64] calculated the energy consumption in every process in producing 1 kg of *Jatropha* biodiesel. The energy analysis results of the present situation of *Jatropha* biodiesel production compared to palm oil methyl ester is shown in Table 5. The results show that the selected biodiesel production process determines energy efficiency and environmental impacts.

9 Conclusions

High cost of biodiesel production is the major impediment to its large-scale commercialization. Methods to reduce the production cost of *Jatropha* biodiesel must be developed. One way to reduce production costs is to increase the added values of protein-rich *Jatropha* seedcakes, by-product of oil extraction, through detoxification process. The development of integrated biodiesel production process and the detoxification process results in two products, namely biodiesel and protein-rich seedcakes that can be used for animal feed. Assuming that an average seed yield on land of 5 tons/ha/year (2 tons/acre/year) could be achieved, the estimated theoretical maximum yield of biodiesel would be 750 kg/acre/year and seedcake products would be 500 kg/acre/year.

Since the cost and efficiency of the selected process will be closely correlated with the production for a long time and affect the capital and operating costs and the environmental load of the product, selecting an appropriate process for the biodiesel production is a critical decision. There are still many future potential improvement of biodiesel production of *J. curcas*. These include (1) development of better and

cheaper oil extraction and postreaction processing methods; (2) development of better and cheaper catalysts; (3) improvements in current technology for producing high-quality biodiesel with cheaper cost production; (4) development of technology to use methanol/ethanol in in situ extraction and transesterification; (5) development of technique to improve fuel stability of *Jatropha* biodiesel; (6) conversion of by-products, such as glycerol and seedcake to useful and value-added products, such as methanol and ethanol or glycerol *tert*-butyl ether (GTBE); and (7) development of integrated *Jatropha* biodiesel processing and detoxification process.

LCA has become an important decision-making tool for promoting alternative fuels because it can systematically analyze the fuel life cycle in terms of energy efficiency and environmental impacts. LCA analysis shows that the selected biodiesel production process determines energy efficiency and environmental impacts of *Jatropha* biodiesel production.

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