

Production and Physicochemical Characterization of Biodiesel from *Senegalia macrostachya* seed oil

Aminu Shehu Zagga¹, Tambari Ishaka¹, Garba, Umar², Ahmad, A³, Abubakar Umar⁴ & Anas Lawal Augie⁵

¹Department of Physics Shehu Shagari College of Education, Sokoto.

²Department of Chemistry Shehu Shagari University of Education, Sokoto.

³Department of Applied Chemistry, College of Science and Technology, Ummaru Ali Shinkafi Polytechnic Sokoto.

⁴Department of Science Technology Waziri Umaru Federal Polytechnic Birnin Kebbi.

⁵Department of Chemistry Adamu Augie College of Education, Argungu.

Corresponding Author's Email & Phone No.: aminuzagga23@gmail.com, +2348030481524

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ABSTRACT

The search for locally available, non-edible and renewable feedstocks for biodiesel production has increased interest in underutilized oil-bearing plants. This study investigated the physicochemical characteristics of *Senegalia macrostachya* seed oil before and after refining and evaluated its suitability for biodiesel production. Mature seeds collected from Wanke village, Shagari Local Government Area, Sokoto State, Nigeria, were dried, milled and extracted with n-hexane using Soxhlet extraction. The crude oil was refined by degumming, neutralization and bleaching, and its physicochemical properties and fatty-acid profile were determined. Biodiesel was produced by methanol-based transesterification using a calcium oxide catalyst prepared from mussel shells. The crude oil yield was $32.50 \pm 0.20\%$, while the reported refined-oil recovery was $13.95 \pm 0.32\%$. Refining reduced moisture, viscosity, acid value, free fatty acids and peroxide value from 1.24 ± 0.05 to $0.31 \pm 0.02\%$, 42.65 ± 0.72 to 38.41 ± 0.63 cSt, 5.84 ± 0.16 to 1.92 ± 0.08 mg KOH/g, 2.94 ± 0.08 to $0.96 \pm 0.04\%$, and 6.32 ± 0.21 to 2.14 ± 0.11 meq/kg, respectively. The major fatty acids reported in the oil were 9-hexadecenoic acid, oleic acid, linoleic acid, palmitic acid and stearic acid. Biodiesel yield was 86.34%, with specific gravity of 0.83 ± 0.01 , kinematic viscosity of 2.92 ± 0.24 cSt at 40 °C, moisture content of $0.03 \pm 0.00\%$, acid value of 0.48 ± 0.02 mg KOH/g, iodine value of 42.36 ± 0.02 g I₂/100 g, cetane number of 58.12 ± 0.20 , copper-strip corrosion rating of 1b and higher heating value of 42.06 ± 0.013 MJ/kg. Sulfated ash was $0.009 \pm 0.001\%$, the results indicate that *S. macrostachya* seed oil is a promising underutilized feedstock for biodiesel production, although further work should include full ASTM/EN fuel-quality testing, oxidative-stability measurement, FAME purity determination and engine-performance evaluation.

Keywords: biodiesel; *Senegalia macrostachya*; seed oil; transesterification; calcium oxide catalyst; fatty acids; physicochemical properties

1.0 INTRODUCTION

Due to the fuel crises, fluctuation of oil price and the emission of greenhouse gases there is needs for the production of ecofriendly diesel fuel (Usman *et al.*, 2022). Global energy demand continues to rise, driven by industrialization and population growth, while fossil fuel reserves are depleting (Akram *et al.*, (2022)). Biodiesel, a biodegradable, non-toxic, and low-emission alternative to petrodiesel, has gained attention as a sustainable solution. However, the use of edible oils (e.g., soybean, palm, rapeseed) raises ethical concerns regarding food vs. fuel competition (Devarajan *et al.*, 2022). Consequently, non-edible oilseed plants, particularly those adapted to marginal lands, are increasingly studied. *Senegalia macrostachya* (syn. *Acacia macrostachya*) belongs to the family *Mimosaceae* and is a multipurpose shrub native to West and Central Africa (Drabo *et al.*, (2023); Zagga *et al.*, 2025). Known locally in Niger and northern Nigeria as “Ya’yan Gardaye”, its seeds are currently underutilized or consumed only during famine.

Preliminary phytochemical studies indicate a high lipid content (Zagga *et al.*, 2025). However, no systematic investigation exists on its biodiesel potential. This research paper, therefore, aims to: extract and quantify oil from *Senegalia macrostachya* seeds, produce biodiesel transesterification and characterize the biodiesel’s physicochemical properties.

2.0 MATERIALS AND METHODS

2.1 Sample Collection and Identification

Mature pods of *Senegalia macrostachya* were collected from wild shrubs in Wanke village along Longu bush Shagari local government area Sokoto state, Nigeria. The plant were identified and authenticated at the Botany unit Department of Biological sciences faculty of chemical and life sciences Usmanu Danfodiyo University Sokoto. Seeds were manually removed from seed pod, cleaned, air-dried for 7 days and grounded into fine powder and preserve until use.

2.2 Oil Extraction

The seed powders' 250g were extracted using a Soxhlet apparatus with n-hexane for 8 hours (AOAC, 2019). The

$$\text{Oil Yiled (\%)} = \frac{\text{mass of oil extract}}{\text{mass of seed powder}} \times 100 \dots\dots\dots(1)$$

2.3 Purification of Extracted Oil**2.3.1 Preparation of Activated Carbon**

The pre-treated adsorbents (charcoal) were activated using chemical activation method. The process mainly divided into two stages namely; the carbonization and activation stage. The pre-treated charcoal was reacted with phosphoric acid (85%) to inhibit the formation of tar and other unwanted particles during carbonization (Hernandez-Montoya *et al.*, 2012). The mixture which was exothermic was continuously stirred for two minutes for proper contact of the acid with the charcoal and then mixed with distilled water to dissolve the filtered and the residue was allowed to dry in an oven at temperature (105°C) for three (3) hours (Kamalu *et al.*, 2012). The dry residue was carbonized in a furnace at temperature (600°C) for thirty (30) minutes after which it was allowed to cool. The oil was purified or refine mainly in three stages. Namely; degumming, neutralizing and bleaching stages.

2.3.2 Degumming Stage

The extracted oil from *S. macrostachya* seed was degummed by the addition of boiled water. The mixture was stirred for 2 minutes and allowed to stand in the separating funnel. Two layers were obtained, the oil layer and the water layer containing the gumming materials. The lower aqueous layer containing gum was decanted leaving the upper layer containing the oil. The procedure was repeated to ensure removal of most gums (Gharby, 2022).

2.3.3 Neutralization

The degummed oil (60g) was poured into a beaker and heated at temperature (80°C) on a water bath, then (40

$$\text{Refractive index } R_i = R + K (T_1 - T_2) \dots\dots\dots(2)$$

Where R_i = refractive index reduced to standard temperature, R = Reading obtained at temperature T ,

T_1 = standard temperature 25°C, T_2 = Temperature at which reading was taken K = Substituting factor (constant) 0.000365 for oil

2.4.2 Determination of Colour

$$\text{Colour} = (aY + 5bR) \text{ or } (aY + 10bR) \dots\dots\dots(3)$$

Where a = sum of various yellow slides (Y) used, b = sum of the various red (R) slides used, $Y+5b$ is the mode of expressing the colour of light coloured oil and $Y+10R$ is for the dark colour oil.

solvent was removed under reduced pressure at 45°C using a rotary evaporator. Oil yield content was calculated using equation 1below:

cm^3 of 0.1M) was added, stirred to a uniform mixture. Sodium chloride was added to help settle out the soap formed. This was transferred into a separating funnel and allowed to stand for 1 hour. The soap formed was separated from the oil. Hot water was added again and again to the oil until the soap remaining in solution was removed. The neutralized oil was then drawn off into beaker (Gharby, 2022).

2.3.4 Bleaching

The neutralized *Senegalia macrostachya* seed oil (50g) was poured into a beaker and heated to at 90°C, activated carbon (15% by weight of oil) was then added, the mixture was stirred continuously for 30 minutes. The temperature was allowed to rise to 110°C for 10 minutes. The content was filtered while hot at temperature 70°C (Gharby, 2022).

2.4 Determination of Physical and Chemical Properties of Oil

The physicochemical properties of the oil was determined via the following method:

2.4.1 Determination of Refractive Index

The prism of the instrument was clean thoroughly and oil sample (2 drops) was placed on the prism. The temperature of the oil was allowed to equilibrate with that of the thermostatic fluid and reading of the thermometer was noted. The knob of the instrument was set and the fluid was separated by a sharp line dividing the field of view into two equal halves and when line conceded with the spot marks "X" in the field of the view. The reading was taken at this point that is at normal temperature of 25°C but 40-60°C is for high melting fats (Gharby, 2022).

$$\text{Refractive index } R_i = R + K (T_1 - T_2) \dots\dots\dots(2)$$

The colour content of the sample was determined using method adopted by Hussain. (2023). The liquid oil sample was placed into 1M cell using lovibond tintometer. The colour was determined at temperature (30°C) by achieving the best possible match with the standard colour slides of red and yellow indices. The result was calculated using equation 3 below;

2.4.3 Determination of Specific Gravity

A specific density bottle was washed, dried and weighed (W_1). It was filled with distilled water, weighed as W_2 . The water was poured off and the bottle was dried then filled with the *S. macroatachya* seed oil and weighed

(W₃). The experiment was carried out in triplicate. The specific gravity was calculated using equation 4 below:

$$\text{Specific Gravity} = \frac{W_2 - W_1}{W_3 - W_1} \dots\dots\dots (4)$$

2.4.4 Determination of Moisture Content

Senegalia macroatchaya seed oil (2g) was heated at 100°C in an oven for 50 minutes. The oil was removed and placed in the desicator to prevent water mixture to it,

then every ten (10) minutes the oil sample was removed and re-weighed. The process was repeated until a constant weight was obtained.

$$\text{Moisture contents (\%)} = \frac{W_2 - W_3}{W_2 - W_1} \times 100 \dots\dots\dots (5)$$

3.3.4.5 Determination of Viscosity

The oil was charged into a viscometer via suction force in a viscometer bench apparatus. The viscometer bath was set to a temperature (40°C) and the oil sample was allowed to come through the bath after fifteen (15)

minutes. Suction force was then applied to the Viscometer's thinner arm to draw the oil sample slightly above the upper timing mark. Afflux time of the sample as it flows freely from the upper timing mark to the lower timing mark was recorded. The viscosity was determined by ASTM method (ASTM D-93).

$$\text{Kinematic viscosity} = \text{time of fall} \times \text{stoke constant} \dots\dots\dots (6)$$

2.4.6 Determination of Saponification Value

The method described by Muhammad *et al.* (2020) was used for this determination. The oil sample (2g) was weighed into a conical flask (250cm³) and ethanolic potassium hydroxide (25cm³ of 0.1M) was added. The conical flask containing the mixture was heated for five

minutes with occasional shaking to ensure complete dissociation of oil. The mixture was allowed to cool and slowly titrated against hydrochloric acid (0.5M) and 2 drops phenolphthalein indicator until the colour changes from purple to colorless. Saponification value was calculated by using equation 7 below:

$$\text{Saponification value} = \frac{56.1M(V_0 - V_1)}{W} \dots\dots\dots (7)$$

Where V_0 = Blank titre value, V_1 = Sample titre value, W = Weight of sample, 56.1 = Equivalent weight of KOH, M = Molar concentration

2.4.7 Determination of Ester Value

Ester value was calculated using equation 8 below.

$$\text{Ester Value} = \text{Saponification Value} - \text{Acid Value} \dots\dots\dots(8)$$

(Gafar *et al.*, 2012).

2.4.8 Determination of Unsaponifiable Matter

After the titration of the Saponification value, KOH solution (1cm^3 of 3M) was added to the solution and transferred into separating funnel and was washed with distilled water (50cm^3), with diethyl ether (50cm^3). The solution was extracted and the extract (the colourless solution) was separated from the lower pink solution. Distilled water (20cm^3) was used to

wash the solution each time separating the extract from the residue, until the wash water gave a neutral pH. Then, KOH (20cm³ of 0.5M) and distilled water (20cm³) were added, the solution swirled and the pink extract collected upon complete separation. The pink extract was heated in a crucible of known weight to dryness, cooled in a desiccator and re-weighed. The unsaponifiable matter was calculated using equation 9;

$$\text{Unsaponifiable matter} = \frac{100(A-B)}{W} \dots\dots\dots (9)$$

Where A = weight in g of the residue, B = weight in g of the free fatty acid in the extract, W = weight in g of the sample

and transferred into a conical flask (250cm³) to which ethanol (50cm³) was added. The content was titrated against KOH (0.1M) using phenolphthalein indicator until it changes to pink colour. Acid value was calculated using equation 10

2.4.9 Determination of Acid Value

Method describe by Muhammad *et al.* (2020) was used for this determination. The oil sample (2g) was weighed

$$\text{Acid Value} = \frac{56.1 \times V \times M}{W} \dots \dots \dots (10)$$

Where V= volume of KOH used (cm³), M = Molarity of KOH (oil), W= weight of oil sample (g), 56.1 = molecular weight of KOH (g)

$$\text{FFA} = \frac{28.5 \times V \times M}{W} \dots\dots\dots(11)$$

2.4.11 Determination of Iodine Value

The method described by Muhammad *et al* (2020) was use for this determination. A measured quantity oil (0.5g) sample was weighed into conical flask (250cm³), acetic acid (10cm³) was added and the mixture stirred until the oil sample completely dissolved in the acid. Iodine monochloride (20cm³) was added to the mixture and stirred, then incubated in the dark for thirty (30) minutes.

$$\text{Iodine} = \frac{(b-a) \times M \times 12.69}{W} \dots\dots\dots(12)$$

Where a = titre value of the oil, b= titre value of the blank, M = Molarity of Na₂S₂O₃, W = weight of oil used,

2.4.12 Determination of Peroxide Value

The oil of *S. macroatachya* seed (2g) was transferred into conical flask (250cm³) and (1g) of powdered potassium iodide (1g) and a solvent mixture (2:1 of glacial acetic

2.4.10 Determination of Free Fatty Acid

The same experimental procedure given above was used for the determination of FFA. This value was calculated by using equation 11 below:

Potassium iodide solution was later added to the mixture. The mixture was titrated against standardized sodium thiosulphate (0.1M) until pale straw colour was obtained. Starch indicator (2cm³) was added to the content, the purple color was observed. The titration was carried on until the colour of the solution turns colourless, the disappearance of the colour was recorded as end point. The procedure was repeated for the blank titration.

acid and trichloromethane) were then added. The solution was then placed on a water bath for five (5) minutes to complete dissolution. Potassium iodide (20cm³ 5%) was introduced and the sample titrated with Na₂S₂O (0.1M) using starch indicator. Blank experiment was similarly performed. The peroxide value was calculated using equation 13 below;

$$\text{Peroxide Value} = \frac{V_2 - V_1 \times M \times 1000}{W} \text{ meq/kg} \dots\dots\dots(13)$$

Where V₂ = titre value of oil, V₁ = titre value of blank, M = Molarity of Na₂S₂O₃, W = weight of oil in gram

on software matching with mass spectra in the library (Baki *et al.*, 2023).

2.5 Determination of Fatty Acid Profile on Oil

Gas chromatography-mass spectroscopy (GC-MS) is an analytical technique that separates the components of a mixture and characterizes each of the components based on the different rates of interaction of samples in mobile phase and the stationary phase. The technique also involves separation of alkyl esters in the mixture into their components base on boiling point and polarity.

2.5.1 Procedure

The fatty acids for both refined and unrefined oil were quantified using GC-MS machine, in the conduct of these analyses. The oil sample (2µl) was injected into the gas chromatograph at injection temperature (200°C). The oven was programmed at temperature (60-280°C/minute) and hold for five (5) minutes at temperature (280°C). All other parameters such as flow control made were set at linear velocity (49.2cm/sec) , pressure (116.9kpa), column flow (1.80ml/min), ion source temperature (200°C), interface temperature (250°C), solvent cut time (2.5 minutes), detector gain mode (relative), detector gain (0.01Lv), threshold (2000). The acquired chromatograms were base scanned and the components identified based

2.6 Preparation and Characterization of the Catalyst

The catalyst was prepared through hydrothermal treatment of swan mussel shells (*Anodonta cygnea*). The powdered shell was calcined in a muffle furnace under static air conditions at temperature (800°C) for three (3) hours and then refluxed in distilled water at 60°C for six(6) hours. The solid particles was filtered and dried in hot air oven at 105 °C overnight. The solid product was re-calcined at 800°C for three (3) hours to change the hydroxide formed to oxide (Baki *et al.*, 2023). The catalyst was characterized using X-Ray Diffraction (XRD), FT-IR and X-Ray Fluorescence (XRF)

2.7 Transesterification of the *S. macrostachya* Seed Oil

Oil sample (50cm³) was measured in beaker (250cm³) and placed on a hot magnetic plate and heated at (105°C) to remove any water present, then cooled to 62°C. The catalyst (0.5g) was weighed and mixed with methanol (8 cm³) into a beaker (250cm³). The mixture of (methanol and CaO) was covered and preheated at temperature (50°C) for two (2) minutes. The mixture was added to the oil and heated in a water bath at temperature 62°C for

three (3) hours with constant stirring. After the reaction time, the mixture was allowed to settle under gravity for twenty four (24) hours in a separating funnel. Two layers were formed; the upper layer consisted of methyl ester and residual catalyst while lower layer consisted of glycerol, and excess catalyst. After separation, the methyl ester layer was centrifuged to remove residual catalyst (Nurhayati, *et al*; 2017). The same method was adopted for the transesterification of each run based on the design of experiment

$$\text{Specific gravity} = \frac{W_1 - W_0}{W_2 - W_0} \dots \dots \dots (14)$$

Where W_0 = weight of empty beaker, W_1 = weight of beaker with sample, W_2 = weight of beaker with water.

2.8.2 Determination of Kinematic Viscosity

The biodiesel was charged into a viscometer via suction force in a viscometer bench apparatus. The viscometer bath was set to a temperature (40°C) and the sample was allowed to come through the bath after fifteen (15) minutes. Suction force was then applied to the Viscometer's thinner arm to draw the sample slightly

2.8 Physicochemical Analysis of the Biodiesel

2.8.1 Determination of Specific Gravity

An empty beaker (50 cm^3) was washed, dried weighed and labeled as (W_0). The biodiesel sample (20 cm^3) was transferred into the beaker and weighed (W_1). The weight of the oil was determined by subtracting the weight of the initial empty beaker from the weight of the final beaker filled with oil. The biodiesel was substituted with water after washing and drying the beaker and weighed (W_2). The specific gravity of the biodiesel was calculated using equation (14) below (Sani *et al.*, 2013).

above the upper timing mark. Afflux time of the sample as it flows freely from the upper timing mark to the lower timing mark was recorded. The viscosity was determined by ASTM method (ASTM D - 93). The viscosity was determined using equation 15 below; (Benedict *et al.*, 2018)

$$\text{Kinematic viscosity} = \text{Time of fall} \times \text{Stoke constant} \dots \dots \dots (15)$$

Where T = Molarity of KOH, V_B = Volume of acid used for the titration of the blank solution

V_S = Volume of acid used for the titration with sample and M = Mass of the sample used

2.8.3 Determination of Acid Value

The acid value was determined by method used by Ma *et al.* (2020). A mixture of ethanol and toluene in the (ratio 1:1) was first prepared and neutralized by potassium

hydroxide solution in the presence of two (2) drops of phenolphthalein indicator per (100 cm^3) of mixture (100 cm^3). Sample (2 g) was then weighed into conical flask (250 cm^3) plus previously neutralized mixture of toluene and ethanol (50 cm^3). A few drops of phenolphthalein indicator were added again and the content titrated against solution of ethanolic potassium hydroxide solution (0.1 M) until the indicator changes to pink colour.

$$\text{Acid value} = \frac{\text{Titre value} \times 0.1 \text{MKOH} \times 56.1}{\text{Weight of sample}} \dots \dots \dots (16)$$

Where 56.1 = molar mass of KOH expressed in grams per mole

2.8.4 Determination of Iodine Value

Sample (2.0g) was weighed into a conical flask (250 cm^3) and carbon tetra chloride (25 cm^3 of CCl_4) was added to dissolve the oil. Then Dam's reagent (25 cm^3) was added to the mixture using a safety pipette in fume chamber. Stopper was inserted and the content of the flask was vigorously swirled. The flask was placed in the dark for two and half (2.5) hours. Then, aqueous potassium iodide (KI) (20 cm^3 , 10%) and distilled water (125 cm^3) were added using a measuring cylinder. The solution was

titrated with (0.1M) sodium thiosulphate (0.1M, $\text{Na}_2\text{S}_2\text{O}_3$) solutions until the yellow color almost disappeared. Starch solution indicator (1%) was added and titration continued by adding sodium thiosulphate drop wise until blue coloration disappeared after vigorous shaking. The same procedure was used for blank test and other samples. The iodine value (I.V) was determined by using equation (17) (Akpan *et al.*, 2006; Kyari, 2008).

$$\text{Iodine value} = \frac{126.9 \times M \times (V_0 - V_1)}{W} \dots \dots \dots (17)$$

M = Concentration of sodiumthiosulphate used, V_0 = Volume of sodiumthiosulphate used for blank, V_1 = Volume of sodiumthiosulphate used for determination, W = Mass of the sample (g)

2.8.5 Higher Heating Value (HHV)

HHV of the oil sample was estimated from saponification number and iodine value using equation (18) below.

$$HHV = 49.43 - 0.041S.V - 0.015I.V \dots\dots\dots (18)$$

2.8.6 Determination of Flash Point of the Biodiesel

The flash point was determined according to ASTM D93 method. The sample was placed in the test cup to the prescribed mark in the interior of the cup. The cup was mounted on to its position on the tester. Bunsen burner was used to supply heat to the apparatus at temperature (1°C) per minute with constant stirring. A small test flame was directed into the cup intermittently. The flash point was taken as the temperature when the test flame caused the vapour above the sample to ignite (Baki *et al.*, 2023).

2.8.7 Determination of Pour Point of the Biodiesel

The biodiesel was poured in the test jar to the marked level and then stoppered with a cork fitted with high-pour thermometer. The thermometer bulb was immersed below the sample surface and the jar placed on a disk inside the bath jacket at temperature (60°C). Jar was removed from bath jacket for every decrease in temperature (3°C) and then tilted to ascertain flow of the sample. This was repeated until the sample cease to flow for a period of three seconds. The temperature at this point was recorded as the pour point of the fuel (ASTM 2010)

2.8.8 Determination of Cetane Number of the Biodiesel

The cetane number of the biodiesel was calculated using Saponification value (SV) and iodine value (IV) of the biodiesel as expressed in equation (19) below;

$$CN = 46.31 + \frac{5458}{SV} - 0.225 (IV) \dots\dots\dots (19)$$

2.8.9 Determination of Copper Corrosion of Biodiesel

Corrosion effects measurement of biodiesel based on ASTM D130 method was carried by immersing a polished strip of copper of (12mm wide and 1.5-3.0mm thick). The sample (30cm³) was heated at temperature (40°C) for three (3) hours. At the end of this test period, the copper strip was removed, washed and compared with ASTM copper strip corrosion standards.

2.8.10 Determination of Sulphated Ash

Sulphated ash was determined by placing sulphuric acid (1cm³) on a platinum crucible of known weight. Biodiesel (10cm³) was also placed on the crucible. The crucible and its contents were weighed accurately and recorded. Then they were transferred to a furnace and the temperature was raised (to 800°C) for ten (10) minutes. Afterwards, the crucible with the charred remain was taken out and cooled in a dessicator before weighing. Sulphated ash determined from the differences between the weight of crucible before being put in the furnace and the weight after cooling (Oriji and Maduga, 2016).

2.8.11 Determination of Moisture Content

A known weight of the biodiesel sample (2g) was heated at a constant temperature (100°C) in an oven for fifty (50) minutes. The sample was removed and placed in the desicator to prevent water mixture to the oil, then every ten (10) minute the sample was removed and re-weighed. The process was repeated until a constant weight was obtained (Benedict *et al.*, 2018).

2.8.12 Fatty Acid Methyl Ester Analysis

FAMES were analyzed using GC-MS 7890B, MSD 5977A Agilent Tech. 0.5ml of the sample was transferred into a (15cm³) plastic centrifuge tube (15cm³) and n-hexane (10cm³) were added and then mixed for ten (10) minutes. The mixture was centrifuge (at 3500rpm) for ten (10) minutes. The supernatant (1.0ul) was injected into GC. The oven temperature was initially set at temperature (80°C), hold time five (5) minutes, later increase to temperature (250°C) at 10°C/min, and then held for five (5) minutes. The injector, transfer and sources temperature were set at 250°C, 200°C and 150°C, respectively. The carrier gas was helium and total scan was twenty four (24) minutes.

3.0 RESULTS AND DISCUSSIONS

Table 1: Physicochemical Properties of Crude Oil from *Senegalia macrostachya* seed

Parameter	Unrefined Oil (Mean ± SD)	Refined Oil (Mean ± SD)
% Yield	32.50±0.20	13.95 ± 0.32
Moisture content (%)	1.24 ± 0.05	0.31 ± 0.02
Specific gravity (g/cm ³)	0.918 ± 0.003	0.912 ± 0.002
Refractive index	1.472 ± 0.001	1.469 ± 0.001
Viscosity at 40°C (cSt)	42.65 ± 0.72	38.41 ± 0.63
Acid value (mg KOH/g)	5.84 ± 0.16	1.92 ± 0.08
Free fatty acid (%)	2.94 ± 0.08	0.96 ± 0.04
Peroxide value (meq/kg)	6.32 ± 0.21	2.14 ± 0.11

Iodine value (g I ₂ /100 g)	101.37 ± 1.15	98.45 ± 0.96
Saponification value (mg KOH/g)	191.52 ± 1.28	188.94 ± 1.07
Unsaponifiable matter (%)	1.18 ± 0.04	0.73 ± 0.03
Ester value (mg KOH/g)	185.68 ± 1.12	187.02 ± 1.05

Table 1 presents the physicochemical properties of unrefined and refined oil obtained from *Senegalia macrostachya* seeds. The oil yield was $32.50 \pm 0.20\%$ for the unrefined oil but decreased to $13.95 \pm 0.32\%$ after refining. The reduction in yield is expected because refining removes non-triglyceride materials, including gums, free fatty acids, pigments and other impurities. The unrefined yield obtained in this study is within the range reported for several Nigerian underutilized seed oils. For example, Ifijen and Nkwor (2020) reported oil yields of approximately 34–55.39% for selected Nigerian plant seeds. The relatively moderate yield obtained from *S. macrostachya* therefore indicates that its seeds have appreciable potential as an oil-bearing raw material. In addition, recent work on *Senegalia* seeds reported lipid contents of approximately 6–12%, demonstrating considerable variation among species and highlighting the influence of species and extraction conditions on oil recovery (Drabo *et al.*, 2024).

The moisture content decreased substantially from $1.24 \pm 0.05\%$ in the unrefined oil to $0.31 \pm 0.02\%$ in the refined oil. This reduction is desirable because high moisture can promote hydrolytic deterioration and facilitate undesirable chemical changes during storage. Similarly, the specific gravity decreased slightly from 0.918 ± 0.003 to $0.912 \pm 0.002 \text{ g/cm}^3$, while the refractive index decreased from 1.472 ± 0.001 to 1.469 ± 0.001 . These values are comparable to those reported for other vegetable and seed oils. For instance, Croton *macrostachyus* seed oil had a specific gravity of approximately 0.90 and a refractive index of 1.461 (Yigezu *et al.*, 2021), while Nigerian underutilized seed oils have generally been reported to possess specific gravities around 0.91–0.95 (Ifijien & Nkwor, 2020).

The viscosity declined from 42.65 ± 0.72 cSt in the unrefined oil to 38.41 ± 0.63 cSt after refining. This reduction may be associated with the removal of suspended and high-molecular-weight components during refining. The value for the unrefined *S. macrostachya* oil is comparable with the 42.50 cSt reported for *Tithonia diversifolia* seed oil, although it is higher than the 30.50 cSt reported for sunflower oil (Malaysian Journal of Applied Sciences, 2020).

A particularly important improvement was observed in the acid value, which declined from 5.84 ± 0.16 to 1.92 ± 0.08 mg KOH/g, representing approximately a 67% reduction. Correspondingly, the free fatty acid (FFA) content decreased from 2.94 ± 0.08 to $0.96 \pm 0.04\%$.

These changes indicate effective removal or neutralization of free fatty acids during refining and suggest improved oil quality and storage stability. The finding agrees strongly with Pan et al. (2019), who reported a reduction in acid value of perilla seed oil from 2.20 to 0.24 mg KOH/g following chemical refining. A similar reduction in FFA following refining has also been reported for avocado oil (2024).

The peroxide value also decreased considerably from 6.32 ± 0.21 to 2.14 ± 0.11 meq/kg. Since peroxide value is an indicator of primary lipid oxidation, the reduction suggests that refining improved the oxidative quality of the oil. This observation agrees with Pan *et al.* (2019), who found that refining reduced the peroxide value of perilla seed oil from 4.32 to 1.26 meq/kg. Similarly, recent research on avocado oil showed that refining reduced both free fatty acids and peroxide value, thereby improving its storage characteristics.

The iodine value decreased slightly from 101.37 ± 1.15 to 98.45 ± 0.96 g I₂/100 g. The relatively high iodine values indicate a considerable degree of unsaturation in the oil and place it within the range associated with semi-drying vegetable oils. The small decrease after refining may reflect the removal of some unsaturated minor components or limited changes during processing. The value obtained is comparable to the 104–128.9 g I₂/100 g range reported for some Nigerian underutilized seed oils (Ifijen & Nkwor, 2020) and is close to the 109 g I₂/100 g reported for *Tithonia diversifolia* seed oil (2020).

The saponification value decreased slightly from 191.52 ± 1.28 to 188.94 ± 1.07 mg KOH/g. These values are relatively high and indicate the presence of fatty acids with comparatively shorter or medium average molecular chain lengths. They also suggest that the oil could have potential applications in soap and related oleochemical industries. The values fall within the range of 137.2–210 mg KOH/g reported for selected Nigerian plant seed oils (Ifijen & Nkwor, 2020). In comparison, *Lagenaria siceraria* seed oil was reported to have a lower saponification value of approximately 159–163 mg KOH/g (Hashimu *et al.*, 2020).

The unsaponifiable matter decreased from $1.18 \pm 0.04\%$ to $0.73 \pm 0.03\%$, confirming that refining removed part of the non-glyceride fraction of the oil. In contrast, the ester value increased slightly from 185.68 ± 1.12 to 187.02 ± 1.05 mg KOH/g. The increase in ester value is

consistent with the substantial reduction in free fatty acids during refining, leaving a greater relative proportion of esterified fatty acids. Overall, the trend observed in Table 3.3 demonstrates that refining substantially improved the chemical quality of *S. macrostachya* oil, particularly by reducing moisture, free

fatty acids, acid value, peroxide value and unsaponifiable matter. This agrees with previous studies showing that refining generally improves the quality and storage stability of vegetable oils through the removal of undesirable components (Pan *et al.*, 2019; 2024).

Table 2: GC-MS composition of *Senegalia macrostachya* seed oil

Fatty Acids	URSM (%)	RSM (%)
9-hexadecenoic acid	39.15	39.71
palmitic acid	10.03	15.02
oleic acid	22.24	32.40
Stearic	7.14	6.83
linoleic acid	21.44	21.15
Total Fatty Acids	100	100

Key: URSM: unrefined *Senegalia macrostachya* seed oil, RSM; Refined *Senegalia macrostachya* seed oil

Table 2 shows that the fatty-acid profile of both unrefined *Senegalia macrostachya* seed oil (URSM) and refined *S. macrostachya* seed oil (RSM) was dominated by unsaturated fatty acids. 9-Hexadecenoic acid was the most abundant fatty acid, accounting for 39.15% in URSM and 39.71% in RSM. This was followed by oleic acid (22.24% and 32.40%) and linoleic acid (21.44% and 21.15%), while palmitic acid accounted for 10.03% and 15.02%, respectively. Stearic acid was present at 7.14% in URSM and 6.83% in RSM. The results indicate that refining produced noticeable changes in the relative proportions of the major fatty acids, particularly oleic and palmitic acids. The predominance of unsaturated fatty acids in the present study is important because fatty-acid composition strongly influences the nutritional, oxidative and fuel properties of vegetable oils. In particular, oleic and linoleic acids are important unsaturated fatty acids, while palmitic and stearic acids are saturated fatty acids. The relatively high combined proportion of oleic and linoleic acids in the present samples indicates that *S. macrostachya* seed oil is predominantly unsaturated. Such a profile can be advantageous for biodiesel production because unsaturated fatty acids generally contribute to improved low-temperature properties, although high levels of polyunsaturation can increase susceptibility to oxidative deterioration.

The present results can be compared directly with a recent study of *S. macrostachya* seeds. A 2025 study reported oleic acid (34.20%) and linoleic acid (32.49%) as the major fatty acids, followed by palmitic acid (15.42%) and stearic acid (10.99%). Compared with those findings, the present URSM contained a lower proportion of oleic acid (22.24%) and linoleic acid (21.44%), but a substantially higher proportion of 9-hexadecenoic acid (39.15%). The RSM similarly contained a lower oleic acid concentration (32.40%) than the 34.20% reported previously, while its palmitic acid

concentration (15.02%) was very close to the previously reported 15.42%. The stearic acid concentration in RSM (6.83%) was lower than the 10.99% reported in the recent study.

The relatively close values for palmitic and oleic acids in the present RSM and the recent literature provide some support for the reliability of the major fatty-acid profile. The differences between the present findings and previous studies may arise from geographical origin, genotype or provenance, environmental conditions, seed maturity, extraction method, sample preparation, refining procedure and GC–MS analytical conditions. This is particularly relevant for *Senegalia* species because recent research has demonstrated substantial differences in chemical composition among species and emphasized that individual *Senegalia* species can possess distinct compositional profiles. In addition, studies of leguminous seed oils have shown considerable variation in fatty-acid composition, with linoleic acid commonly ranging from approximately 42–62%, oleic acid from about 14–33%, and palmitic acid from approximately 5–23% among the species examined.

Refining also appears to have modified the fatty-acid distribution. Oleic acid increased from 22.24% in URSM to 32.40% in RSM, representing an increase of about 10.16 percentage points, while palmitic acid increased from 10.03% to 15.02%. Conversely, stearic acid declined slightly from 7.14% to 6.83%, while linoleic acid changed only marginally from 21.44% to 21.15%. These changes suggest that the refining process may have removed or concentrated particular lipid fractions and other minor components. The fatty-acid composition is also relevant to the biodiesel results presented in this study. The relatively high proportion of unsaturated fatty acids may contribute to favourable fuel-flow characteristics, while the presence of appreciable

saturated fatty acids such as palmitic and stearic acids may contribute positively to cetane quality and oxidative stability.

Table 3: Physicochemical properties of Biodiesel produced from *S. macrostachya* seed oil

Properties	Methyl Ester Biodiesel from <i>S.macrostachya</i> seed oil	ASTMD6751 Specification limit
Methyl Ester yield (%)	86.34	
Specific Gravity	0.83±0.01	0.81-0.90
Kinematic viscosity (cst)at 40 ⁰ C	2.92±0.24	1.9-6.0
Moisture content (%)	0.03±0.00	0.05% max
Sulphated ash (%)	0.009±0.001	0.02
Flash point (°C)	162±0.56	100-170
Pour point (°C)	-6±0.00	-15-10
Acid value(mgKOH/g)	0.48±0.02	0.8
Iodine value(gI ₂ /100g)	42.36±0.02	
Cetane number	58.12±0.20	48-65
Copper strip corrosion	1b	No.3
High Heating Value (MJ/kg)	42.06±0.013	

Table 3 presents the physicochemical properties of biodiesel produced from *Senegalia macrostachya* seed oil. The methyl ester yield obtained was 86.34%, indicating that the transesterification process was effective in converting the triglycerides in the seed oil into fatty acid methyl esters (FAMES). The yield is comparable with those reported for other non-edible and underutilized vegetable oils investigated for biodiesel production. For example, a biodiesel yield of 93.68% was reported from watermelon seed oil, while optimized *Jatropha curcas* seed oil biodiesel production has produced yields approaching 96–98% (Mujtaba *et al.*, 2023). The relatively high yield obtained in the present study therefore demonstrates that *S. macrostachya* seed oil has good potential as a feedstock for biodiesel production.

The specific gravity of 0.83 ± 0.01 falls within the range indicated in the table (0.81–0.90). Specific gravity is an important biodiesel property because it influences fuel injection, spray characteristics and the quantity of fuel delivered to the combustion chamber. Similar values have been reported for biodiesel derived from different vegetable oils. For example, *Jatropha curcas* biodiesel has been reported with specific gravity values around 0.87–0.88, while recent work on other seed oils has similarly demonstrated that transesterification generally reduces the density of the original vegetable oil (Mujtaba *et al.*, 2023). The value obtained for *S. macrostachya* is therefore within the acceptable range for biodiesel and suggests favourable fuel-injection characteristics. The kinematic viscosity of 2.92 ± 0.24 cSt at 40°C was within the stated ASTM range of 1.9–6.0 cSt. Viscosity is an important parameter because excessively viscous fuel can cause poor atomization, incomplete combustion

and injector deposits. Transesterification substantially reduces the viscosity of vegetable oils by converting high-molecular-weight triglycerides into lower-molecular-weight methyl esters. A recent study on Niger seed oil biodiesel reported a reduction in viscosity from 7.4 mm²/s for the raw oil to 3.9 mm²/s after transesterification, with the resulting biodiesel falling within the ASTM range (2022). Similarly, Angassa *et al.* (2023) reported a viscosity of 5.22 mm²/s for castor methyl ester. Therefore, the relatively low viscosity of *S. macrostachya* biodiesel indicates good fluidity and potentially favourable atomization in diesel engines.

The moisture content of $0.03 \pm 0.00\%$ was below the 0.05% maximum reported in the table. Low moisture content is desirable because water in biodiesel can promote hydrolysis, microbial growth, corrosion and deterioration during storage. ASTM D6751 identifies water and sediment among the properties requiring control in B100 biodiesel. The low moisture value obtained in the present study consequently indicates that the biodiesel was adequately dried and is less likely to experience water-associated deterioration during storage. The sulfated ash content was $0.009 \pm 0.001\%$. This parameter was found to be within the ASTM range (0.02). Sulfated ash represents inorganic residues that may originate from catalysts, metallic contaminants or other inorganic materials remaining after biodiesel processing. Such residues can contribute to deposits and ash accumulation in engine components. ASTM D6751 specifically includes sulfated ash among the quality parameters required for B100 biodiesel.

The flash point of $172 \pm 0.56^\circ\text{C}$ indicates that the biodiesel has relatively low volatility and good handling

and storage safety. Flash point is important because fuels with higher flash points are less likely to ignite accidentally during transportation and storage. Recent biodiesel research has reported high flash points for vegetable-oil-derived methyl esters. For example, recent *Jatropha curcas* biodiesel research reported flash-point values substantially above the minimum requirement. The value obtained for *S. macrostachya* is therefore favourable. However, it should be noted that ASTM D6751 primarily specifies a minimum flash point.

The pour point of $-6 \pm 0.00^\circ\text{C}$ indicates that the biodiesel can maintain fluidity at temperatures moderately below freezing. Pour point is particularly important in determining the low-temperature operability of biodiesel. The value obtained falls within the -15 to 10°C range presented in the table. A recent study of *Jatropha curcas* biodiesel reported pour points of approximately 2 – 2.3°C , demonstrating that cold-flow behaviour varies considerably with feedstock and fatty-acid composition (Mujtaba *et al.*, 2023). The relatively low pour point of *S. macrostachya* biodiesel is therefore advantageous, particularly when compared with biodiesels having higher pour points.

The acid value of 0.48 ± 0.02 mg KOH/g is low and below the 0.8 mg KOH/g maximum indicated in the table. Acid value reflects the amount of free fatty acids and acidic compounds present in biodiesel. A low acid value generally indicates effective conversion and purification and reduces the possibility of corrosion in engine fuel systems. A recent study of Niger seed oil biodiesel reported a reduction in acid value from 14 mg KOH/g in the original oil to 0.36 mg KOH/g after biodiesel conversion, demonstrating the effectiveness of transesterification in reducing acidity. Similarly, recent *Jatropha* biodiesel research reported an acid value of 0.463 mg KOH/g (Desta *et al.*, 2025). The value of 0.48 mg KOH/g obtained in the present study therefore indicates satisfactory fuel quality.

The iodine value of 42.36 ± 0.02 g I₂/100 g is relatively low, indicating a relatively low degree of unsaturation in the constituent fatty acid methyl esters. Iodine value is related to the number of carbon-carbon double bonds in biodiesel and is therefore associated with oxidative stability. Biodiesels containing highly unsaturated fatty acids tend to be more susceptible to oxidation during storage. Research on biodiesel feedstocks has shown that iodine value is strongly related to fatty-acid composition and can influence oxidation behaviour and deposit formation (Angassa *et al.*, 2023; Mujtaba *et al.*, 2023). The relatively low iodine value of *S. macrostachya* biodiesel may therefore indicate better resistance to oxidative deterioration compared with biodiesels having

substantially higher iodine values. The cetane number of 58.12 ± 0.20 indicates good ignition quality. The value lies within the range of 48–65 reported in the table and is higher than the minimum cetane requirements generally applied to biodiesel. Cetane number is an important indicator of ignition quality because a higher cetane number is generally associated with shorter ignition delay and smoother combustion. Recent biodiesel studies have reported cetane numbers within similar ranges. For instance, watermelon seed biodiesel had a cetane number of approximately 53.17, while castor methyl ester has been reported at approximately 54.8 (Mujitaba *et al.*, 2023). Thus, the cetane number of 58.12 obtained from *S. macrostachya* biodiesel indicates favourable ignition characteristics.

The copper strip corrosion rating of 1b indicates relatively low corrosive activity. Copper-strip corrosion testing is used to determine the tendency of fuels to corrode copper and copper-containing components of fuel systems. ASTM D6751 includes copper-strip corrosion as one of the required quality parameters for biodiesel. A rating of 1b is considerably better than the No. 3 maximum value and therefore suggests that the biodiesel has acceptable corrosive behaviour. Comparable biodiesel studies have reported copper-strip corrosion ratings of approximately 1, supporting the suitability of properly processed vegetable-oil biodiesel for fuel applications (Enkataramana *et al.*, 2022).

The high heating value of 42.06 ± 0.013 MJ/kg indicates that the biodiesel possesses substantial energy content. Heating value is important because it determines the amount of energy released during combustion. The result obtained in this study is comparable with values reported for several plant-derived biodiesels. For example, watermelon seed biodiesel was reported to have a calorific value of 40.10 MJ/kg, whereas Niger seed biodiesel had a reported value of approximately 40.40 MJ/kg (Mujtaba *et al.*, 2023). The slightly higher value observed for *S. macrostachya* suggests that its methyl esters have favourable energy characteristics for use as a diesel substitute.

Finally, the physicochemical results demonstrate that biodiesel produced from *S. macrostachya* seed oil possesses good fuel-quality characteristics, particularly its relatively high methyl ester yield (86.34%), acceptable specific gravity, low kinematic viscosity, low moisture content, high flash point, low pour point, low acid value, relatively low iodine value, high cetane number, favourable copper-strip corrosion rating and high heating value. These properties compare favourably

with those reported for biodiesel produced from several other non-edible and underutilized seed oils.

4.0 CONCLUSION

This study demonstrates that *S. macrostachya* seeds can provide an appreciable quantity of extractable oil and that the oil can be converted to biodiesel through calcium-oxide-catalyzed transesterification. Refining improved several important feedstock properties, particularly moisture, acid value, free fatty acid content, peroxide value and unsaponifiable matter. The reported biodiesel yield of 86.34% and the measured viscosity, acid value, cetane number, copper-strip corrosion and heating value indicate promising fuel characteristics. However, sulfated ash is also found within the region (0.02 mass%) value commonly applied to B100 biodiesel. Accordingly, *S. macrostachya* should be regarded as a promising biodiesel feedstock.

5.0 RECOMMENDATIONS

- i. Further study to optimize methanol-to-oil molar ratio, catalyst loading, reaction temperature and reaction time to improve biodiesel yield above 86.34% should be carried out
- ii. Determination of free and total glycerin, residual methanol, phosphorus, sulfur, sodium and potassium, carbon residue and oxidation stability should be also carried
- iii. Measure cloud point and cold-soak filtration properties in addition to pour point.
- iv. The conduct of engine-performance and exhaust-emission studies using B100 and appropriate biodiesel–diesel blends should be also investigated

REFERENCES

- Akram, F., Haq, I. U., Raja, S. I., Mir, A. S., Qureshi, S. S., Aqeel, A., & Shah, F. I. (2022). Current trends in biodiesel production technologies and future progressions: A possible displacement of the petrodiesel. *Journal of Cleaner Production*, 370, 133479. <https://doi.org/10.1016/j.jclepro.2022.133479>
- Angassa, K., Tesfay, E., Weldmichael, T.G., Kebede, S. (2023). Response Surface Methodology Process Optimization of Biodiesel Production from Castor Seed Oil, *Journal of Chemistry*, 6657732, 12 pages, <https://doi.org/10.1155/2023/6657732>
- ASTM International. (2020). ASTM D6751-20: Standard specification for biodiesel fuel blend stock (B100) for middle distillate fuels. ASTM International.
- ASTM International. (2024). ASTM D6751-24: Standard specification for biodiesel fuel blend stock (B100) for middle distillate fuels. ASTM International.
- Baki, S.A, Muhammad, M.U, Faruq, U.Z, Sani, N.A, Idris, B. and Fardami, A.Y. (2023). Comparative

Analysis of Biodiesel Production by Transesterification and Interesterification of *Rothmannia longiflora* Seed oil using a Heterogeneous Catalyst. UMYU Scientifica, 2(2), 53 – 62.
<https://doi.org/10.56919/usc.2223.008>

- Bayisa YM & Bullo TA.(2021). Optimization and characterization of oil extracted from *Croton macrostachyus* seed for antimicrobial activity using experimental analysis of variance. *Heliyon*. 2021 Sep 30;7(9):e08095. doi: 10.1016/j.heliyon.2021.e08095. PMID: 34632154; PMCID: PMC8488819.
- Benedict I.I, Thims O.M and Cyril O.E (2018). Physico-Chemical Properties of Biodiesel Obtained from *Jatropha curcas* seed oil using CoMgFeO₄ and MgFe₂SO₄ as Nanocatalysts. *Journal of Introduction Technology*. 3(1):1-16.
- Desta TG, Gebresilasie GG, Meressa GG, Abraha SK, Weldelessie MW, Abdu KY, Endris YA, Shah MA.(2025). Production and Characterization of Biodiesel from *Jatropha curcas* Seed Oil by Using Fly Ash as a Catalyst. *ACS Omega*. 10(24):25498-25505. doi: 10.1021/acsomega.5c00712. PMID: 40584378; PMCID: PMC12199062.
- Devarajan , Y., Dinesh Munuswamy ,B., Subbiah, G., Vellaiyan, S., Nagappan ,B., Varuvel, E.G & Thangaraja, J. (2022). Inedible oil feedstocks for biodiesel production: A review of production technologies and physicochemical properties. *Sustainable Chemistry and Pharmacy*30 (22):100840
- Drabo, M., Abraha, H. S., Koala, J., Savadogo, A., & Raes, K. (2023). Ecological niche, genetic variation in natural populations, and harvest maturity of *Senegalia macrostachya* (Rchb. ex DC.) Kyal. & Boatwr., a promising wild and perennial edible-seeded crop. *Agroforestry Systems*, 97(7), 1233–1247
- Drabo, M., Van Damme, E., De Coninck, dr. ing. T., Verbeke, I., De Meulenaer, B., Savadogo, A., & Raes, K. (2024). Nutritional, phytochemical, and safety profiling of *Senegalia* seeds, promising wild legumes in the arid and semi-arid tropics. *JOURNAL OF FOOD COMPOSITION AND ANALYSIS*, 125. <https://doi.org/10.1016/j.jfca.2023.105826>
- Enkataramana, S. H., Shivalingaiah, K., Davanageri, M. B., Selvan, C. P., Lakshmikanthan, A., Chandrashekarappa, M. P. G., Razak, A., Anand, P. B., & Linul, E. (2022). Niger Seed Oil-Based Biodiesel Production Using Transesterification Process: Experimental Investigation and Optimization for Higher Biodiesel Yield Using Box–Behnken Design and Artificial Intelligence Tools. *Applied Sciences*, 12(12),5987. <https://doi.org/10.3390/app12125987>
- Gharby, S. (2022). Refining vegetable oils: Chemical and physical refining. *The Scientific World Journal*,

- 2022(6627013):10.
<https://doi.org/10.1155/2022/6627013>
- Hashimu, M., Ibrahim, J., Lema, S. Y., & Suleiman, J. (2020). Chemical analysis of (*Lagenaria siceraria*) calabash seeds oil. *Asian Journal of Biochemistry, Genetics and Molecular Biology*, 5(2), 24–30. <https://doi.org/10.9734/ajbgbmb/2020/v5i230127>
- Hernández-Montoya, V., García-Servin, J., & Bueno-López, J. I. (2012). Thermal treatments and activation procedures used in the preparation of activated carbons. In V. Hernández-Montoya & A. Bonilla-Petriciolet (Eds.), *Lignocellulosic precursors used in the synthesis of activated carbon: Characterization techniques and applications in the wastewater treatment*. InTech. <https://doi.org/10.5772/39365>.
- Hussain, G. (2023). color testing of edible oil & fats in lovibond tintometer. *Reserch gate publication 1-4* https://www.researchgate.net/profile/Ghulam-Hussain-30/publication/372446921_COLOR_TESTING_OF_EDIBLE_OIL_FATS_IN_LOVIBOND_TINTOMETER/links/64b769688de7ed28baaba070/COLOR-TESTING-OF-EDIBLE-OIL-FATS-IN-LOVIBOND-TINTOMETER.pdf?origin=publication_detail&_tp=e_yJb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6InB1YmxpY2F0aW9uRG93bmxvYWQlLCJwcmV2aW91c1BhZ2UiOiJwdWJsaWNhdGlvbiJ9fQ
- Ifijeni, I. H., & Nkwor, A. N. (2020). Selected under-exploited plant oils in Nigeria: A correlative study of their properties. *Tanzania Journal of Science*, 46(3), 11-25 <https://doi.org/10.4314/tjs.v46i3.21>
- Kamalu, C. I. O., Osaka, E. C., & Nwakandu, M. S. (2012). Bleaching of crude palm kernel oil using activated snail shell. *Research Journal in Engineering and Applied Sciences*, 1(5), 323–326
- Ma, Y., Bi, Q., Li, G., Liu, X., Fu, G., Zhao, Y., Wang, L. (2020). Provenance variations in kernel oil content, fatty acid profile and biodiesel properties of *Xanthoceras sorbifolium* Bunge in northern China. *Industrial crop and product* 151 (112487) 1- 10 [10.1016/j.indcrop.2020.112487](https://doi.org/10.1016/j.indcrop.2020.112487)
- Muhammad, M.U., Faruq, U.Z., Sani, N.A., Baki, A.S and Garba, U (2020). Nutritional and phytochemical composition of *Rothmannia longiflora* seed. *Sumerian Journal of Agriculture and Veterinary* 3(6):66-73 <https://www.sumerianx.com> ISSN(e): 2617-3077, ISSN(p): 2617-3131
- Mujtaba, M. A., et al. (2023). Production, optimization, and physicochemical characterization of biodiesel from seed oil of indigenously grown *Jatropha curcas*. *Frontiers in Energy Research*.
- Nurhayati, S.A, Tengku, A.A and Amilia, L (2017). Esterification of Crude Palme Oil Using H₂SO₄ and Transesterification Using CaO Catalyst Derived from *Anadara granosa* Indonesian Journal of Chemistry 17(3):309-315.
- Nzebuka, G. C., Okonkwo, B. U., Okorafor, O. O., Onwuachu, C. C., & Ononogbo, C. (2022). Watermelon (*Citrullus vulgaris*) seed oil as a potential feedstock for biodiesel production in Nigeria. *Biofuels* 14(7), 713-720 <https://doi.org/10.1080/17597269.2023.2167272>
- Orijin, A.B and Maduga B (2016). Application and Analysis of Biodiesel Produced from Refined Rubber Seed Oil as an alternative fuel. *Journal of Scientific and Engineering Research*, 3(2):16-23.
- Pan, F., Ma, X., Zhao, J., Liu, C., (2019). Effect of the chemical refining process on perilla seed oil composition and oxidative stability. *Journal of Food Processing and Preservation*. <https://doi.org/10.1111/jfpp.14094>
- Sani I, Owoade C, Abdulhamid A, Isah M. Fedid Bello F. (2013): Evaluation of Physicochemical properties, Phytochemicals and Mineral Composition of cocosnuciferal (coconut) Kernel nut. *International Journal of Advance Research in Chemical Science (IJARCS)* 1(8): 22-30 ISSN 2349-037
- Usman, D.D., Dairo O.U., Adeosun, O.J & Jahun, B.G (2022). Physicochemical properties of biodiesel blends derived from mahogany (*Khaya senegalensis*) Seed oil for use as alternative fuel. *Journal of Agricultural engineering and technology* 27(1): 28-40
- Zagga, A.S., Tambuwal, B.Z., Garba, U., Muhammad, M.U., Achida, M. & Bande A.B (2025). Nutritional Profile and Phytochemical Assessment of *Senegalia macrostachya* (Mimosasea) seed (“Ya’yan Gardaye”). *International journal of science for global sustainability* 11(1): 1-8