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# Biodiesel Production from *Jatropha Curcas*, Waste Cooking, and *Camelina Sativa* Oils

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Process parameter evaluation and catalyst performance study was conducted for biodiesel production using *jatropha curcas*, waste cooking, and *camelina sativa* oils. Conversion of triglycerides to methyl esters involves esterification and/or transesterification, depending on the nature of the feedstock. A two-step transesterification process (acid esterification followed by alkali transesterification) was employed to produce biodiesel from high free fatty acids (FFA) in *jatropha curcas* and waste cooking oils, and a single-step transesterification process (alkali transesterification) was used for *camelina sativa* oil conversion. Catalyst selection is vital in transesterification process because it determines biodiesel yield and cost. Transesterification of *jatropha curcas* and waste cooking oil was optimized by using  $\text{H}_2\text{SO}_4$  and ferric sulfate catalysts in the acid esterification step and a KOH catalyst in the alkali transesterification, respectively. Heterogeneous metal oxide catalysts including BaO, SrO, MgO, and CaO were used for the transesterification of *camelina sativa* oil.

*Jatropha curcas* oil was observed to have yields in the range of 90–95%, with a maximum of 95% obtained at the following process conditions: acid esterification, methanol to oil molar ratio of 6:1, 0.5% of  $\text{H}_2\text{SO}_4$ , and  $40 \pm 5$  °C; alkali transesterification, methanol to oil molar ratio of 9:1, 2% of KOH, and 60 °C. Waste cooking oil yielded biodiesel in the range of 85–96%, with a maximum of 96% observed at the following optimized process conditions: 2 h reaction at 100 °C, methanol to oil molar ratio of 9:1, and 2% of a ferric sulfate catalyst. Comparative experiments on *camelina sativa* oil conversion showed that the most effective catalyst was BaO that showed >80% yield of *camelina* to biodiesel. Fuel properties of biodiesel produced from the three different feedstocks were determined and compared with the ASTM standards for biodiesel and petroleum diesel.

## 1. Introduction

Biodiesel can be produced from any raw materials that contain fatty acids that are linked to other molecules or present as free fatty acids. Thus, various vegetable fats and oils, animal fats, waste greases, and edible oil processing wastes can be used as feedstocks for biodiesel production. Biodiesel, due to its fuel properties similar to diesel fuel, can be used in diesel engines with few or no modifications. Biodiesel has a higher cetane number than petroleum diesel fuel, no aromatics, and contains 10–11% oxygen by weight. These characteristics enable biodiesel combustion with lower emissions of carbon monoxide (CO), hydrocarbon (HC), and particulate matter (PM) in the exhaust gas as compared with the regular petroleum diesel fuel.<sup>1</sup> In addition, biodiesel is superior to petroleum diesel fuel in terms of sulfur content, flash point, and biodegradability.<sup>2</sup>

Traditionally, vegetable oils including canola, soybean, and corn are used as feedstocks for biodiesel production. However, increasing concern of food shortage throughout the world due to usage of edible oils for biodiesel production that conflicts with human consumption has developed a contradictory situation of “*food vs fuel*”. Other factors of particular interest will be, if the biodiesel production from these natural sources is economical and has net positive energy. Nonedible oils meet the requirement for these two considerations because they are inedible and can be grown in waste land with low fertilizer and pesticide inputs. Therefore, it is crucial to develop environmentally friendly processes with low-cost feedstock containing high net energy ratios.

The high cost of vegetable oils, especially edible oils, is the main barrier for expansion of biodiesel applications. Reducing

the cost of the feedstock is necessary for biodiesel's long-term commercial viability. One way to reduce the cost of this fuel is to use less expensive feedstocks including waste cooking oils and vegetable oils that are nonedible and/or require low harvesting costs. The cost of vegetable oil production is mainly due to land and water requirements, fertilizer, and pesticide inputs. In this study, three different low-cost feedstocks are chosen on the basis of availability, economic, and energy values. The three different feedstocks are, namely, *jatropha curcas* and waste cooking oil (nonedible and low-cost or free raw materials) and *camelina sativa* oil (underexploited edible oil but low-cost raw material for biodiesel).

*Jatropha curcas* is one such forest-based tree-borne nonedible oil, having oil content of 25–30% in the seeds and 50–60% in the kernel.<sup>3</sup> *Jatropha curcas* is a slow-drying oil that is odorless and colorless when fresh but becomes yellow on standing. The oil content of *jatropha* seed ranges from 30 to 50% by weight, and the kernel itself ranges from 45 to 60%. The fatty acid composition of *jatropha* is classified as a linoleic or oleic acid type, which are unsaturated fatty acids. The fatty acid composition of *jatropha* oil consists of myristic, palmitic, stearic, arachidic, oleic, and linoleic acids. However, from the properties of this oil, it is envisaged that the oil would be suitable as fuel oil. The oil compares well against other vegetable oils and more importantly to diesel itself in terms of its fuel rating per kilogram or hectare of oil produced.

Waste cooking oil, which is much less expensive or sometimes available at free of cost, can be a promising alternative to edible vegetable oil.<sup>4</sup> Waste cooking oils and rendered animal fats are less expensive than food-grade soybean oil. Waste cooking oil and fats set forth significant disposal problems in many parts of the world. This environmentally threatening

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problem could be solved by proper utilization and management of waste cooking oil as a fuel. Many developed countries have set policies that penalize the disposal of waste cooking oil in the waste drainage.<sup>5</sup> The Energy Information Administration in the United States estimated that around 100 million gallons of waste cooking oil is produced per day in the USA, where the average per capita waste cooking oil was reported to be 9 pounds.<sup>6</sup> The estimated amount of waste cooking oil collected in Europe is about 700000–1000000 tons/year.<sup>7</sup> Therefore, it is beneficial to develop and optimize the processes for converting waste cooking oil to biodiesel that is carbon-neutral, reduces waste, and improves resource efficiency.

Camelina sativa is an underexploited crop species of great economical potential. Camelina sativa oil is rich in Omega-3 fatty acids and yields an average 1200–1400 pounds/acre.<sup>8</sup> Camelina seed contains 30–40% oil. The cold-pressed filtered camelina sativa oil indicates an increased maximum power output for the seed oil of 43.25 kW compared to 38.50 kW for the mineral fuel.<sup>9</sup> The production cost for camelina sativa oil is substantially lower than many other oil crops such as rapeseed, corn, and soybean, which makes camelina an attractive potential crop for biodiesel and many other industrial applications.<sup>10</sup> Camelina sativa has positive energy balance for the production of biodiesel ester (net energy ratio of 1.47).<sup>11</sup>

Biodiesel production by transesterification reaction can be catalyzed with alkali, acid, or enzyme. Alkali and acid transesterification processes require shorter reaction time and lower costs as compared to the enzyme-catalyzed process.<sup>12,13</sup> The alkali process gives high purity and yield of biodiesel in shorter reaction time;<sup>14</sup> however, this process is not suitable for feedstocks with a high free fatty acid (FFA) content. Therefore, a two-step transesterification process (acid esterification followed by alkali transesterification) was developed to remove the high free fatty acid content and to improve the biodiesel yield.<sup>15,16</sup> The maximum biodiesel yield for jatropha curcas was obtained at 1% (w/w) H<sub>2</sub>SO<sub>4</sub>, 1.4% (w/w) NaOH, and 2 h of reaction time.<sup>17</sup> The most probable pathway and the rate determining step in transesterification of jatropha oil are estimated from molecular orbital calculation.<sup>18</sup> Waste cooking oil, as an alternative feedstock for biodiesel, was studied with different aspects such as optimization using supercritical methanol (SCM) transesterification, process design and technological assessment, fuel property estimation, and cost estimation approaches.<sup>19–21</sup>

Although numerous studies have been reported for jatropha and waste cooking oil biodiesel, their process parameter evaluation and detail fuel properties using ferric sulfate and sulfuric acid as catalysts was not reported. Similarly, for camelina oil, no significant work has been studied with a single-step transesterification process utilizing heterogeneous metal oxide catalysts. The heterogeneous catalysts considered in this study are BaO, CaO, MgO, and SrO. In this paper, an attempt has been made to compare the process parameter evaluative studies conducted for three different feedstocks, viz., jatropha curcas, waste cooking oil, and camelina oil that have greater potential for large-scale application to produce biodiesel. The following sections will discuss the experimental methods, process parameter evaluative studies for each feedstock, summary, and comparison of the biodiesel properties produced from the three different feed stocks with ASTM biodiesel standards.

## 2. Experimental Methods

**2.1. Materials.** Waste cooking oil samples used in this study were collected from a local restaurant in Las Cruces, NM. Cold-pressed camelina sativa oil was obtained from Marx Foods Co.,

**Table 1. Properties of Jatropha, Waste Cooking, and Camelina Oils**

properties	jatropha oil	waste cooking oil	camelina sativa oil
specific gravity	0.91	0.92	0.91
viscosity at 40 °C (mm <sup>2</sup> /s)	20.5	28.8	14.03
calorific value (MJ/kg)	37.07	44.44	44.5
acid value (mg of KOH/g)	28.15	17.41	3.1635
cetane no.	35.37	32.48	35.16
pour point (°C)	1	−12	−23

NJ. Jatropha Curcas oil was obtained from Purandhar Agro & Biofuels (Pune, India). Potassium hydroxide flakes, methanol (AR grade), and chloroform were procured from Fisher Scientific. The ferric sulfate catalyst was obtained from MP Biomedical. Heterogeneous metal oxide catalysts, i.e., SrO, CaO, MgO, and BaO, were purchased from Alfa Aesar. To test the physicochemical properties of oil, ethanol (95% (v/v)), hydrochloric acid, and diethyl ether were purchased from Fisher Scientific. A round-bottom flask with water-cooled reflux condenser arrangement was used as laboratory-scale reactor for the experimental studies in this work, and a hot plate with magnetic stirrer was used for heating the mixture in the flask. For transesterification of oil, the mixture was stirred at the same agitation speed of 1000 rpm for all test runs. In addition, the boiling chips were added into the laboratory-scale reactor which provides nucleation sites so the liquid boils easily without becoming superheated at high temperature.

**2.2. Characteristics of Oils.** The quality of oil is expressed in terms of the physicochemical properties such as acid value and saponification value. The saponification value of jatropha, waste cooking oil, and camelina oil was reported as 196, 186.3, and 193.31 mg of KOH/g, respectively. The acid value of unrefined jatropha curcas oil was estimated as 28 mg of KOH/g corresponding to a FFA level of 14 wt %. It has been reported that transesterification would not occur if FFA content in the oil were above 3 wt %.<sup>22</sup> The acid value of camelina oil and waste cooking oil was found to be 3.16 and 17.41 mg of KOH/g, respectively. The properties of the oils are presented in Table 1.

**2.3. Transesterification of Jatropha Curcas and Waste Cooking Oil.** The process consists of two steps, namely, acid esterification (step 1) and alkali transesterification (step 2). The mechanism of synthesis of biodiesel via the two-step process is represented by two equations in Figure 1.

For a successful reaction, the oils must be heated above 100 °C for 1 h to remove the water and other impurities, known as the pretreatment method. The FFA content was determined by a standard titrimetry method.<sup>23</sup> After the reaction, the mixture was allowed to settle for 8 h in a separating funnel. The acid value of the pretreated oil from step 1 was determined. The pretreated oil having an acid value less than  $2 \pm 0.25$  mg of KOH/g was used for the main transesterification reaction.

A 25 mL aliquot of jatropha curcas oil was poured into the flask and heated to about 45 °C in the acid esterification of jatropha curcas oil. Then 8 mL of methanol was added and stirred at low stirring speed for 10 min followed by 0.5% (v/v) sulfuric acid. The reaction mixture was then poured into a separating funnel to remove excess alcohol, sulfuric acid, and impurities. The experimental setup for alkali-catalyzed transesterification was the same as that used for the acid esterification. A 0.45 g (2 wt %) amount of KOH was dissolved in 10 mL of methanol, and half of that was poured into the flask containing an unheated mixture from the acid esterification step and stirred for 10 min. After 10 min, the mixture was heated and stirred

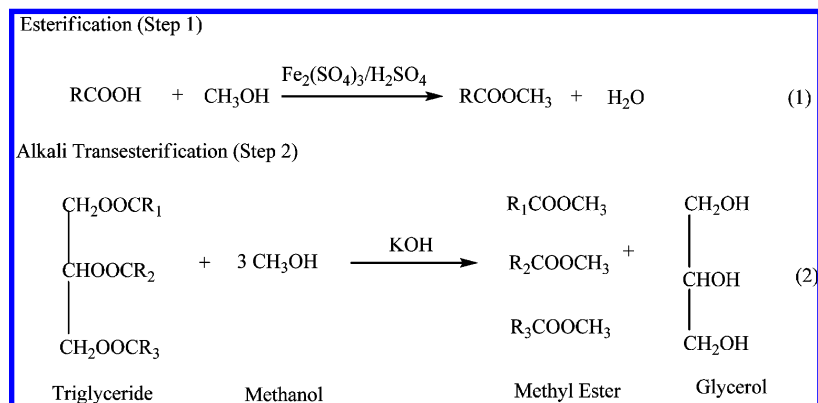


Figure 1. Two-step transesterification process for high free fatty acid oils.

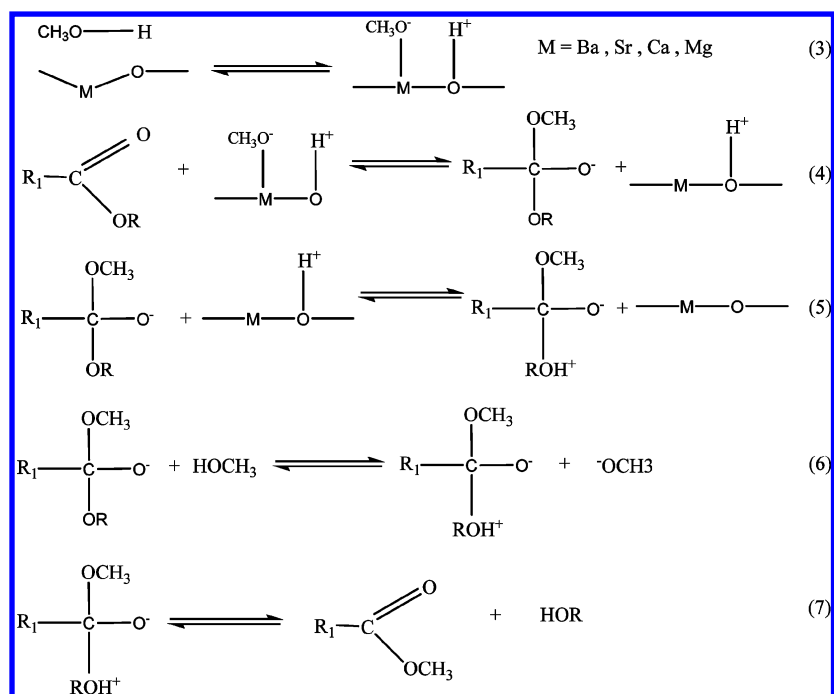


Figure 2. Transesterification mechanism of camelina oil by heterogeneous catalysts.

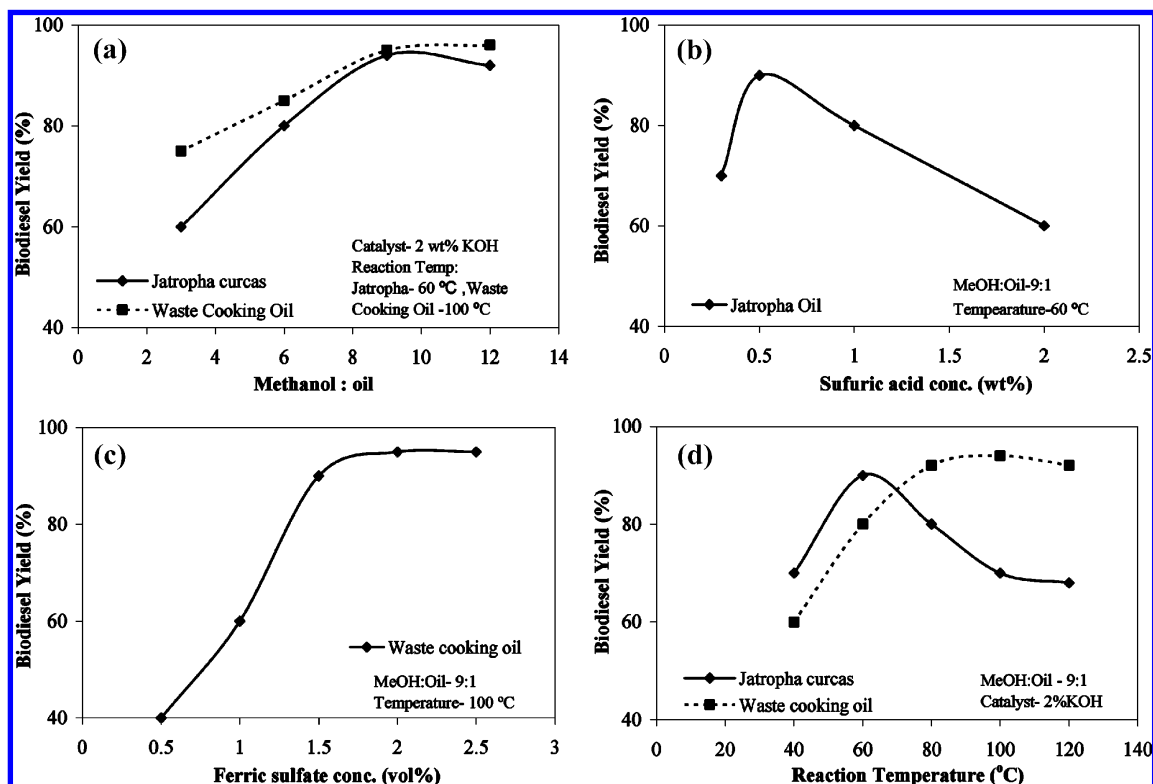
continuously to about 60 °C, and then the remaining methoxide was added to it. The reaction was continued for the next 2 h.

For waste cooking oil, in step 1, 50 mL of the sample was mixed with 10 mL of methanol and 2 wt % ferric sulfate catalyst in a 250 mL round-bottom flask. This mixture was heated to about 100 °C for 60 min at atmospheric pressure. The reaction mixture was then poured into a separation funnel. The excess alcohol with impurities moved to the top layer and was removed. The catalyst along with the ester oil phase settled at the bottom layer. The ferric sulfate mixture after separation was collected in an ashing crucible and ashed at 500 °C for 5 h in a muffle furnace to remove the organic impurities. The recovered ferric sulfate catalyst by the above ashing process can be reused for the next batch of oil. The ferric sulfate acted as a heterogeneous acid catalyst and had very low solubility in the oil.<sup>24</sup> The lower layer after removal of catalysts was collected for further processing (step 2). The treated oil (ester) having acid value less than  $2 \pm 0.25$  mg of KOH/g was used for the transesterification process. The product of the first step was preheated to the required reaction temperature of 100 °C in the flask. Meanwhile, 0.92 g (2 wt %) of KOH was dissolved in 15 mL of methanol and poured into the flask. The mixture was heated and stirred for 60 min.

After the alkali transesterification, the reactant mixture was allowed to be separated into two layers. The bottom layer having a brownish red color and containing the impurities and crude glycerol was drawn off. The esters along with the catalyst in the upper layer were then separated from the reactant mixtures. The transesterified product (biodiesel) after separation was first distilled to remove the unreacted methanol and then washed 2–3 times with hot water to remove the dissolved glycerol in the biodiesel phase. Washed biodiesel was then dried using sodium sulfate.

**2.4. Transesterification of Camelina Sativa Oil.** For camelina oil, a single-step alkali transesterification was employed with four different heterogeneous metal oxide catalysts, namely, BaO, CaO, MgO, and SrO. The experimental plan involved five levels of methanol to oil ratio varying from 3:1 to 15:1; five levels of catalyst concentration, 0.25, 0.5, 1, 1.5, and 2% (w/w) oil; five levels of reaction time, 0.5, 1, 1.5, 2, and 3 h; and five levels of reaction temperature varying from 40 to 130 °C. The reaction mechanism is described in Figure 2.

In transesterification, 15 mL of oil from the pretreatment procedure was allowed to cool to normal temperature. Meanwhile, 1 wt % MO, metal oxide, catalyst was dissolved in 7.5



**Figure 3.** Process parameter evaluation study for jatropha and waste cooking oils conversion. Effects on yield: (a) From methanol to oil molar ratio (step 2); (b, c) from catalyst concentration (step 1); (c) from reaction temperature (step 2).

mL of methanol, and the mixture was agitated for 10 min to ensure the complete mixing as part of catalyst activation.<sup>25</sup> Then the catalyst–methanol mixture was poured in the 250 mL glass reactor containing pretreated oil and heated to the temperature of 100 °C for 3 h. At the end of the reaction, the reaction mixture was allowed to separate into two layers. The lower layer, which contained catalyst and glycerol, was drawn off. The crude methyl ester remained in the upper layer. The excess methanol in ester phase was distilled off under vacuum. Hot distilled water was sprayed over the surface of the ester and stirred gently to remove the entrained impurities and the glycerol. Washing was done 2–3 times to remove all dissolved catalysts and glycerin in the ester layer. The lower layer was discarded, and the yellow colored layer (biodiesel) was separated and then dried using sodium sulfate.

Actual (FAME) yield is defined as the ratio of volume of cleaned methyl ester (biodiesel) to the volume of oil (raw material) taken (uncertainty of  $\pm 0.1\%$ ).

### 3. Results and Discussion

**3.1. Influence of Reaction Parameters on Jatropha Curcas and Waste Cooking Oil.** The transesterification reaction was studied for four different molar ratios. The molar ratios of methanol to oil were varied for jatropha oil and waste cooking oil in the range of 3:1 to 12:1. Figure 3a depicts the effect of methanol to oil molar ratio on the conversion of oil. The maximum ester conversions for jatropha oil and waste cooking oil were found at the methanol to oil molar ratio of 9:1. The yield remains the same with further increase in the methanol to oil molar ratio. The excess methanol in the ester layer can be removed by distillation. Therefore, the methanol to oil molar ratio was kept at 9:1 in the remaining experiments with jatropha oils. For waste cooking oil, a similar trend has been observed. The yield of the process increased with an increase in the

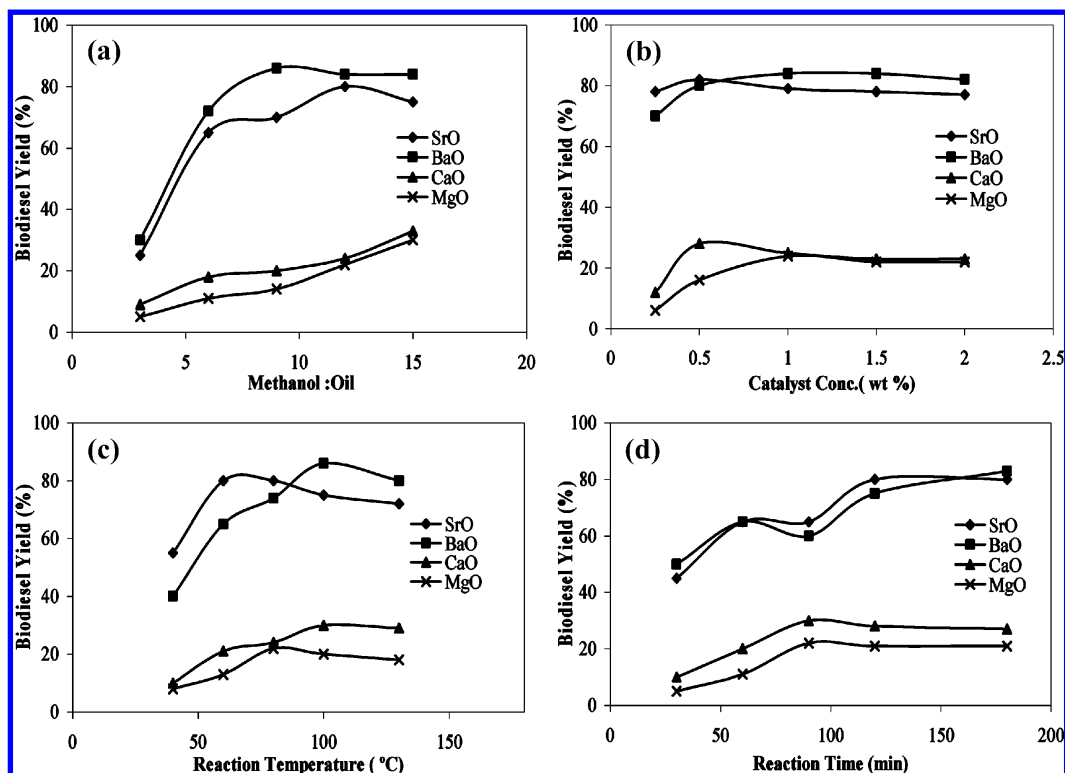
methanol to oil molar ratio up to 9:1. With further increase in the molar ratio, the change in the yield was insignificant. At higher levels, an excess methanol starts to interfere in the separation of glycerin due to an increase in the solubility.<sup>26</sup>

The sulfuric acid catalyst amount was varied in the range of 0.3–2% for jatropha oil. These percentages are based on the volume of the oil used for the acid esterification reaction. The catalyst amount also affects the yield of the process as shown in Figure 3b. The acid-catalyst process attained maximum yield for jatropha oil at 0.5% catalyst concentration. For jatropha oil, it was observed that the yield started to decline when the catalyst concentration was increased above 0.5%. The effect of alkali catalyst (KOH) was studied in the ranges of 0.3–2.5% and 0.5–2% by weight for waste cooking oil and jatropha oil, respectively.

Figure 3c shows the influence of the amount of ferric sulfate on biodiesel yield for waste cooking oil. The yield was quite low for less quantity of catalyst. The amount of catalyst required depends on the amount of free fatty acid content. In this study, the catalyst concentration of ferric sulfate to waste cooking oil was varied within a range of 0.5–2.5%. Ferric sulfate showed good catalyst activity as solid Lewis acid<sup>27,28</sup> for the oils which contain high free fatty acid content. The yield appeared to increase with an increase in the catalyst amount. The maximum yield was obtained at 2% catalyst amount. However, a slight increase in yield was observed above 2% catalyst loading.

To study the reaction temperatures, some alkali transesterification experiments were conducted at temperatures close to the boiling point of methanol.<sup>29</sup> As shown in Figure 3d, the reaction temperature effect on the yield was studied in the temperature range of 40–100 °C for jatropha curcas oil at atmospheric pressure. The maximum yield was obtained at a temperature of 60 °C for jatropha oil. A decrease in yield was observed when the reaction temperatures were above 60 °C.





**Figure 4.** Process parameter evaluation study for camelina sativa oil conversion. Effects on yield: (a) From methanol to oil molar ratio; (b) from catalyst concentration; (c, d) from reaction temperature.

Other researchers have achieved optimum yield at temperatures above 60 and 70 °C while using refined linseed oil and brassica carinata oil, respectively.<sup>30,31</sup> The reaction temperature for processing jatropha oil should be maintained below 60 °C because saponification of glycerides by the alkali catalyst is much faster than the alcoholysis at temperatures above 60 °C. For waste cooking oil, the reaction temperature was studied in the range of 60–120 °C. The maximum biodiesel yield was obtained at 100 °C.

**3.2. Influence of Reaction Parameters on Camelina Sativa Oil.** Textural characteristics of the catalysts were determined by the N<sub>2</sub> adsorption–desorption at –196 °C in a Micromeritics ASAP 2020. Before the analysis, the samples were degassed under a vacuum overnight at 450 °C. From the textural characteristics of the metal oxide catalyst, it was found that MgO and CaO had the largest surface area of 10.2 and 5.1 m<sup>2</sup>/g, respectively, whereas the BaO and SrO had the minimum of 0.0760 and 0.0637 m<sup>2</sup>/g, respectively. However, it was interesting to note that despite having a lower surface area, BaO and SrO gave the highest biodiesel yield, as explained later in Results and Discussion. The order of basic strength and catalyst activity of BaO and SrO catalysts are found to be higher than CaO and MgO.<sup>32,33</sup>

X-ray powder diffractograms were recorded in a Rigaku Miniflex II X-ray diffractometer equipped with a graphite monochromator using Cu K $\alpha$  radiation, 30 kV, and 15 mA, in order to identify the crystalline structure present in the samples. The changes in the catalyst structure and integrated intensities of peaks were examined by the X-ray diffraction (XRD). The experimental study and XRD pattern<sup>34</sup> suggested that catalyst activity of the fresh catalyst remains the same or differs slightly as compared to the used catalyst after the reaction, which suggests the catalyst can be reused several times.

The amount of methanol required for the transesterification was analyzed in terms of the methanol to oil molar ratio. For

this experiment, methanol to oil molar ratio was changed from 3:1 to 15:1. Figure 4a shows that the reaction rate increased when the molar ratio of methanol to oil was increased. For the BaO catalyst, the maximum yield was obtained at 9:1 molar ratio, and then yield remains the same for the higher molar ratio. For the SrO catalyst, 12:1 is the optimum molar ratio. However, when the amount of methanol to oil molar ratio was over 12:1, an excess methanol started to interfere in the separation of glycerin due to an increase in the solubility and resulted in the decreasing biodiesel yield. The maximum camelina biodiesel yield using CaO and MgO was obtained at 15:1 optimum molar ratio of methanol to oil. High catalytic activity depends on the catalyst processing strong basic sites.<sup>35</sup> In this study, the catalyst concentration of metal oxides to camelina oil was varied within a range of 0.25–2%. The influence of the catalyst amount on yield is shown in Figure 4b. The maximum yield for camelina oil using BaO, SrO, CaO, and MgO was obtained at 1, 0.5, 0.5, and 1%, respectively. It was observed that the production yield remains the same or slightly decreased with an increase in the catalyst concentration. At higher catalyst concentration, the intensification of mass transfer becomes more important than the increased catalyst amount. For heterogeneous metal oxide catalysts, besides the specific surface area, acidity/basicity, acid/base site, and leaching tendencies in glycerol are also the contributing factors of catalysts in biodiesel formation.

In the transesterification of heterogeneous catalysts, the reaction proceeds with a three-phase system, oil–methanol–catalyst, in which the reaction rate could slow down due to mass transfer diffusion resistance.<sup>36</sup> However, reaction rate and biodiesel yield can be increased by increasing reaction temperature. The reaction temperature was changed within a range of 40–130 °C. For all the metal oxide catalyst, from Figure 4c, reaction rate was slow at low temperature. The biodiesel yield was increased with increasing reaction temperature up to a certain level and then decreased. The maximum ester yield for camelina

**Table 2. Summary of Process Parameter Evaluation Studies for Jatropha, Waste Cooking, and Camelina Oils**

oil	type	process	catalyst	evaluated parameters [MeOH:oil, catalyst (wt %), temp (°C), time (min)]	biodiesel yield (%)
camelina sativa	edible	one-step (alkali transesterification)	BaO	9:1, 1%, 100 °C, 180 min	84
			SrO	12:1, 0.5%, 60 °C, 120 min	82
			CaO	15:1, 0.5%, 100 °C, 90 min	33
			MgO	15:1, 1%, 80 °C, 90 min	30
jatropha curcas	nonedible	two-step (step 1, acid esterification; step 2, alkali transesterification)	Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> /H <sub>2</sub> SO <sub>4</sub> (step 1); KOH (step 2)	6:1, 0.5% H <sub>2</sub> SO <sub>4</sub> , 40 ± 5 °C (step 1); 9:1, 2% KOH, 60 °C (step 2)	90
waste cooking oil				9:1, 100 °C, 2% Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> (step 1); 9:1, 100 °C, 0.5% KOH (step 2)	96

**Table 3. Comparison of Fuel Properties of Methyl Esters from Different Feedstocks**

properties	jatropha methyl ester	waste cooking methyl ester	camelina methyl ester	regular diesel	biodiesel standard ASTM D 6751-09	testing method
specific Gravity	0.86–0.88	0.88–0.89	0.87–0.88	0.85	0.86–0.90	ASTM D4052
viscosity at 40 °C (mm <sup>2</sup> /s)	2.35–2.47	2.25–3.10	2.9–3.15	2.6	1.9–6.0	ASTM D445
calorific value (MJ/kg)	39.65–41.63	44.92–45.07	45.05–46.15	42	report	ASTM D240
cetane no.	60.74–63.27	55.45–56.10	49.26–51.17	46	47 min	ASTM D613
pour point (°C)	–6 to +2	–4 to –1	–11 to –8	–20	report	ASTM D97

oil using BaO, SrO, CaO, and MgO was obtained at 100, 60, 100, and 80 °C, respectively. At higher temperature, methanol was distilled off and formed a large number of bubbles, which reduce the reaction on the three-phase interface. Figure 4d depicts the influence of reaction time on the yield of biodiesel. The maximum yield for camelina oil using BaO, SrO, CaO, and MgO was obtained at 180, 120, 90, and 90 min, respectively.

Process parameter evaluative studies for the three different feedstocks are summarized in Table 2. As it has been reported before, homogeneous catalyst KOH in transesterification of jatropha curcas and waste cooking oils resulted in high biodiesel yields.<sup>28,37</sup> The heterogeneous catalyst used for transesterification of camelina oil resulted in decent biodiesel yields except for CaO and MgO catalysts. Heterogeneous catalysts are advantageous over homogeneous catalysts in separation and cleaning of the biodiesel fuel.

#### 4. Fuel Properties of Methyl Esters from Oils

The fuel properties of biodiesel from jatropha curcas, camelina sativa oil, and waste cooking oil with testing methods are given in Table 3. The viscosities of biodiesel from these oils were closer to that of viscosity of regular diesel. Hence, no hardware modifications are required for handling this fuel (biodiesel) in the existing engine. The calorific values of jatropha, camelina, and waste cooking oil esters were lower than that of diesel because of their oxygen content. The presence of oxygen in the biodiesel helps for complete combustion of fuel in the engine. The cetane numbers were found to be higher than ASTM standards for biodiesel and regular diesel. Higher cetane number indicates good ignition quality of fuel.

The pour point of jatropha and waste cooking biodiesel was found to vary between –6 and +2 °C and between –4 and –1 °C, respectively. The free and total glycerin contents in waste cooking biodiesel were estimated as 0.006 and 0.1596% (% mass), while for camelina oil, the values were 0.018 and 0.1195% (% mass). According to ASTM D-6751 biodiesel standards, the free glycerin limit is 0.02% and the total glycerin (free + bound) is 0.24% (% mass). The low level of free and total glycerin ensured high conversion of oil to methyl ester. The pour point of camelina biodiesel was found to be between –11 and –8 °C, which indicates a good compatibility of fuel in the cold season.

#### 5. Conclusions

Three different types of feedstocks, namely, camelina, jatropha curcas, and waste cooking oils were evaluated for biodiesel production under various conditions. The process parameters such as methanol to oil ratio, catalyst concentration, reaction temperature, and reaction time were optimized in the experimental studies. The results obtained from the experimental studies show that the two-step transesterification method is best suited for jatropha and waste cooking oil, while the one-step method is applicable for camelina oil for the production of biodiesel. The fuel properties of biodiesel produced from these feedstocks meet the ASTM biodiesel standards and are comparable to those of the regular petroleum diesel fuels.

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