Rheological and Thermal Properties of Canarium Schweinfurthii Linn (Atili) Oil and Its Suitability as A Biodiesel Feedstock: A Comparison of Oblong and Round Fruit Morphotypes

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Abstract
Canarium schweinfurthii Linn (atili) oil, extracted from the mesocarp of an underutilised indigenous African fruit, has been proposed as a potential feedstock for biodiesel production, but its flow and heat-transfer behaviour has not been well characterised or benchmarked against established feedstocks. This study determined the rheological and thermal properties of oil extracted from two fruit morphotypes (oblong and round) of C. schweinfurthii Linn and compared them with published values for common biodiesel feedstock oils. Dynamic viscosity was measured with a Brookfield viscometer at seven temperatures (30-90°C) and five shear rates (3-60 rpm); specific heat, thermal diffusivity and thermal conductivity were determined at 40, 50, 70 and 90°C; and oil density was measured gravimetrically. Both oils exhibited shear-thinning (pseudoplastic) behaviour, with viscosity decreasing from 92.1 x 10^{-3} Ns/m² (oblong) and 94.3 x 10^{-3} Ns/m² (round) at 30°C/3 rpm to 4.8 x 10^{-3} and 5.9 x 10^{-3} Ns/m² at 90°C/60 rpm, and power-law flow behaviour indices below unity (0.504-0.840 for oblong; 0.524-0.844 for round) at all temperatures. Viscosity-temperature dependence followed the Arrhenius relationship ($R^2 > 0.98$), with activation energies of 0.1156 kJ/mol (oblong) and 0.1292 kJ/mol (round). Specific heat, thermal diffusivity, thermal conductivity and density all varied linearly with temperature (R^2 = 0.84-0.999); density decreased while the other three properties increased with rising temperature. Compared with rapeseed, palm, corn, sunflower and soybean oils, C. schweinfurthii Linn oils showed comparable density, higher specific heat and thermal conductivity, and viscosity within the operating range of established feedstocks. These results indicate that C. schweinfurthii Linn oil possesses flow and thermal characteristics broadly compatible with biodiesel processing and support its consideration as an alternative non-edible feedstock oil.

Keywords: *Canarium schweinfurthii Linn; atili oil; rheology; viscosity; thermal properties; biodiesel feedstock*

1. Introduction

Canarium schweinfurthii Linn, an indigenous oil-bearing fruit tree of tropical Africa, yields a mesocarp oil that has traditionally been used for cooking, in cosmetics and in folk medicine, and has more recently attracted interest as a feedstock for biolubricants and biodiesel (Omeje et al., 2022; Omale et al., 2023; Muhammad et al., 2023; Kiin-Kabari et al., 2020). Rising interest in non-edible and underutilised plant oils as alternatives to conventional diesel is driven by the need to reduce dependence on fossil fuels without competing with food supply (Shaah

et al., 2021; Bukkarapu & Krishnasamy, 2022; Jamil, 2023). However, the suitability of a vegetable oil for fuel or industrial application depends strongly on its rheological behaviour (viscosity, flow index) and thermal properties (specific heat, thermal diffusivity and conductivity), which govern pumping, atomisation, heat exchanger design and combustion performance (Choudhury et al., 2021; Wanatasanappan et al., 2022; Ribeiro-Sanches et al., 2025). Although the chemical composition of C. schweinfurthii oil has received some attention (Omeje et al., 2022; Muhammad et al., 2023), its rheological and thermal characteristics — and how these vary between its two commonly recognised fruit morphotypes, oblong and round — have not been comprehensively reported or benchmarked against established biodiesel feedstock oils such as rapeseed, palm, corn, sunflower and soybean. Such data are essential for designing extraction, storage, pumping and heat-exchange equipment, and for assessing the oil's technical suitability as a biodiesel feedstock.
This study therefore determined the effects of temperature and shear rate on the rheological properties, and the effect of temperature on the thermal properties and density, of oblong and round C. schweinfurthii Linn oils, and compared these values against literature data for known vegetable oil biodiesel feedstocks.

2. Materials and Methods

2.1 Oil extraction

Oblong and round C. schweinfurthii Linn fruits were steeped in warm water (18-20°C) for 15 minutes to soften the mesocarp, then pulped by hand to separate the pulp from the seed. The pulp paste (15 kg) was mixed with 15 L of water and boiled at 100°C; the liberated oil, being less dense than water, floated to the surface and was skimmed off with a sterilised wooden spoon, then gently heated to remove residual moisture. Oil was stored in sterilised plastic bottles at room temperature (25°C) prior to analysis.

2.2 Rheological property determination

Dynamic viscosity was measured with a Brookfield viscometer (Model LV8, spindle No. 2) at seven temperature levels (30, 40, 50, 60, 70, 80 and 90°C), maintained by immersing the sample holder in a thermostated water bath (Choudhury et al., 2021; Wanatasanappan et al., 2022). At each temperature, an 18 cm^3 oil sample was tested at five shear rates (3, 6, 12, 30 and 60 rpm), with readings taken in triplicate at 3-minute intervals. Flow behaviour was characterised by fitting the power-law (Ostwald-de Waele) model to log-log plots of viscosity against shear rate at each temperature, and the temperature dependence of apparent viscosity was described using the Arrhenius relationship; a semi-log plot of viscosity against inverse absolute temperature (1/T) yielded the activation energy (Ea) from the slope (Ea/R).

2.3 Thermal property determination

Specific heat capacity was determined by the method of mixtures using a copper calorimeter: equal volumes (150 cm^3) of oil and distilled water (reference) were heated to each target temperature (40, 50, 70 and 90°C), then allowed to cool under identical conditions while temperature was logged at 5-minute intervals; cooling curves were used to compute specific heat from a standard calorimetric relation. Thermal diffusivity was determined by the transient method of recent transient thermal-diffusivity approaches reported for food and oil systems (Arif et al., 2021; Raj et al., 2022) using a cylindrical stainless-steel cell instrumented with T-type thermocouples immersed in a heated water bath, with time-temperature data recorded at 5-minute intervals and fitted to the Dickerson diffusivity equation. Thermal conductivity was calculated from the measured specific heat, thermal diffusivity and density using k = alpha x rho x c (Mohsenin, 1980). All thermal measurements were replicated three times per temperature.

2.4 Oil density determination

Oil density was determined gravimetrically at each test temperature by weighing a known volume (50 cm^3) of oil on an electronic balance (Mettler MT400) and dividing mass by volume.

2.5 Statistical analysis

Rheological and thermal properties followed a 2 x 5 completely randomised design (two oil types, five replications; 10 observations per temperature level). Data were analysed by ANOVA in SPSS version 20, with mean separation by Duncan's Multiple Range Test at $P \leq 0.05$. Linear and log-log regression models were fitted to describe the dependence of viscosity, specific heat, thermal diffusivity, thermal conductivity and density on temperature and/or shear rate.

3. Results and Discussion

3.1 Rheological properties

Table 1 presents the apparent viscosity and power-law flow behaviour index of oblong and round oils at each temperature.

Temp (°C)	Apparent viscosity (Ns/m^2) Oblong	Apparent viscosity (Ns/m^2) Round	Power-law index (n) Oblong	Power-law index (n) Round
30	104.90	108.44	0.840	0.844
40	89.70	92.50	0.826	0.829
50	80.60	82.40	0.792	0.804
60	71.30	72.60	0.691	0.714
70	65.00	62.90	0.591	0.647
80	54.20	52.50	0.513	0.586
90	41.20	42.90	0.504	0.524

Viscosity of both oils decreased sharply with increasing shear rate and temperature: at 30°C, viscosity fell from 92.1 x 10^{-3} Ns/m^2 at 3 rpm to 56.1 x 10^{-3} Ns/m^2 at 60 rpm for oblong oil, and from 94.3 to 58.3 x 10^{-3} Ns/m^2 for round oil over the same range, while at 90°C the corresponding values fell to 24.3-4.8 x 10^{-3} Ns/m^2 (oblong) and 26.6-5.9 x 10^{-3} Ns/m^2 (round). This shear-thinning behaviour is characteristic of pseudoplastic fluids and has been widely reported for hydrocolloidal solutions and food pastes with sensitive internal structure (Mitrea et al., 2022), and is generally attributed to progressive alignment of fluid molecules in the direction of flow with increasing shear (Choudhury et al., 2021; Mitrea et al., 2022).

Power-law indices (n) ranged from 0.840 to 0.504 for oblong oil and 0.844 to 0.524 for round oil across the 30-90°C range (Table 1), confirming pseudoplastic ($n < 1$) behaviour at all temperatures, with the index decreasing (i.e., shear-thinning becoming more pronounced) as temperature increased. ANOVA indicated no significant difference in apparent viscosity or power-law index between the two morphotypes ($P > 0.05$), indicating that flow behaviour is broadly similar irrespective of fruit shape.

Table 2 gives the regression equations describing log-log viscosity versus shear rate at each temperature, all with high coefficients of determination (R^2 = 0.957-0.998), confirming the power-law model is an appropriate description of flow behaviour across the full temperature range.

Temp (°C)	Oblong regression eq.	R^2	Round regression eq.	R^2
30	Y = −0.157X + 2.017	0.963	Y = −0.153X + 2.025	0.957
40	Y = −0.172X + 1.951	0.976	Y = −0.168X + 1.961	0.971
50	Y = −0.205X + 1.904	0.985	Y = −0.192X + 1.910	0.977
60	Y = −0.300X + 1.842	0.995	Y = −0.282X + 1.854	0.995
70	Y = −0.400X + 1.802	0.994	Y = −0.346X + 1.789	0.993
80	Y = −0.478X + 1.720	0.998	Y = −0.406X + 1.701	0.994
90	Y = −0.538X + 1.602	0.987	Y = −0.487X + 1.637	0.986

Table 3 presents the Arrhenius regression parameters describing the temperature dependence of apparent viscosity.

Regression parameter	Oblong oil	Round oil
Number of data points	7	7
Slope (K)	−14.928	−15.530
Intercept	112.1	115.5
Activation energy, Ea (kJ/mol)	0.1156	0.1292
R^2	0.989	0.994

The high R^2 values (0.989 for oblong, 0.994 for round) confirm that the Arrhenius model adequately describes the viscosity-temperature relationship of C. schweinfurthii Linn oils (Ribeiro-Sanches et al., 2025). The activation energies obtained (0.1156 kJ/mol for oblong, 0.1292 kJ/mol for round) are markedly lower than values reported for other common vegetable oils, such as sunflower (24.64 kJ/mol), soybean (21.58 kJ/mol), peanut (29.69 kJ/mol), olive (24.57 kJ/mol) and grape seed (24.11 kJ/mol) (Ribeiro-Sanches et al., 2025), indicating that the viscosity of C. schweinfurthii Linn oil is comparatively less sensitive to temperature change than these established feedstocks.

3.2 Thermal properties and density

Table 4 presents the specific heat, thermal diffusivity, thermal conductivity and density of oblong and round oils at 40, 50, 70 and 90°C.

Property	Oil type	40 °C	50 °C	70 °C	90 °C
Specific heat (J/kg·K)	Oblong	3312.09	3408.17	3673.35	3883.31
	Round	3329.17	3431.60	3689.13	3919.95
Thermal diffusivity ($\times10^{-7}$ m²/s)	Oblong	1.16	1.43	1.48	1.68
	Round	1.18	1.46	1.51	1.67
Thermal conductivity (W/m·K)	Oblong	0.3920	0.4513	0.4645	0.5143
	Round	0.3959	0.4591	0.4637	0.5092
Density (kg/m³)	Oblong	918.80	901.20	878.20	870.40
	Round	915.90	898.80	862.00	855.90

Specific heat capacity increased with temperature for both oils, from 3312.1 to 3883.3 J/kg·K (oblong) and 3329.2 to 3920.0 J/kg·K (round) between 40 and 90°C, following linear regressions of YO = 11.67X + 2839 (R^2 = 0.997) and YR = 11.97X + 2843 (R^2 = 0.999), consistent with the trend reported for canola, hazelnut, peanut and almond oils by Fasina and Colley (2008). Round oil had a significantly higher specific heat than oblong oil at all temperatures ($P <= 0.05$), indicating it requires marginally more energy to raise its temperature by a given increment.

Thermal diffusivity increased from 1.16 x 10^{-7} to 1.68 x 10^{-7} m^2/s (oblong) and 1.18 x 10^{-7} to 1.67 x 10^{-7} m^2/s (round) between 40 and 90°C. Round oil diffused heat faster than oblong oil between 40 and 70°C but slower at 90°C; ANOVA showed no significant difference between oil types, temperature, or their interaction for this property ($P > 0.05$). Thermal conductivity increased from 0.392 to 0.514 W/m·K (oblong) and from 0.396 to 0.509 W/m·K (round) over the same range, with a significant effect of oil type, temperature and their interaction ($P <= 0.05$); the increase with temperature is attributed to the density gradients that develop within the heated oil, producing a buoyancy-driven flow that opposes viscous resistance (Ribeiro-Sanches et al., 2025).

Oil density decreased linearly with increasing temperature for both morphotypes (YO = -0.959X + 952.1, R^2 = 0.930; YR = -1.213X + 958.0, R^2 = 0.907), from 918.8 to 870.4 kg/m^3 (oblong) and 915.9 to 855.9 kg/m^3 (round) between 40 and 90°C — a trend consistent with thermal expansion of the oil and one that has also been reported for rapeseed, sunflower, soybean, palm and grape-seed oils by Bernat et al. (2012). ANOVA confirmed significant effects of oil type, temperature and their interaction on density ($P <= 0.05$).

3.3 Suitability of C. schweinfurthii Linn oil for biodiesel production

To assess the technical suitability of C. schweinfurthii Linn oil as a biodiesel feedstock, its density, viscosity and thermal properties were compared with published values for established feedstock oils.

Density. Table 5 compares oil density across temperatures.

Temp (°C)	Corn	Grape seed	Rapeseed	Sunflower	Soybean	Palm	Oblong CSL	Round CSL
40	0.9046	0.9060	0.9127	0.9043	0.9061	0.8996	0.9186	0.9159
50	0.8979	0.8998	0.8963	0.8994	0.8998	0.8922	0.9012	0.8948
70	0.8864	0.8874	0.8848	0.8877	0.8879	0.8789	0.8782	0.8620
90	0.8740	0.8754	0.8724	0.8743	0.8750	0.8664	0.8704	0.8559

Benchmark values for the comparison oils are retained from the original manuscript dataset. These historical numerical values require re-verification against 2020-2026 primary sources before journal submission; they should not be re-attributed to newer papers unless the values are reproduced there. CSL = Canarium schweinfurthii Linn (this study).

Densities of oblong and round C. schweinfurthii Linn oils (0.856-0.919 g/cm^3 across 40-90°C) fall within the range of the established feedstock oils (0.866-0.913 g/cm^3), indicating density is not a limiting factor for its use in biodiesel processing.

Viscosity. Table 6 compares kinematic viscosity of the study oils with common biodiesel feedstocks.

Temp (°C)	Rapeseed	Palm	Corn	Sunflower	Soybean	Oblong CSL	Round CSL
40	34.06	45.34	32.53	33.78	31.42	44.90	53.10
50	24.68	28.19	23.74	24.48	23.00	34.80	36.90
70	14.48	15.60	14.01	14.44	13.67	11.81	14.40

Temp (°C)	Rapeseed	Palm	Corn	Sunflower	Soybean	Oblong CSL	Round CSL
90	9.45	9.94	9.34	9.44	9.13	4.80	5.90

Benchmark values for the comparison oils are retained from the original manuscript dataset. These historical numerical values require re-verification against 2020-2026 primary sources before journal submission; they should not be re-attributed to newer papers unless the values are reproduced there. CSL = Canarium schweinfurthii Linn (this study).

At 40 and 50°C, both oblong and round C. schweinfurthii Linn oils were more viscous than the five reference feedstocks, but by 70°C the oblong oil viscosity (11.81 m^2/s) had fallen below all five reference oils, and at 90°C both C. schweinfurthii Linn oils (4.80 and 5.90 m^2/s) were markedly lower than rapeseed, palm, corn, sunflower and soybean oils (9.13-9.94 m^2/s). This indicates that, with modest preheating consistent with standard biodiesel processing (transesterification is typically conducted at 50-65°C), the viscosity of C. schweinfurthii Linn oil converges towards, and eventually falls below, that of established feedstocks.

Thermal properties. Table 7 compares thermal diffusivity, thermal conductivity and specific heat capacity at a common reference temperature of 40°C.

Oil	Thermal diffusivity $\times 10^{-7}$ (m^2/s)	Thermal conductivity (W/m·K)	Specific heat (kJ/kg·K)
Canola	1.100	0.153	2.223
Macaw	1.160	0.148	-
Olive oil	0.840	0.146	-
Castor oil	0.790	0.150	-
Pinhão manso (Jatropha)	0.882	0.157	-
Phalerata	1.120	0.186	-
Pequi (Caryocar brasiliense)	1.200	0.195	-
Hazelnut	-	-	1.731
Peanut	-	-	2.055
Almond	-	-	2.368
Oblong CSL oil	1.161	0.392	3.312
Round CSL oil	1.182	0.395	3.329

Benchmark thermal-property values are retained from the original manuscript dataset. These historical numerical values require re-verification against 2020-2026 primary sources before journal submission; they should not be re-attributed to newer papers unless the values are reproduced there. CSL = Canarium schweinfurthii Linn (this study).

Thermal diffusivity of C. schweinfurthii Linn oils (1.161-1.182 x 10^{-7} m^2/s) was higher than olive, castor, canola and Jatropha (pinhão manso) oils, and comparable with macaw and phalerata oils, exceeded only by pequi (Caryocar brasiliense) oil. Thermal conductivity of C. schweinfurthii Linn oils (0.392-0.395 W/m·K) was substantially higher than all comparison oils (0.146-0.195 W/m·K), and specific heat capacity (3.312-3.329 kJ/kg·K) was likewise higher than canola, hazelnut, peanut and almond oils (1.731-2.368 kJ/kg·K). Taken together, these results indicate that C. schweinfurthii Linn oil requires relatively more energy to heat but also transfers heat more readily than most of the reference oils — properties relevant to the design of heat exchangers for oil pre-heating and transesterification reactors.

Overall, the density, viscosity (at process-relevant temperatures) and thermal properties of both oblong and round C. schweinfurthii Linn oils fall within, or are favourably comparable to, the range reported for established vegetable oil biodiesel feedstocks, supporting the technical feasibility of C. schweinfurthii Linn oil as an alternative, non-edible biodiesel feedstock, subject to further work on fatty-acid profile, cetane number and cold-flow properties.

4. Conclusion

Oblong and round C. schweinfurthii Linn oils exhibited pseudoplastic, shear-thinning flow behaviour that was well described by the power-law model at all temperatures tested (R^2 = 0.957-0.998), with viscosity-temperature dependence following the Arrhenius relationship (activation energies of 0.1156 and 0.1292 kJ/mol, respectively) — values markedly lower than those reported for common vegetable oils. Specific heat, thermal diffusivity and thermal conductivity increased, while density decreased, linearly with temperature for both morphotypes. When benchmarked against rapeseed, palm, corn, sunflower and soybean oils, C. schweinfurthii Linn oil showed comparable density, viscosity that converged to below reference-oil levels at process-relevant temperatures, and higher thermal conductivity and specific heat capacity. These findings support the technical suitability of C. schweinfurthii Linn oil as a candidate feedstock for biodiesel production and provide design data for the heat-transfer and fluid-handling equipment required for its processing.

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