



KINETIC MODELING OF ALGAL TRIGLYCERIDES TRANSESTERIFICATION FOR SUSTAINABLE BIODIESEL PRODUCTION

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ABSTRACT :

The global demand for clean and sustainable energy has intensified due to environmental challenges associated with fossil fuels combustion. This study investigated the conversion of oil extracted from algal biomass (*Chlorella vulgaris*) into biodiesel and evaluated the kinetic behavior of the transesterification process. The *Chlorella vulgaris* cultivated at Gubi Dam, Bauchi was extracted using *n*-hexane and the oil was transesterified into biodiesel using methanol and KOH as catalyst. The physicochemical characteristics of the oil and the biodiesel were evaluated, while GC-MS and FT-IR were used to analyze the fatty acid profile and functional groups of the fatty acid methyl ester. The Physicochemical analysis revealed transesterification reduced the viscosity from 36.52 to 3.65 mm²/s at 40 °C and the density from 960 kg/m³ to 866 kg/m³. The biodiesel met ASTM D6751 and EN 14214 limits for viscosity, density, flash point (152 °C), iodine value (31.74 g I₂/100 g) and cetane number (63.43). It also had a high heating value of 38.35 MJ/kg. Its acid value (3.02 mg KOH/g), however, exceeded the 0.50 mg KOH/g limit. GC-MS showed a fatty acid profile dominated by saturated fatty acids (C8:0–C22:0), with oleic and linoleic acids also present. FT-IR showed a strong ester carbonyl band at 1742.5 cm⁻¹, confirming conversion to methyl esters. Kinetic data were fitted to zeroth-, first- and second-order models. The first-order model gave the best fit ($R^2 = 0.997$, $k = 0.007 \text{ min}^{-1}$), followed by the second-order ($R^2 = 0.986$) and zeroth-order ($R^2 = 0.953$) models. Algal triglyceride transesterification therefore follows first-order kinetics under the conditions studied, and algal oil is a viable feedstock for biodiesel production.

Keywords: algal oil, biodiesel, transesterification, kinetic modelling, first-order kinetics

INTRODUCTION

The rapid increase in population led to continuous industrial expansion which resulted in high energy consumption to meet demand. Undoubtedly, this led to consistent combustion of fossil fuels for energy generation in the industrial and transportation sector leading to the release of vast amount of greenhouse gases and other pollutants. These accumulate in the atmosphere causing global warming, climate change, and air pollution. In addition, the extraction of these fuels left human health in peril, caused land degradation and biodiversity loss, and generates large amount of pollutants through oil spills and leakages. Therefore, the world is faced with great challenges of mitigating the environmental effects of fossil fuels and to develop a potent, clean and sustainable alternative energy sources. These challenges necessitate the need for global transition from dirty fossil fuels to clean and renewable alternatives. Transitioning to renewable energy sources such as biodiesel offers a promising solution to the environmental challenges posed by conventional fossil fuels (Verma *et al.*, 2024).

A bio-based diesel is a sustainable and renewable fuel for internal combustion prepared from various sources like soybean oil, vegetable oils, or animal fat which meet the predefined ASTM D-6751 standard (Nautiyal *et al.*, 2014). It's a non-petroleum based fuel that is made up of alkyl esters derived either from the transesterification of triglycerides (TGs) which is found in vegetable oils, animal fat or waste grease, or the esterification of free fatty acid with low molecular weight alcohol- methanol or ethanol (Lotero *et al.*, 2005) and its properties were determined by the physiochemical and calorific value of the fuel according to ISO norms (Dermibas, 2009). Interestingly, biodiesel is less toxic, less sulphur content, and biodegradable fuel from renewable sources, which is an alternative for fossil fuel for use in a sustainable approach involving economic and environmentally friendly aspects (Fant *et al.*, 2011; Yunusa *et al.*, 2013; Abubakar *et al.*, 2020; Abubakar *et al.*, 2022). However, the feedstock used for conventional biodiesel production such as rapeseed, soy bean and palm oil compete with food crops for arable land and water resources igniting food-versus-fuel conflict. Unfortunately this led to food price volatility, food insecurity, deforestation, habitat destruction and soil degradation caused by intensive farming practices. Remarkably, algal biomass has emerged as a significant resource in biofuel production due to its high lipid content, rapid growth rate and can be cultivated on non-arable land or in waste water (Mensah *et al.*, 2024).

Biodiesel derived from triglycerides extracted from algal biomass offers a sustainable solution to end fuel-versus-food conflict. Among the most important

advantages of biodiesel is that it can be used directly in existing compression ignition engines without any modifications and can be blended appropriately with petrol diesel. The exploration of biofuels from microalgae is based on their potential characteristics features which are evident through its ecofriendly nature, non-toxic characteristics, biodegradability, and lower net carbon cycle compared to conventional diesel fuel (Alberto et al., 2011). Furthermore, microalgae contribute to environmental management by capturing atmospheric CO₂ and assimilate nutrients in waste water, thereby integrating fuel production with bioremediation processes (Rawat et al., 2011). Although algal biodiesel possesses numerous advantages, its industrial viability depends on the understanding of the transesterification and kinetics studies of the process.

Consequently, optimizing every stage of algal triglycerides transesterification is necessary to improve the efficiency of the biodiesel production process. Kinetic studies describe how the rate of conversion of triglycerides to biodiesel varies with reaction conditions such as temperature, catalyst loading, and alcohol:oil molar ratio, and they provide the rate constants and activation energies needed to design, optimise, and scale up production processes (Ezzati et al., 2021). Several kinetic models, including zeroth, pseudo-first-order, second-order, and more comprehensive multi-step models accounting for the three consecutive and reversible steps of triglyceride conversion, have been developed and applied to various vegetable and waste oil feedstocks, with reaction rate constants and activation energies determined for each (Hazrat et al., 2022; Farouk et al., 2024). The establishment of mathematical models is important to explain the conversion of algal triglyceride into biodiesel. The Development of scientific relationship between factors affecting the transesterification process and kinetic modelling can help to identify the reaction behaviour and provide parameters required for the process optimization. This research aimed at investigating the kinetic modelling of algal triglycerides transesterification for sustainable biodiesel production.

MATERIALS AND METHOD

Sample collection and Oil Extraction

The algal biomass (*Chlorella vulgaris*) was cultivated and collected from open pond at Gubi Dam, Bauchi state and then transported to Science Laboratory complex, Abubakar Tattari Ali Polytechnic Bauchi for analysis. The wet biomass was dried under sunlight to remove the moisture content and ground into powder using mortar and pestle. A 500 g of the powdered sample was defatted in a Soxhlet's extractor using n-hexane as solvent. After extraction, the oil was recovered by evaporating the solvent in a rotary evaporator and the oil was characterized using physicochemical analysis.

TRANSESTERIFICATION

A 100 mL of the algae oil was transesterified using methanol and potassium hydroxide as catalyst. The resulting mixture was stirred vigorously on a magnetic stirrer for 1 hour and left over night in a separatory funnel. The produced biodiesel was collected in a beaker as upper layer of the funnel while the lower layer was discard which comprises of glycerol. The biodiesel was washed with warmed water to remove excess catalyst, methanol, and other impurities. The produced biodiesel was characterized using GC-MS, FT-IR and physicochemical analysis.

PHYSICOCHEMICAL ANALYSIS

The algal oil and its biodiesel were subjected to physicochemical analysis such as pH, density, specific gravity, viscosity, acid value, free fatty acid value, iodine value, saponification value, peroxide value, cloud, pour and flash point to determine its quality.

pH

The pH of the oil and the biodiesel were determined by inserting pH meter electrode into the samples and the pH values were recorded from the screen of the pH meter.

Density

The density of the oil and biodiesel were determined using gravimetric method. The weight of an empty 50 mL density bottle was recorded as W1, it was then filled to the mark with the oil and recorded the weight as W2. The procedure was repeated with biodiesel and the density was calculated

$$\text{Density} = \frac{W_2 - W_1}{\text{Volume}} \dots\dots\dots \text{i}$$

Specific Gravity

The specific gravity was also determined using gravimetric method. The weight of an empty 50 mL density bottle was recorded W1, it was filled to the mark with water and afterward with the samples and recorded as W2 and W3 respectively. The specific gravity is calculated

$$\text{Specific gravity} = \frac{W_3 - W_1}{W_2 - W_1} \dots\dots\dots \text{ii}$$

Kinematic Viscosity

The viscosity of the oil and biodiesel were determined by placing the viscometer in a water bath kept at 40 °C and the samples were added to and allowed to flow freely. The time taken for the samples to flow from first to second timing mark was recorded and multiplied with the viscometer calibration to obtain the viscosity.

Determination of Acid Value and Free Fatty Acid

A 50 mL solution made from a mixture of petroleum ether and ethanol at ratio 1:1 was added into a conical flask containing 2 mL of the samples and the resulting mixture was stirred vigorously for 1 hour. A 3 drops of phenolphthalein indicator was added and titrated against 0.1 M KOH until a pink color which persisted for 15 secs is obtained. The acid value and free fatty acid was calculated

$$\begin{aligned} \text{Acid value} &= \frac{TDX \times N \times 56.1}{\text{Volume}} \dots\dots\dots \text{iii} \\ \text{Free fatty acid} &= \frac{\text{Acid value}}{2} \dots\dots\dots \text{iv} \end{aligned}$$

Saponification Value

A 25 mL of freshly prepared alcoholic KOH was poured into a conical flask containing 2 g of the samples. The resulting solutions were covered and placed in a water bath for 30 mins with constant shaking. A 1 mL of phenolphthalein indicator was added into the solutions and titrated against 0.5 M HCl.

$$\text{Saponification value} = \frac{TDX \times N \times 56.1}{M} \dots\dots\dots v$$

Iodine Value

A 20 mL of chloroform was added into a conical flask containing 2 g of the samples. The resulting solutions were kept in a dark at 25 °C for 30 mins, thereafter 100 mL of distilled water and 1 ml of 30% KI were added. The resulting solution was titrated with 0.10 M sodium thiosulphate using starch solution as indicator.

$$\text{Iodine Value} = \frac{TD \times N \times 1269}{M} \dots\dots\dots vi$$

Peroxide Value

A 30 mL of glacial acetic acid-chloroform solution was added onto 5 g of the samples in a conical flask. The resulting solution was warmed on a heating mantle, after which a 0.5 mL of saturated KI and 30 mL of distilled water was added and the content was shaken vigorously to liberate iodine from chloroform layer. The mixture is titrated with 0.1 sodium thiosulphate using 1 mL of starch solution as indicator.

$$\text{Peroxide Value} = \frac{TDX \times N \times 1000}{M} \dots\dots\dots vii$$

Pour Point

The pour point was determined by placing 10 mL of the samples into test tube containing thermometer. It was placed into ice bath and the lowest temperature at which the sample was observed to flow is recorded as the pour point.

Cloud Point

The cloud point was determined by placing 10 mL of the samples into test tubes containing thermometer. The test tube was placed into ice bath and the temperature at which a distinct wax precipitation appeared was recorded as the cloud point of the oil.

Flash Point (F.P)

The flash point was determined by heating 10 mL of the samples at slow constant rate on a hot plate. The flash point was taken as the lowest temperature when an application of the test flame caused the vapor above the samples to ignite.

Table 1: physicochemical Properties of the Algae Oil

Parameters	Concentration
Yield (%)	38.4
pH	6.93
Viscosity (mm ² /s @ 40 °C)	36.52
Density (g/cm ³ @ 25°C)	0.96
Specific gravity	0.98
Acid value (mgKOH/g)	4.25
Peroxide Value (mEq/g)	7.81
Free Fatty Acid Value (mgKOH/g)	2.13
Saponification Value (mgKOH/g)	208.35
Iodine Value (gI ₂ /100g)	65.55
Cloud Point (°C)	18
Pour Point (°C)	9
Flash Point (°C)	237

The results in Table 1 revealed the physicochemical properties of the Algae oil. The oil has a pH of 6.93 which is close to 6.61 for shea butter as reported by Mudi *et al.* (2021). Notably, Oils with near neutral pH value are considered good for base catalyzed transesterification and exhibited minimal acid degradation prior to transesterification. The viscosity of 36.52 mm²/s @ 40 °C of the oil was found to be higher than 4.5 mm²/s @ 40 °C for shea butter as reported by Datti *et al.* (2020), 4.8 mm²/s @ 40 °C for Terminalia mantaly seed oil (Abubakar *et al.*, 2020) and 22.80 mm²/s @ 40 °C for Jatropha curcas seed oil (Abubakar *et al.*, 2022). The high viscosity result from unsaturated and long-chain fatty acids present in the triglyceride. The density of the oil is 0.96 g/cm³ @ 25°C which is little bit higher than 0.938 g/cm³ for shea butter (Mudi *et al.*, 2021), 0.992 g/cm³ for Soy beans (Mosisa and Endale, 2022), 0.88 g/cm³ for Jatropha curcas L. seed oil (Abubakar *et al.*, 2022), 0.92 g/cm³ for Terminalia mantaly seed oil (Abubakar *et al.*, 2020). This high density is attributed to presence of long-chain fatty acid, unsaturation and cultivation condition which leads to high energy density. The specific gravity of oil in this study is 0.98 which is greater than 0.86 for Allanblackia seed oil (Balogun *et al.*, 2024) and 0.95 for Desert seed oil (Joseph, 2025). The acid value of the oil is 4.25 mgKOH/g which is higher than 0.504 mgKOH/g (*Sterculia setegers*), 0.463 mgKOH/g (*Butyrospermum parkii*), 0.340 mgKOH/g (*Blighia sapida*), 0.250 mgKOH/g (*Schorocarya birrea*), 0.204 mgKOH/g (*Detarium microcarpum*), and 0.034 mgKOH/g (*Lophira lanceolata*) (Kyari, 2008). The higher acid value of the oil resulted from enzymatic activity, moisture content and oil with this property is suitable for base-catalyzed transesterification. The peroxide value of the oil in this study was 7.81 mEq/kg which is lower than 13.41 mEq/kg for melon seed oil, 8.33 mEq/kg (Sesame seed oil), 10.22 mEq/kg (Bitter kola) (Saeed and Shola, 2015). The peroxide value indicates primary lipid oxidation and degree of rancidity which reflects quality deterioration. The saponification value of the algae oil was 208.35 mgKOH/g is higher than 202.39 mgKOH/g (Palm oil), 191.38 mgKOH/g (Mustard oil), 187.10 mgKOH/g (soy bean oil) and 181.60 mgKOH/g (Bran oil) (Wazed *et al.*, 2023). The high saponification value indicated a predominance of short chain or medium chain fatty acid and lower molecular weight triglycerides. The iodine value of the oil is 65.55 mgI₂/g which is less than 98.80 mgI₂/g (Cashew nut oil), 93.18 mgI₂/g (Orange seed oil), 183.08 mgI₂/g (Water melon seed oil), 85.58 mgI₂/g (Paw-paw seed), and 275.55 mgI₂/g (Cherry seed) (Oghenewogaga, *et al.*, 2024). Iodine value indicates the presence of unsaturation in the oil which resulted from unsaturated fatty

acid contained in the algal triglyceride. The cloud point of the algae oil was 18 °C which similar to 18 °C (Castor oil) and in turn higher than -4 °C (soybean oil), -9.5 °C (Sunflower oil), -2 °C (Rape seed oil), -0.5 °C (Cotton seed oil), and -11 °C (olive seed oil) (Karmakar *et al.*, 2017). The pour point of the oil was 9 °C which is lower than 25 °C reported by (Idris and Usman, 2018). The flash point of the oil was 237 °C which is higher than 155 °C (*Jatropha Curcas L.*) (Abubakar *et al.*, 2022), while lower than 310 °C (Soybean) (Uchenna, 2012).

Table 2: physicochemical Properties of the Algae Biodiesel

Parameters	Concentration
pH	7.27
Viscosity (mm ² /s @ 40°C)	3.65
Density (kg/m ³ @ 25°C)	866
Specific gravity	0.89
Acid value (mgKOH/g)	3.02
Peroxide Value (mEq/g)	2.56
Free Fatty Acid Value (mgKOH/g)	1.51
Saponification Value (mgKOH/g)	187.32
Iodine Value (gI ₂ /100g)	31.74
Cloud Point (°C)	10.00
Pour Point (°C)	6.00
Flash Point (°C)	152.0
Cetane Number	63.43
Cetane Index	60.11
High Heating Value (MJ/kg)	38.35

The physicochemical properties of the algal biodiesel revealed the viscosity of 3.65 mm²/s @ 40°C agrees with ASTM D6751 (1.9–6.0 mm²/s) and EN 14214 (3.5–5.0 mm²/s) standards for biodiesel. This moderate viscosity value indicates strong fuel atomization, injection, spray formation and combustion in spark-ignition engine. The lower viscosity value has a direct advantage for both engine performance and reaction engineering: lower viscosity improves fuel atomisation and injector performance relative to unconverted vegetable oil, while in the kinetic study it implies a shorter mass-transfer-limited induction period at the start of the reaction, since the oil–methanol emulsion disperses more readily when the parent oil is less viscous (Ezzati *et al.*, 2021).

The Density of the algal biodiesel in this study is 866 kg/cm³ at 25 °C falls within the range specified by ASTM D6751 (860–900 kg/m³), EN 14214 (860–900 kg/m³) standards and relatively lower than 872 kg/m³ for microalgae reported by Ariyanti *et al.* (2024). This lower density value necessary for fuel handling and determine the volume fuel delivered during volumetric injection.

The specific gravity of the algal biodiesel in this study is 0.89 and this value is attributed to low density nature of the biodiesel. This property contributed to ease and suitable fuel flow through delivery systems. The combination of low density, viscosity, and specific gravity observed in this study are relevant because these properties affect fuel injection, spray formation and atomization. Consequently, the values obtained indicated that the algal biodiesel possesses required physical characteristics to replace conventional diesel fuel.

The acid value obtained in this study was 3.02 mg KOH/g which is higher than 0.50 mg KOH/g (ASTM D6751 standard for biodiesel) and 0.50 mg KOH/g reported by Ariyanti *et al.* (2024) for microalgal biodiesel. Higher acid resulted from incomplete conversion of triglyceride to biodiesel and hydrolysis which can lead to corrosion and adversely affect storage stability and fuel quality. Therefore, the algal biodiesel requires further purification to reduce the acid content or needs better tranesterification process optimization.

The peroxide value indicates the degree of primary oxidation. The value obtained in this study was

2.56 mEq/g which is relatively low compared relevant studies. This lower peroxide value can be connected to high concentration of saturated fatty acid in the triglycerides used for the biodiesel production as revealed by the GC-MS analysis. This is important because primary oxidation can adversely affect biodiesel quality during storage leading to increased acidity, viscosity and peroxide formation and can eventually result in the formation of undesirable degradation products (Ariyanti *et al.*, 2024).

The saponification value in this study was 187.32 mgKOH/g described the molecular weight of fatty acid present in the biodiesel. Higher saponification values is generally attributed to short chain fatty acid in the methyl ester. While iodine value (31.74 g I₂/100 g) indicates degree of unsaturation in the algal biodiesel. The result agrees with the GC-MS profile, which showed several saturated fatty acids alongside oleic and linoleic acids. The iodine value in this study is lower than 120 g I₂/100 g EN 14214 standard for biodiesel.

The cloud point and pour point in this study are 10.00 °C and 6.00 °C respectively. Collectively these properties described the low-temperature flow behaviour of the fuel and are strongly influenced by the proportion of long-chain saturated esters present in the methyl ester. Fuels containing high level of long-chain saturated fatty acids typically exhibit poorer cold-flow properties because the esters crystallise at lower temperatures. The moderate cloud and pour point values obtained in this study suggested a balanced fatty acid distribution leading to better cold-flow performance against the higher cetane number and oxidative stability normally associated with saturated esters (Bamgboye & Hansen, 2008), reflecting the mixed saturated–unsaturated composition of the algal oil (Table 3).

The flash point (152.0 °C) exceeds the minimum limit specified by both ASTM D6751 (93 °C) and EN 14214 (120 °C). A high flash point reduces the risk of auto-ignition during transport, handling, and storage, which is a considerable operational benefit in the context of small-scale or informal biodiesel handling common in developing regions (Kumar & Sharma, 2022). The result revealed the safety advantage algal biodiesel.

The cetane number 63.43 and cetane index 60.11 observed in this study indicates good ignition quality of the algal biodiesel. These values are above 45 (cetane number) ASTM D675 and 51 (cetane number) EN 14214 standard for biodiesel. Cetane number measures the tendency of diesel fuel to ignite after injection into a compression ignition engine. A higher cetane number generally corresponds to a shorter ignition delay and improved ignition

characteristics. The higher value can related to high composition of saturated and long chain fatty acid in the methyl ester.

The high heating value (38.35 MJ/kg) is within the range typically reported for biodiesel (37–41 MJ/kg) and only modestly below that of petroleum diesel, confirming that the algal biodiesel retains most of the energy density of conventional diesel while offering the renewability and emissions advantages associated with biological feedstocks (Mata et al., 2010). The high heating value of 38.35 MJ/kg implies that the fuel contains considerable chemical energy and can release required energy during combustion.

Table 3: Fatty acid Profile of Algal Triglycerides from GC-MS Analysis

S/N	Retention Time	Structure	Chemical Formula	Common Name
1	5.8	C8:0	C ₈ H ₁₆ O ₂	Caprylic acid
2	8.3	C10:0	C ₁₀ H ₂₀ O ₂	Capric acid
3	8.5	C12:0	C ₁₂ H ₂₄ O ₂	Lauric acid
4	8.7	C14:0	C ₁₄ H ₂₈ O ₂	Myristic acid
5	9.2	C16:0	C ₁₆ H ₃₂ O ₂	Palmitic acid
6	9.6	C18:1	C ₁₈ H ₃₆ O ₂	Oleic acid
7	10	C18:0	C ₁₈ H ₃₆ O ₂	Stearic acid
8	18.5	C18:2	C ₁₈ H ₃₂ O ₂	Linoleic acid
9	19.9	C20:0	C ₂₀ H ₄₀ O ₂	Arachidic acid
10	20.6	C22:0	C ₂₂ H ₄₄ O ₂	Behenic acid

Table 3: The GC-MS analysis revealed the fatty acid composition of the algal triglycerides is dominated by medium to long chain saturated fatty acid. These ranged from caprylic acid (C8:0), lauric acid (C12:0), myristic acid (C14:0), palmitic acid (C16:0), stearic acid (C18:0), arachidic acid (C20:0) to behenic acid (C22:0). These saturated fatty acids improve cetane number, ignition properties, energy density and oxidative stability. However high concentration of saturated fatty acid caused the chains to pack together in a cold weather forming crystals leading to poor flow property. The result also indicated the presence of unsaturated fatty acids including oleic (C18:1) and linoleic (C18:2) acids. The unsaturated fatty acids improved cold flow properties, better viscosity characteristics and lowers melting point. The findings indicated several composition depended properties of algal oil as sustainable feed stock for biodiesel production.

Table 4: FT-IR Analysis of Algal Biodiesel

Wavenumber (cm ⁻¹)	Types of Vibration	Characteristic Band	Functional Group
3006.1	Stretching	Weak band	C=C-H (Alkene)
2920.4	Asymmetric Stretching	Strong band	-CH ₃ (Alkane)
2840.5	Symmetric stretching	Strong band	-CH ₃ and -CH ₂ (Alkane)
1742.5	Stretching	Very strong and sharp	-C=O (ester carbonyl)
1457.4	Bending	Medium band	-CH ₂ (Alkane)
1235.6	Stretching	Strong band	-C-O (O-C=O)
1161.1	Stretching	Strong band	C-O-C (ester)

Fourier Transform Infrared characterization of the algal biodiesel revealed the presence of characteristic band at 3006.1 cm⁻¹ which indicates **C=C-H stretching, this signified the presence of unsaturation in the fatty acid methyl ester which corresponds with the result of GC-MS analysis of the algal tryglyceride. The strong streatching band at 2920.4 and 2840.4 cm⁻¹ result from the presence of alkanes, indicating a combination of both saturated and unsaturated fatty acid in the algal fatty acid methyl ester. A very strong and sharp peak at 1742.5 cm⁻¹ indicated the presence of ester carbonyl (C=O) stretching formed during transterification and this confirms the conversion of triglycerides into fatty acid methyl ester which aligns with the report of Bose, (2018). The strong peaks which appeared at 1235.6 and 1161.1 cm⁻¹ are due to presence of O-C=O and C-O-C ester linkage vibrations respectively, confirming the esterified nature of the biodiesel. Notably the absence of FT-IR broad absorption in the 3200-3600 cm⁻¹ region which indicates O-H stretching vibration due to alcohol or moisture in the biodiesel. The absence of this band suggests a complete purging of unreacted methanol, indicating the purity of the biodiesel (Knothe, et al., 2005).**

Table 5. Calculated kinetic parameters for algal triglyceride transesterification

Kinetic model	Linear kinetic equation	Rate constant, <i>k</i>	Unit of <i>k</i>	Intercept	R ²
Zeroth order	C ₀ - C _t = <i>kt</i> + <i>b</i>	0.399	mg mL ⁻¹ min ⁻¹	3.081	0.953
First order	ln(C ₀ /C _t) = <i>kt</i> + <i>b</i>	0.007	min ⁻¹	0.006	0.997
Second order	1/C _t - 1/C ₀ = <i>kt</i> + <i>b</i>	1.45 × 10 ⁻⁴	mL mg ⁻¹ min ⁻¹	3.15 × 10 ⁻⁵	0.986

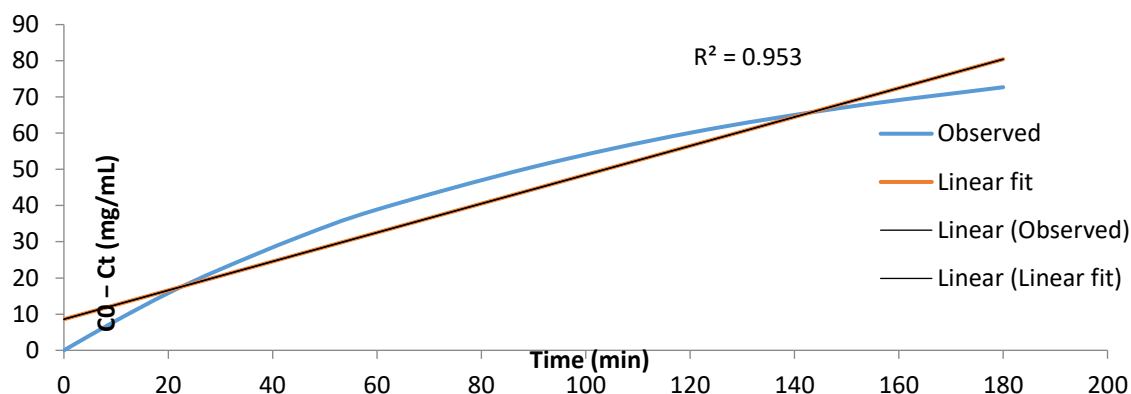


Fig 1: Zeroth Order Kinetic of Algal Biodiesel

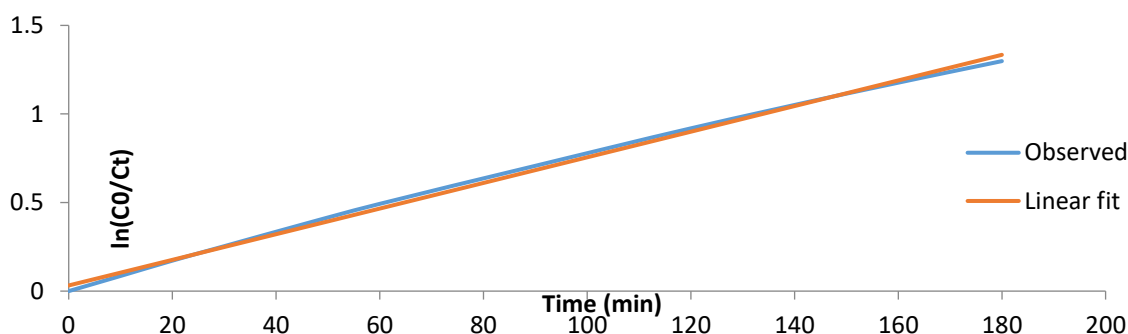


Fig 2: First Order Kinetic of Algal Biodiesel

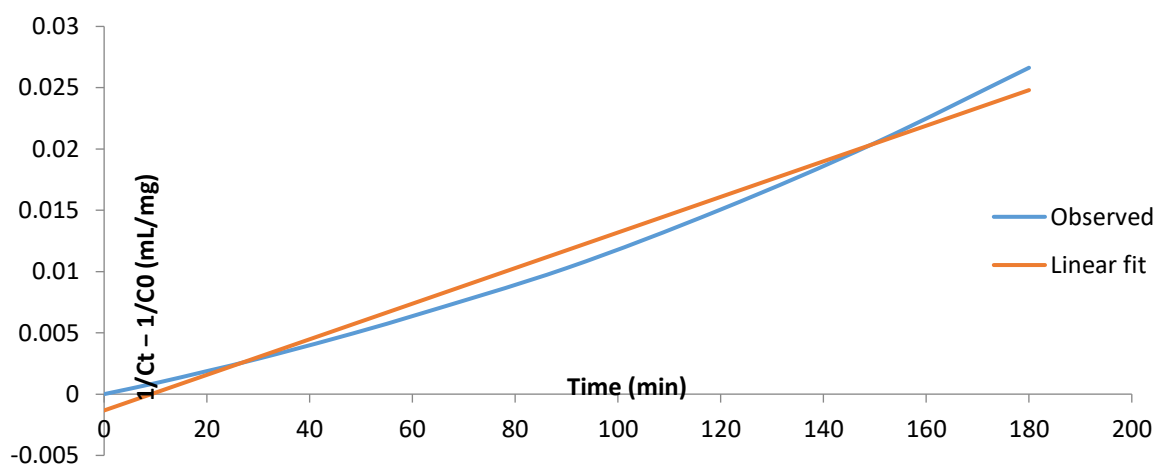


Fig 3: First Order Kinetic of Algal Biodiesel

Table 5: Shows the reaction kinetic of algal triglycerides conversion into biodiesel was studied by fitting the experimental data into three integrated rate models: the zeroth-order, the first-order, and the second-order model. The strongest correlation with the experimental data $R^2 = 0.997$ was observed for the first-order model, followed by $R^2 = 0.986$ for the second-order model, while $R^2 = 0.953$ was obtained for the zeroth-order model. The results of the kinetic studies also illustrated a continuous decline in the concentration of algal triglycerides with increasing reaction time. This progressive decreasing pattern confirmed the continuous conversion of the algal triglycerides into biodiesel during transesterification process. The zeroth-order model has a relatively high $R^2 = 0.953$ and a rate constant of $0.399 \text{ mg mL}^{-1} \text{ min}^{-1}$. However its fit was weaker compared to those obtained with the first and second-order models. This finding also illustrated that the reaction rate was inadequate to be described by a rate constant over the entire reaction period. The highest correlation coefficient, $R^2 = 0.997$ and a rate constant of 0.007 min^{-1} , was obtained for the first-order kinetic model. The fitted concentrations were near the experimental values throughout the transesterification period. The results therefore revealed the complete conversion of algal triglycerides into biodiesel under the observed experimental conditions follow first-order kinetics. This is consisted with the finding of Nguyen *et al.* (2021) which reported a first-order kinetics for the in-situ transesterification of *Chlorella vulgaris*. The present result is also agree with the report of Atashkar and Saidi (2024), who investigated the conversion of *Nannochloropsis* microalgae-derived oil into biodiesel using a ZnAl layered double hydroxide catalyst. Their investigation reported a pseudo-first-order kinetic model and an activation energy of 28.53 kJ/mol, achieving above 90% fatty acid methyl ester yield

under optimized conditions. The agreement in kinetic order suggests that first-order or pseudo-first-order behaviour can occur in algal biodiesel systems even when different algal feedstocks and catalysts are employed. A similar first-order response was reported recently by Binhweel *et al.* (2025) who applied first-order kinetic modelling for the transesterification of *Ulva lactuca* oil into biodiesel and reported an activation energy of 46.35 kJ/mol. The report described the transesterification process as temperature-dependent, endothermic and nonspontaneous under their experimental conditions. The R^2 value produced by second-order model was 0.986 with a rate constant of $1.45 \times 10^{-4} \text{ mL mg}^{-1} \text{ min}^{-1}$. The model explained the obtained experimental data comprehensively, but its fit was lower than the first-order model. The stronger performance of the first-order model in this study can be explained in terms of the changing substrate concentration in the course of the transesterification process. It was found that, as the observed rate of disappearance decrease, the concentration of the algal triglycerides also decreased. The first-order model represent more realistic trend of the concentration observed in the experiment than the zeroth-order model, which assumes a constant rate. The experimental values support this interpretation because the rate of concentration decrease was higher at the beginning of the reaction and lower toward the end.

CONCLUSION

This study revealed that oil extracted from algal biomass (*Chlorella vulgaris*) possessed necessary required property needed for biodiesel feedstock. The algal triglyceride was converted to biodiesel via base-catalysed transesterification and most fuel properties of the product met ASTM D6751 and EN 14214 requirements, including viscosity, density, flash point, iodine value, cetane number and heating value. Kinetic studies of process showed that the concentration of triglycerides decrease linearly with time and the first-order model gave highest correlation ($R^2 = 0.997$, $k = 0.007 \text{ min}^{-1}$).

Conflict of Interest

The authors declare no conflict of interest.

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