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Original Article

Design, construction and performance evaluation of a mini-scale batch reactor for biodiesel production: A case study of shea butter

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Abstract

This study developed a mini-scale batch reactor after evaluating the kinetics of biodiesel production. The reactor was evaluated for its performance by two-stage and one-pot syntheses methods using shea butter. The biodiesel produced was characterized and compared with the ASTM standards for biodiesel and diesel. The reactor was designed for 6.5 L total and 4.5 L working volume; the power rating and power delivery were 2.0 and 1.5 hp, respectively. The operating conditions for the reactor to attain its highest yields of 91.01% and 76.67% with the two alternative methods had 800 rpm agitation speed and 40°C temperature. The reactor achieved the design objective of better than 90% biodiesel yield with the two-stage method only. The biodiesel quality satisfied the ASTM standards. Therefore, the reactor could be scaled up for industrial production of biodiesel.

Keywords: design, construction, performance, reactor, shea butter, biodiesel

1. Introduction

Biodiesel is a fuel made up of mono-alkyl esters of long chain fatty acids that exhibit combustion properties similar to those of conventional diesel fuel. It is considered a renewable, alternative and sustainable replacement to conventional diesel oil. This alternative fuel is biodegradable, non-toxic, and has lower emission profiles than diesel oil. Among the various alternative fuels, biodiesel derived from vegetable oils is the most promising sustainable fuel alternative to diesel, due to numerous benefits and advantages (Ajala, Aberuagba, Odetoye, & Ajala, 2015). The synthesis of biodiesel requires transesterification of any vegetable oil or animal fat, done with alcohol in appropriate proportion in the presence of a catalyst. This reaction can take place in any type of reactor, but high conversion is desirable (Hosseini, Nikbakht, & Tabatabaei, 2012; Leevijit, Wisutmethangoon, Prateepchaikul, Tongurai, & Allen, 2006).

The technologies in biodiesel production are improving greatly with the emergence in the last decade of several reactor types that are available in various sizes. The

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common types of reactor investigated for the production of biodiesel are batch reactor, plug flow reactor, continuous stirred tank reactor (CSTR) and combined plug flow/ CSTR arrangement, but the most common reactor in biodiesel production is of batch type (Leevijit *et al.*, 2006). The most important objective of reactor design is the extent of conversion; and the major reactor variables that influence conversion and selectivity are temperature, reaction time, and degree of mixing (Gerpen, 2005). There are some technical challenges facing biodiesel production through transesterification, which include long residence times, high operating cost and high energy consumption with low production efficiency (Hosseini *et al.*, 2012). In recent years, studies on biodiesel synthesis have focused on the development of process intensification technologies to resolve some of these challenges (Qiu, Zhao, & Weatherley, 2010) Numerous studies have been conducted on the kinetics of methanolysis in order to achieve the best reactor design that would overcome the mentioned challenges (Reyes, Malverde, Melin, & De Bruijn, 2010), but to achieve a high conversion, the reactor design must take into consideration some important elements, including size of reactor (reactor dimensions), its construction material, agitation system, hydrodynamics, physical properties of the reactants, and methods to supply or remove heat. Meanwhile, various agitators in commercial use have been employed to improve biodiesel production in batch mode, by reducing the reaction time. These agitators are mechanical stirrers, magnetic stirrers, turbines, two motionless mixers combined with a high shear mixer, anchor, Rushton turbine, helix and two flat-blade paddles (Hosseini *et al.*, 2012). However, the choice of agitator remains important in the reactor design for biodiesel production, to attain a high degree of mixing.

Since vegetable oil and alcohol are immiscible as the main reactants in biodiesel production in the reactor, intense mixing of these two is required to break the alcohol phase into small drops that provide sufficient interfacial area for the reaction. This is a difficult area in the current technology for biodiesel production (Abbaszadeh, Ghobadian, Najafi, & Motevali, 2014). In batch reactors, the degree of mixing is directly related to the amount of energy introduced through the impeller (Gerpen, 2005). Other factors that determine the process efficiency of the reactor include temperature control and agitator speed control systems, for the transesterification of oil to biodiesel (Rahmat, Setiasih, & Kasta man, 2013).

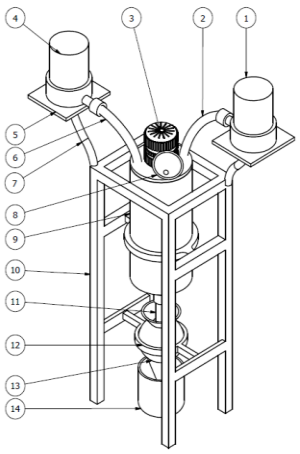
This study therefore developed a reactor for biodiesel production with impeller type mixing and an adequate power rating for proper mixing of a vegetable oil, such as shea butter with high viscosity and high FFA, as well as with agitator speed regulation between 200 and 1400 revolutions per minute (rpm), and with temperature control. In order to develop this reactor, a kinetic study was carried out to determine the size of the reactor. The developed reactor was tested for the production of biodiesel using shea butter in a two-stage and alternatively a one-pot process, and the biodiesels produced were characterized and compared to ASTM standards for biodiesel and diesel.

2. Methodology

2.1 Design concept of a reactor for biodiesel production

The technology of biodiesel production was studied to develop a batch reactor supported by a frame for easy operation. The components of the reactor include heating elements that supply heat into the reactor chamber, since the reaction for biodiesel production is endothermic.

The reaction chamber was cladded with glass fibers, to reduce heat loss from the reactor. There were two storage tanks, one of which stored vegetable oil and the other for methoxide, as shown in Figure 1.



PARTS LIST	
PART NUMBER	DESCRIPTION
1	METHOXIDE TANK
2	HOSE (METHOXIDE)
3	D.C. MOTOR
4	SHEA NUT OIL TANK
5	TANK PLATFORM
6	HOSE (SHEA NUT OIL)
7	SUPPORT
8	ADDITIVE INLET
9	MAIN VESSEL
10	SUPPORTING FRAME
11	OUTLET
12	SEPARATING FUNNEL HOLDER
13	SEPARATING FUNNEL
14	PRODUCT RECEIVER

Figure 1. Schematic design of the developed reactor

2.2 Design objective and materials of construction

Based on relevant literature information, the design specifications were as follows (Winardi & Khalid, 2009):

(a) Above 90% of conversion was targeted
(b) Stainless steel (SS304) was used for the interior layer
(c) Galvanized steel was used for the exterior layer
(d) Heating element.

The following assumptions were made for reactor design:

(a) The reactor volume equals the volume of the reaction mixture.
(b) The reaction was assumed irreversible as excess methanol was used to shift the equilibrium towards products (1: 6 ratio of oil: methanol).
(c) Downtime of 30 minutes.
(d) Production rate (F_P) of 2,000 g per batch.
(e) The reaction was assumed to be of second order in this study, since the Molecularity of reaction ≠ Order of reaction for a non-elementary reaction (n = 2 assumed).

2.3 Kinetic analysis for dimensioning of the reactor

It is a known fact that the transesterification reaction between alcohol and triglycerides is reversible at astoichiometric molar ratio of alcohol to triglycerides (3:1). However, this reaction became in practice irreversible with excess alcohol shifting the reaction toward completion. The excess also improved miscibility and enhanced the contact of alcohol with triglyceride.

Hence the molar ratio of alcohol to triglycerides at 6:1 was adopted to produce a high biodiesel yield in a short reaction time.

The irreversible reaction that takes place between triglycerides (A) and alcohol (B) to give biodiesel (C) and glycerol (D) with stoichiometric coefficients a, b, c, and d is shown in Equation 1. We set a = 1 and b = 6, which is expected to produce c = 3 and d =1.

$$aA + bB \dashrightarrow cC + dD \quad \text{Equation 1}$$

The reaction rate (r) is expressed in Equation 2 for assumed 2nd order reaction.

$$-r_{TG} = \frac{-dC_A}{dt} = KC_AC_B \quad \text{Equation 2}$$

Here r_{TG} = rate of reaction, K = rate constant, C_A = triglycerides concentration, and C_B = methanol concentration. With the stoichiometry of Equation 1, the rate can be rewritten as

$$-r_{TG} = \frac{-dC_A}{dt} = K[C_{Ao}(1 - aX_A)C_{Bo}(1 - bX_B)] \quad \text{Equation 3}$$

where X = conversion

From Equation 3, when $X_A = X_B$, and M = $\frac{C_{BO}}{C_{Ao}}$, we obtain

$$-r_{TG} = \frac{-dC_A}{dt} = KC_{Ao}(1 - aX_A)MC_{Ao}(1 - bX_A) \quad \text{Equation 4}$$

Solving this differential equation gives

$$\ln\frac{M - bX_A}{M(1 - aX_A)} = K(aM - b)\,C_{Ao}t \quad \text{Equation 5a}$$

where we define $Y = \ln\frac{M - bX_A}{M(1 - aX_A)}$ Equation 5b

and $\check{K} = K(aM - b)C_{Ao}$ Equation 5c

with 'a' being the stoichiometric coefficient of tryglyceride (A).

The result is

$$Y = \check{K}t \quad \text{Equation 6}$$

where Ǩ is the slope.

A plot of Y against t should give a straight line with slope determining the rate constant K of the reaction. With Equation 5a used to determine the time it requires for the reaction to complete, the volume of reactor (V) needed was estimated as (Hill & Root, 2014)

$$V = \frac{F_P\,(t + t_D)}{C_{AO}X} \quad \text{Equation 7}$$

where F_P = Production rate
t = time of reaction
t_D = down time per batch

2.4 Design criteria and dimensioning of the reactor chamber

The reactor was designed with 4.5 L working volume and 2 L clearance volume, and baffles. Adequate heat distribution within the reactor was factored into the design process.

The reactor vessel was a concentric cylindrical vessel containing an inner and an outer vessel, made of stainless and galvanized steels, respectively (Winardi & Khalid, 2009). The methanol and vegetable oil storage tanks made of polyvinyl chloride (PVC) were attached to the carrier platform and placed slightly above the reactor chamber. This was to allow the free flow of vegetable oil and methanol under gravity into the chamber (Figure 1). The detailed material specifications for the design are summarized in Table 1. The dimensioning of the reactor vessel was carried out so as to obtain the required capacity of 6.5 L with working volume of 4.5 L. The choice of agitator was based on fluid properties, the location of the impeller, and number and proportions of baffles were decided. Each of these decisions affects mixing, flow patterns, and the power required. Figure 2a shows typical proportions of these features (McCabe & Smith, 1993).

Table 1. Design specifications

Item	Specifications
Inner vessel	Stainless steel (SS304)
Outer vessel	Galvanized steel
Propeller	Stainless steel rod
Impeller (turbine blade)	Stainless steel
Lagging material	Fibreglass
Methoxide and oil tank	Transparent PVC plastic
Support	Galvanized steel pipe
Hoses	Rubber hose
Power cable	2.5mm (Nigeria cable)
Heating element	Electric heating coil
Heating element's control	Thermocouple
Power requirement of the DC motor	2.0 HP
Power delivered by the motor	1.5 HP
Power ratio	1.4

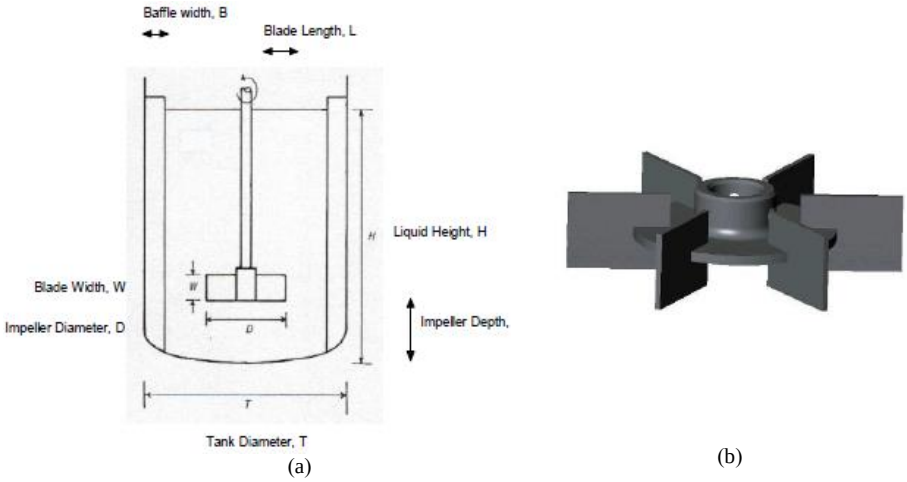


Figure 2. Features of the reactor for (a) dimensioning and sizing of the chamber, (b) the flat blade disk turbine in a 3D plot.

$$\frac{D}{T}=\frac{1}{3},\quad \frac{H}{T}=\frac{1}{1},\ \frac{B}{T}=\frac{1}{12},\ \frac{E}{T}=\frac{1}{3},\ \frac{W}{D}=\frac{1}{5}\quad and\quad \frac{L}{D}=\frac{1}{4} \qquad \text{Equation 8}$$

where: H = Liquid Height D = Impeller Diameter T = Tank Diameter
B = Baffle Width W = Blade Width L = Blade Length
E = Distance between the midpoints of the impeller

Table 2 shows the correlations employed to obtain the volume, area and other useful parameters, and Equation 9 was used to determine the side view proportions of the vessel with a stirrer. The flat blade disk turbine was chosen as the stirrer blade (Figure 2b) to attain effective mixing of the reactants.

$$\frac{E}{T}=\frac{1}{3} \quad \text{(McCabe \& Smith, 1993)} \qquad \text{Equation 9}$$

Table 2. Measurements of the reactor chamber and accessories

Parameter	Formula
The volume of cylinder	$\frac{\pi {D_t}^2}{4} H$
The area of the cylinder	$\pi D_t \left(\frac{D_t}{2} + H\right)$
The area of the spreadsheet	$2(lH + lw + Hw)$
The volume of cylinder (the volume of the impeller)	$\frac{\pi {D_t}^2}{2} h_i$
The volume of rectangle (blades attached)	$l \times w \times D_a$
The volume of a rectangular bar (inserted baffle)	$J \times H \times k$
The volume of irregular shapes	$W_a = W_o - W_{af}$

where: h_i = height of the baffles with an offset $(W/6)$ (Perry and Green, 2008)
l = length of the spreadsheet of the internal vessel
w = width of the spreadsheet
W_a = Apparent weight of the immersed object
W_o = weight of the object and W_{af} = weight of the displaced fluid

Another choice made was that the length of blade is always $\frac{2}{3}$ of the inner diameter of the vessel. The thickness of the wall of the main vessel plus the corrosion allowance were calculated using Equation 10 (Bhattacharyya, 2005; Coulson & Richardson, 2002).

$$t = \frac{PD_o}{2FJ+P} + C \qquad (mm) \qquad \text{Equation 10}$$

where: t = minimum thickness required;
D_o= outer diameter of the inner vessel,
F = the allowable design stress for material specified
P = probable pressure build up;
C = corrosion allowance thickness,
J = the welded joint efficiency factor

The impeller horsepower (P) (hp) delivered was determined using Equation 13 through the interrelation of Reynolds Number and Power Number (Np), in Equations11 and 12 respectively (Winardi & Khalid, 2009).

$$Re = \frac{ND_a^2\rho}{\mu} \qquad \text{Equation 11}$$

$$Np = \frac{Pg_c}{\rho N^3 D_a^5} \qquad \text{Equation 12}$$

where: D_a = impeller diameter,
P = impeller
ρ and μ = fluid density and viscosity respectively.
N = rotational speed,
g_c = Newton's-law proportionality factor

$$P_{delivered} = Np \times \rho \times N^3 \times D^5 \qquad \text{Equation 13}$$

Power of the motor **(P_{motor})** required to agitate the vegetable oil at losses of 30% is

$$P_{motor} = {Power\ _{delivered}}/{(1 - Losses)} \qquad \text{Equation 14}$$

and the power to volume ratio with vegetable oil is

$$P_{ratio} = {P_{motor}}/{volume\ of\ reactor} \qquad \text{Equation 15}$$

2.5 Testing of the reactor for biodiesel production using shea butter

The developed reactor was tested for biodiesel production using high FFA (>6. 85%) shea butter, because shea butter is a highly viscous vegetable oil and the reactor was designed to handle various viscous vegetable oils. In addition, biodiesel produced from shea butter has been reported as having high quality in terms of ignition, heat of combustion, oxidative stability, exhaust emissions, cetane number, kinematic viscosity, oxidative stability, and cloud and pour points, due to the effects of structural features of the FAMEs in it, such as chain length, degree of unsaturation, and branching of the chains (Ajala, Aberuagba, Olaniyan, Ajala, & Sunmonu, 2016).

The butter was filtered after melting to remove all insoluble impurities, followed by heating at 100ºC for 10 min to remove all the moisture to obtain pure shea butter. The pure shea butter was used for biodiesel production in a two-stage process and in a one-pot synthesis.

For the two-stage process, the procedure described by (Ajala *et al*, 2016; Ajala, Aberuagba, Olaniyan, & Onifade, 2015; Goyal, Sharma, & Jain, 2012) was followed by using methanol: oil ratio of 1: 6, sulphuric acid (1%, v/ v) (esterification), potassium hydroxide of 1% (w/w) (transesterification) at the temperatures 40, 50, or 60ºC under constant mixing at the speeds 200, 800, or 1400 rpm.

The esterification by sulphuric acid was initially carried out, followed by transesterification using potassium hydroxide. The modified methods of (Ajala, Aberuagba, Olaniyan, *et al.* 2015; Bojan & Durairaj, 2012; Refaat, 2010; Viele, Chukwuma, & Uyigue, 2013) were employed for one-pot synthesis, in which transesterification and esterification were done simultaneously using only a base catalyst. At the expiration of reaction time for the two procedures, methanol was evaporated at 65ºC and the products were allowed to separate into an upper organic phase and a lower aqueous catalyst phase (Saifuddin, Raziah, & Nor farah, 2009). The product was discharged into a separating funnel and was allowed to cool and settle for 24 h. The biodiesel was separated from the glycerol to obtain crude biodiesel. The biodiesel was purified and the yield was determined using Equation 16.

$$\text{Yield of Biodiesel (\%)} = \frac{\text{Total weight of biodiesel produced}}{\text{Total weight of the shea butter used}} \text{ X } 100\% \qquad \text{Equation 16}$$

2.6 Characterization of the shea biodiesel produced in the developed reactor

Properties of the biodiesel produced were determined in order to evaluate its suitability as a replacement for diesel. The standard methods of ASTM were employed in characterizing the biodiesel produced by two-stage synthesis. The density and specific gravity were determined according to ASTM D4052-11 at 15ºC and 60ºF temperatures, respectively. Kinematic viscosity was investigated following ASTM 445-12 at 40ºC. The ASTM 93-02a was employed to study the flash point of the samples.

Cloud and pour points were investigated according to ASTM 2500-11 and ASTM 97-12, respectively (Ajala, Aberuagba, Olaniyan, *et al.*, 2015). The heating value was also determined, using the method described by Sivarama krishnan and Ravikumar (2011).

3. Results and Discussion

3.1 Kinetic study

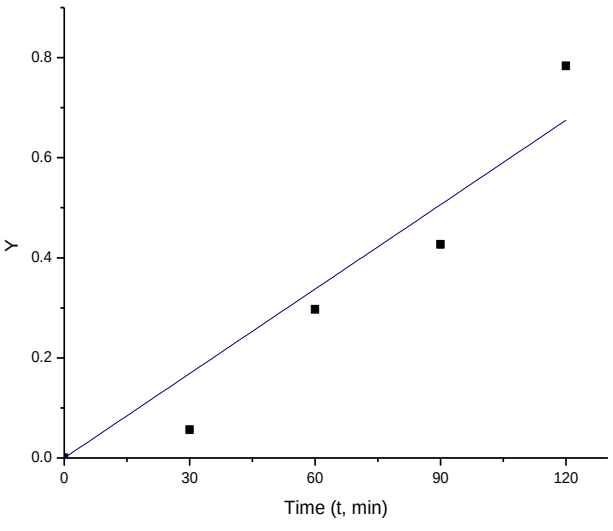
The experimental results of conversion (X) were transformed with Equation (5b) to Y. The Y was plotted against time (t) (Equation 6) as shown in Figure 3. The slope (K̆) was determined, and the reaction constant (K) was obtained from Equation (5c) as 3.62 X 10^{-3} (L/mol. min.) with corresponding coefficient of determination (R^2) 0.9816, Adj R^2 being 0.9544, the residual sum of squares 0.03234, the standard error 5.47 X 10^{-4}. These diagnostic values indicate that the kinetic second order model is appropriate, and it was employed to design the batch reactor for biodiesel production. Therefore, the time of reaction in Equation (6a) was used to evaluate the volume of the reactor in Equation (8) as 4.5 L. The remaining 2 L that made up the 6.5 L total volume of the reactor was based on the other parameters obtained, as shown in Table 3.

3.2 The developed reactor

The important design parameters obtained from the design equations are presented in Table 3**.** The power delivery by the motor was obtained as 1.5 hp (Table 1). The reactor was developed to operate at the agitation speeds 200, 800, or 1400 rpm and at temperatures from 35 to 150ºC, regulated by controllers**.** The reactor was coupled with methoxide and vegetable oil tanks**.** A photo of the reactor system is shown in Plate 1**.**

3.3 Performance evaluation of the reactor in biodiesel production from shea butter

The developed reactor was tested in biodiesel production with both two-stage and one-pot syntheses, and was successfully operated at the agitation speeds 200, 800 and 1400 rpm, and at the temperatures 40, 50, and 60ºC for each type of syntheses.

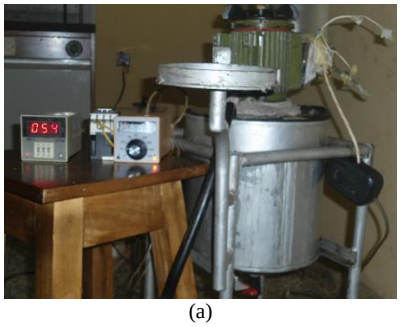


Equation	y = a + b*x		
Residual Sum of Squares	0.03234		
Pearson's r	0.9816		
Adj. R-Square	0.95441		
		Value	Standard Error
Y	Intercept	0	
	Slope	0.00563	5.47222E-4

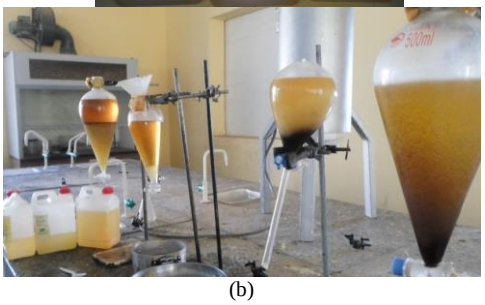
Figure 3. Second order kinetic model fit for biodiesel production

Table 3. Development of internal vessel parameters

Parameter	Obtained value
Diameter	190 mm
Main height	180 mm
Clearance height	30 mm
Thickness	2 mm
Working volume	4,500,000 mm^3 (4.5 L)
Clearance volume	1,500,000 mm^3 (1.5 L)
Volume occupied by Impeller shaft and blades	500, 000 mm^3 (0.5 L)
Total Volume	6,500,000 mm^3 (6.5 L)
Agitation Unit Dimensions	
Impeller diameter	180 mm
Length of the turbine blade	120 mm
Distance of the impeller to the base	60 mm
Height of the impeller	150 mm



(a)



(b)

Plate 1. Photos of (a) the reactor, and (b) biodiesel produced

Figures 4a and 4b show the effect of agitation speed on the yield of biodiesel for the two-stage and one-pot syntheses, respectively. It was noticed that the agitation speed 800 rpm gave the highest biodiesel yield with the two procedures in all cases, whereas both 200 and 1400 rpm speeds gave lower biodiesel yields. This is due to incomplete reaction with poor mixing intensity at 200 rpm, while the high turbulence at 1400 rpm potentially caused soap reaction (Ajala *et al.*, 2016). In addition, the transesterification of vegetable oil to biodiesel initially forms a two-phase liquid system, and as the mixing continues the reactant mixture formed a single phase system. This is due to the fact that the reaction is diffusion-controlled. The poor diffusion between the phases results in a slow rate at 200 rpm; at 800 rpm the single phase was quickly established, which was responsible for the higher yield; and at 1400 rpm the yield of biodiesel was reduced (Noureddini & Zhu, 1997). This is because the saturation of the reaction mixture was reached at 800 rpm for methylation, and the fact that mass transfer was further enhanced at 800 rpm. As a result, the highest biodiesel yield was achieved within the agitation speed range designed (Shahidul Islam & Bundy, 2012).

The effect of temperature on the biodiesel yield was studied at the mixing intensities 200, 800 and 1400 rpm, a catalyst concentration of 2% (w/w), and methanol:oil ratios of 8:1 and 12:1 for each type of synthesis. It was observed that temperature had a prominent effect on the shea biodiesel yield, as shown in Figures 4c and 4d for the two-stage and one-pot syntheses, respectively.

The figures reveal that in all cases tested the 40°C temperature gave the highest yield of biodiesel, followed by 50°C and 60°C in this order. The results show that reaction temperatures above 40°C accelerate the saponification reaction of shea butter to form soap and reduce the biodiesel yield (Momoh, Audu, & Binta, 2014).

The reaction temperature should be precisely controlled to avoid overheating of the reaction mixture and to prevent the evaporation of methanol (boiling point at 65°C) (Shahidul Islam & Bundy, 2012). The biodiesel yield with two-stage synthesis was 91.01%, while that with one pot synthesis was 76.67%, as shown in Table 4. The difference in yields with the two alternative procedures may be due to reaction time, the pre-treatment in the two-stage process, and the presence of high FFA in the shea butter used. Therefore, the design objective of better than 90% yield was only achieved with the two-stage process. Furthermore, the 91.01% biodiesel yield attained with this reactor was better than the 87% yield of Novel Oscillatory Flow Reactor, which was developed to improve biodiesel production in a continuous system (Suryanto, Wahyu, & Marwan, 2015). The results indicate that the mixing intensity and the controlled temperature are key factors for achieving a high yield of biodiesel in any reactor.

3.4 Properties of biodiesel produced

Table 5 shows the properties of biodiesel produced using the two-stage process, as measured by the ASTM standards. The tested fuel properties show that the biodiesel meets the requirements and specifications of ASTM standards. The density (specific gravity) of the biodiesel is 0.8137 (0.8023) Kg/m^3. This result is within the standard requirements for biodiesel as shown in Table 5, but is higher than that of diesel.

The fatty acids may give higher density to biodiesel than that of diesel (Ajala, Aberuagba, Olaniyan, *et al.*, 2015; Roseli, Anna, Turtelli, & Kil Jin, 2011).

The kinematic viscosity obtained was 5.34 mm^2s^{-1}, which is within the range for biodiesel but higher than that of diesel (Table 5). Meanwhile, the viscosity of biodiesel is normally higher than that of diesel. This is due to the fatty acids in biodiesel (Ajala, Aberuagba, Olaniyan, *et al.*, 2015;

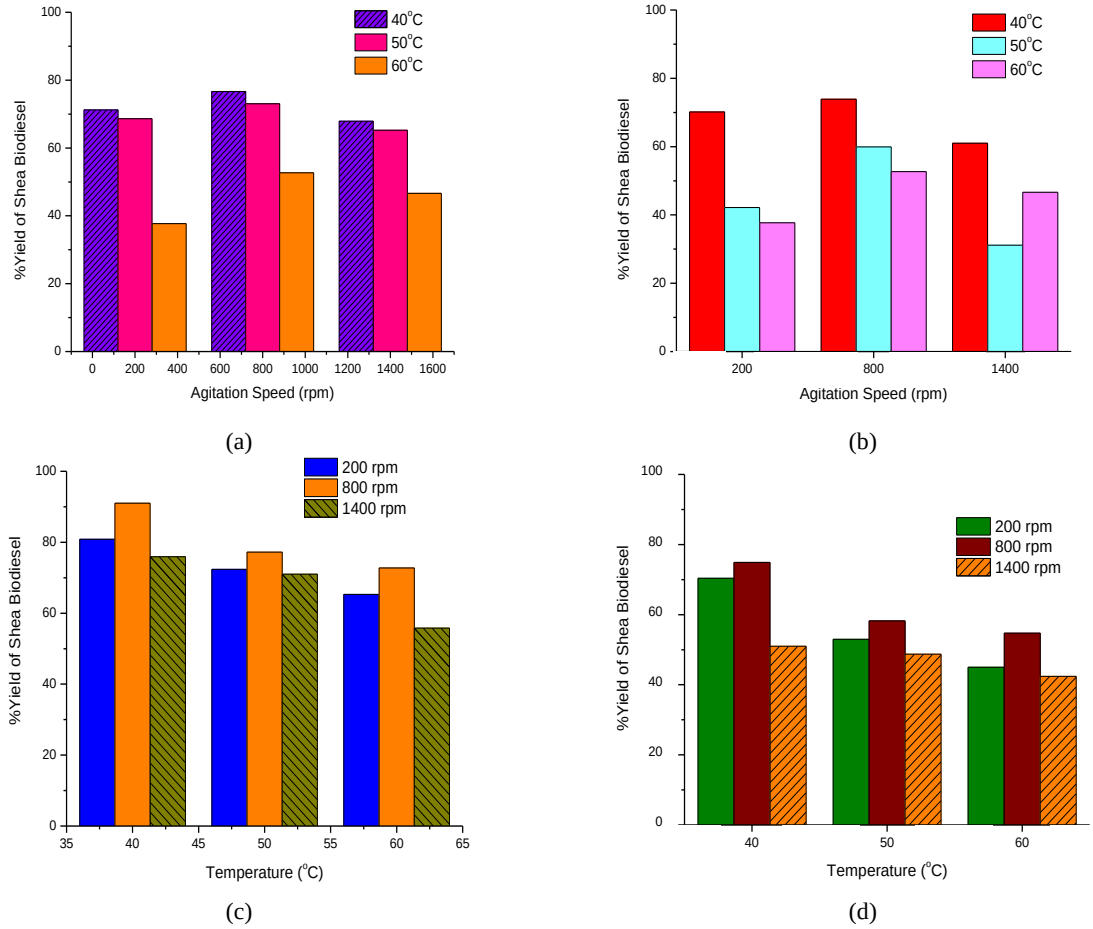


Figure 4. Effects on biodiesel yield of agitation speed: (a) two-stage, and (b) one-pot synthesis. Effects of temperature: (c) two-stage, and (d) one-pot synthesis. Fixed conditions: MeOH:Oil molar ratio 8:1; catalyst concentration 2% (w/w)

Table 4. Yield of biodiesel from shea butter using the developed reactor

Method	Biodiesel Yield (w/w, %)
Two-stage process	91.01
One-pot synthesis	76.67

Table 5. Properties of the biodiesel by the reactor as compared with the standards

Properties	Biodiesel Produced	ASTM D6751 Standard (Biodiesel)	ASTM D0975 Standard (Diesel)
Density at 15°C (kg m^{-3})	0.8137	0.875 - 0.900	0.876
Specific gravity	0.8023	0.88	0.850
Kinematic viscosity at 40°C (mm^2s^{-1})	5.34	1.9 – 6.0	1.9 – 4.11
Flash point (°C)	120	100 -170	60 – 80
Pour point (°C)	-9	-15 to +16	-35 to +15
Cloud point (°C)	11	-3 to +12	-14 to +5
Heating value (MJ kg^{-1})	41	40 – 50	50

Bello, Akinola, Otu, & Owoyemi, 2013). However, when the viscosity of biodiesel is higher than the upper limit shown in the table, it leads to incomplete combustion and increases carbon deposits, while biodiesel with viscosity below the lower limit increases fuel leakage between the pump plunger and barrel, thereby leading to a hot start and low fuel. This can cause difficulties with starting the engine, particularly when the fuel pump is worn-out (Rao, Ramadhas, Nallusamy, & Sakthivel, 2010).

A flash point of 120°C was observed for the biodiesel produced. This value falls within the acceptable range but is higher than the value for diesel, as shown in Table 4. This implies that fire hazard associated with transportation, storage, and utilization of the biodiesel is lesser than with diesel (Oghenejoboh & Umukoro, 2011).

Cloud point (CP) is defined as the temperature where wax first appears and becomes visible, when the fuel is cooled. Pour point (PP) is the temperature at which the amount of wax formation is sufficient to gel the fuel: it is the lowest temperature at which the fuel can flow (Bello, Mogaji,

& Agge, 2011). The CP and PP of the biodiesel are 11 and -9ºC, which fall within the respective ASTM ranges from -3 to +12 and from -15 to + 16ºC (Table 5).

The heating value obtained in this study was 41 $MJkg^{-1}$. This is within the specification range 40 – 50 MJ kg^{-1} and slightly below that of diesel, as shown in Table 5.

The oxygen content of biodiesel may be responsible for the difference from diesel, as it improves the combustion efficiency by improved access to oxygen during combustion. Because of this, the combustion efficiency of biodiesel is higher than that of diesel (Sivaramakrishnan & Ravikumar, 2011).

4. Conclusions

A mini scale reactor of 4.5 L, equipped to agitate high viscosity and high FFA vegetable oil (shea butter) with alcohol, was developed. The operation of the reactor was successful without any challenges. Appropriate mixing of the two immiscible reactants was achieved at deliverable 1.5 hp (motor power rating 2.0 hp). The design objective of better than 90% conversion was achieved with a two-stage process, operated at 800 rpm for efficient mixing of the two phases (shea butter and methanol) in the ratio 1:6, reaction temperature 40ºC and potassium hydroxide (1% w/w) as the catalyst, for 2 h reaction time. The biodiesel yield was 91.01%, while the one-pot synthesis reached only up to 76.67%. Further studies are recommended for the one-pot synthesis to improve its performance. The shea biodiesel produced compared favorably, in terms of its quality characteristics, with the ASTM standards. Therefore, the present study demonstrated a reactor that can easily be scaled up for the production of high-quality biodiesel in industrial quantities by the conversion of vegetable oils.

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