Scientific Research Publishing

Green and Sustainable Chemistry, 2026, 16(4), 128-138
https://www.scirp.org/journal/gsc
ISSN Online: 2160-696X
ISSN Print: 2160-6951

Production of Biodiesel from Five Unconventional Oils Derived from Oil Seeds in the Congo Basin, Such as Palm Kernel Oil of the Tenera Guinessis Variety, Loukoko Palm Oil of the Tenera Guinessis Variety, Refined Oil, Raphia Laurentii Oil, and Raphia Sesse Oil

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How to cite this paper: Makomo, H., Lipinda, A.V., Pouambeka, T.W., Mutinsumu, P.C., Bopoundza, F.C. and Silou, T. (2026) Production of Biodiesel from Five Unconventional Oils Derived from Oil Seeds in the Congo Basin, Such as Palm Kernel Oil of the Tenera Guinessis Variety, Loukoko Palm Oil of the Tenera Guinessis Variety, Refined Oil, Raphia Laurentii Oil, and Raphia Sesse Oil. *Green and Sustainable Chemistry*, **16**, 128-138.
https://doi.org/10.4236/gsc.2026.164008

Received: July 29, 2026
Accepted: November 24, 2026
Published: November 27, 2026

Abstract

Today, the search for alternatives to fossil fuels has become a priority for reducing greenhouse gas emissions and addressing the depletion of petroleum resources. Biodiesel derived from plant sources offers a promising solution, although its processing methods need optimization to maximize yield. This study aims to optimize the synthesis of biodiesel through transesterification of Loukoko palm oil (HPL), Tenera variety (*Elaeis guineensis*), palm kernel oil (HPm) of the same variety, Raphia laurenti oil (HK), Raphia sese oil (HMb), and refined oil (HR). For each sample, three replicates were performed, generating HPL123, HPL223, HPL323, and so on. The first digit of the code 123 indicates the sampling order, while the last two digits correspond to the labeling date. The same applies to code 323 (3rd sample taken on the 23rd). The transesterification reaction was carried out by reacting the aforementioned oils with methanol in the presence of potassium hydroxide (KOH). The temperature was set at 65˚C ± 1˚C, and the methanol/oil volume ratio (3/1) and the catalyst concentration 3% by mass were evaluated to maximize conversion (eq1). The

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yields of the biodiesels obtained ranged from 87.17% to 94.80% for a reaction time of 2 hours. Physicochemical analyses, including density, kinematic viscosity, pour point, flash point, ash content, color, and external appearance of the sample, were performed exclusively on the first and third replicates of each oil type. The kinematic viscosity at 40˚C for replicates HR123 and HR323; HMb123 and HMb323; HK123 and HK323; HPm123 and HPm323; and HPL123 and HPL323, among which five samples (HR123, HR323, HK123, HK323, and HPm123) yielded values that meet the international standards ASTM D 6751 and EN 14214. These results demonstrate that the alkaline transesterification of the aforementioned oils allows for the efficient production of biodiesel of comparable quality to conventional diesel. The densities and flash points of all the synthesized biodiesels comply with standard norms. The sulfated ash contents also comply with current requirements, with a few exceptions such as HPL123, HPL323, HMb123 and HMb323 (Table 2).

Keywords

Biodiesel, Alkaline Transesterification, *Eleaisis guinenais*, Raphia Laurentii Oil, Palm Kernel Oil, Raphia Sese Oil, Refined Oil

1. Introduction

Global demand for fossil fuels is experiencing uninterrupted growth, generating profound economic, geopolitical, and environmental challenges [1]. The progressive depletion of oil and natural gas reserves—inherently non-renewable resources—coupled with massive greenhouse gas (GHG) emissions, is now one of the major drivers of climate change [2] [3]. Faced with this global environmental crisis, the need for a structured ecological transition has been reaffirmed at the various Conferences of the Parties (COPs) since COP21 in 2015, emphasizing the transformation of energy production and consumption patterns [4]. Nevertheless, fossil fuels (coal, oil, and natural gas) still account for more than 80% of global primary energy consumption [5]. The transport sector is particularly critical, as it relies on liquid fuels for more than 95% of its energy needs and contributes substantially to global carbon dioxide (CO_2) emissions [6]. In this context, the development of renewable alternative fuels appears as a priority requirement. Biodiesel stands out as a particularly promising alternative for replacing fossil-based diesel or for incorporation into blends, thus significantly reducing the carbon footprint of the transport sector [7] [8]. Historically, the use of crude vegetable oils in internal combustion engines dates back to the early work of Rudolf Diesel with peanut oil. However, their high kinematic viscosity, low volatility, and low cetane number quickly revealed major technological limitations [9]. To circumvent these constraints, the transesterification process has established itself as the preferred transformation route: it consists of the reaction of triglycerides from vegetable oils or animal fats with a short chain alcohol (generally methanol or ethanol), in the presence of an acidic, basic or enzymatic catalyst, to produce fatty acid methyl

esters (FAME) [10]-[12]. However, over 95% of biodiesel produced industrially worldwide currently comes from edible vegetable oils (soybean, palm, rapeseed, sunflower) [13]. This direct competition with the food chain poses significant risks of food insecurity and socio-economic tension, particularly in developing countries [14]. To overcome this "food versus fuel" dilemma, current research is shifting towards the exploitation of non-edible or unconventional oilseed sources such as Jatropha curcas or Madhuca indica [15] [16]. In this context, the Congo Basin holds exceptional potential in terms of unconventional plant resources that are still underutilized [17]. This study contributes to this approach of valorizing local biomass and this study focuses on the synthesis of biodiesel by methanol transesterification using four promising oilseed resources from the region: Loukoko palm oil (HPL), Tenera variety (*Elaeis guineensis*), palm kernel oil (HPm), Raphia laurenti oil (HK), Raphia sese oil (HMb), and refined oil (HR), representing five vegetable oil samples. The main objective is to determine the physicochemical parameters of the synthesized biodiesels in order to assess their compliance with international fuel standards and their potential application in diesel engines.

2. Materials and Methods

2.1. Sampling and Collection of Raw Materials

Palm nuts (*Elaeis guineensis*) were collected at the Loukoko palm grove waste disposal site. The kernels, obtained by manually shelling the nuts, were subjected to continuous solar drying until a consistent mass was achieved for each batch of samples. In addition, three samples of artisanal palm oil (HPL) were collected directly from local producers in the Loukoko palm grove. *Raphia oils*, derived from *Raphia laurentii* (HK) and *Raphia sese* (HMb), were purchased at the Ouenze market (5th arrondissement, Brazzaville), with three samples of each variety. Similarly, three samples of refined palm oil (HR) were purchased at the Total market (2nd arrondissement, Bacongo, Brazzaville).

2.2. Mechanical Extraction and Determination of Palm Kernel Oil Yield

Palm kernel oil was extracted from the dried kernels using a mechanical screw press.

The extraction yield (%) was determined according to Equation (1):

$$\text{Yield}\ (\%) = \left(\frac{m_{oil}}{m_{seeds}}\right) \times 100 \tag{1}$$

m_{oil} represents the mass of oil extracted and m_{seeds} designates the initial mass of dried seeds subjected to the press. An average extraction yield of 48% was obtained.

2.3. Sample Conditioning and Pretreatment

All the collected oil samples (three replicates per oil type) were oven-dried at 105˚C for 24 hours to eliminate any residual moisture. The purified oils were then

placed in hermetically sealed amber glass bottles and stored at room temperature (20˚C ± 2˚C) protected from light before the transesterification reaction.

2.4. Transesterification and Purification Procedure for Biodiesel

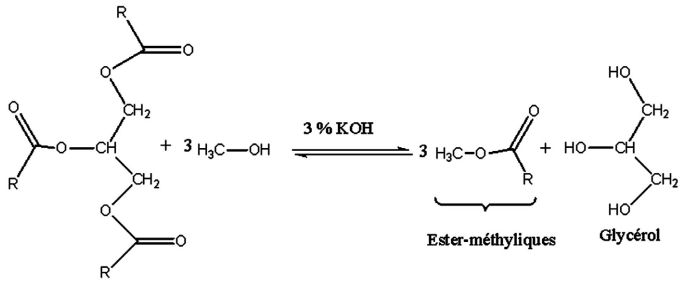

Figure 1. Transesterification reaction.

The transesterification reaction was carried out in a 250 mL two-necked round-bottom flask equipped with a reflux condenser and a thermometer (Figure 1). A volume of 32 mL of vegetable oil was introduced into the reactor, followed by the simultaneous addition of 90 mL of methanol and 10 mL of a previously prepared potassium methoxide solution. The catalyst was titrated at a ratio of 0.812 ± 0.012 g relative to the mass of oil, resulting in an alcohol/oil molar ratio of 3:1. Placed in an oil bath, the reaction mixture was maintained under constant magnetic stirring (500 rpm) at a temperature of 65˚C ± 1˚C for 2 hours. After the reaction, the mixture was cooled to room temperature and then transferred to a 500 mL separatory funnel.

After a 2-hour settling period, two distinct phases separated: a lower phase containing crude glycerol and an upper phase consisting of crude biodiesel. The upper phase was collected and washed with hot water (approximately 80˚C) until the wash water was completely neutralized. The purified biodiesel was then oven-dried at 105˚C for 5 hours to remove residual water. For each type of oil, the tests were performed in triplicate (Figure 2).

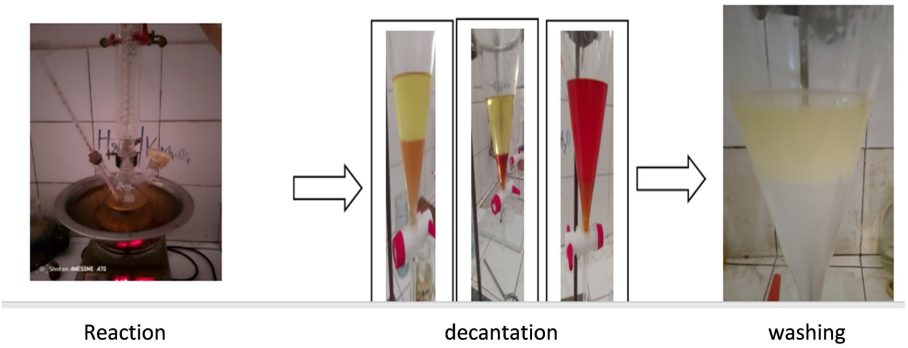

Figure 2. Extraction method and separation of biodiesel.

$$\text{Yield}(\%) = \left(\frac{m_{biodiesl}}{m_{oil}} \right) \times 100$$

3. Results Discussion

3.1. Results

Biodiesel yields from HR, HMb, HK, HPm and HPL were analyzed and the results were shown in Table 1.

Table 1. Biodiesel yields from HR, HMb, HK, HPm and HPL.

	Yield (%) 1st attempt	Yield (%) 2nd attempt	Yield (%) 3rd attempt
HR123	94.80	91.56	94.78
HR323	91.08	88.38	89.17
HMb123	88.89	91.05	86.94
HMb323	88.36	89.17	87.39
HK123	94.75	90.83	95.72
HK323	93.34	90.80	89.84
HPm123	91.19	92.14	87.39
HPm323	88.36	87.46	87.17
HPL123	92.08	89.02	93.86
HPL323	90.23	89.64	87.38

For code 123, the first digit indicates the sampling order, while the last two correspond to the labeling date. The same applies to code 323 (3rd sample taken on the 23rd).

The results of the physicochemical analyses of the biodiesels produced from HR, HMb, HK, HPm, and HPL oils are presented in Table 2.

Table 2. Physicochemical characteristics of biodiesels.

	Colors	External appearance of the sample	Density	Viscosity 40˚C in cSt	Pour point	Flash point	Ash content
HR123	L1.0	C&B	0.883	4.13	−5	167	0.01
HR323	L1.0	C&B	0.897	6.29	4	174	0.01
HMb123	L4	C&B	0.918	37.85	12	>200	0.2
HMb323	L4	e	0.928	41.24	17	>200	0.5
HK123	L4.0	C&B	0.887	5.14	1	156	0.01
HK323	L4.0	C&B	0.885	4.38	−5	145	0.01
HPm123	L1.0	C&B	0.885	4.15	−5	168	0.01
HPm323	L0.5	e	0.888	23.59	1	164	0.01
HPL123	L4.0	C&B	0.901	31.67	17	>200	0.2
HPL323	L4.0	e	0.937	23.59	21	>200	0.5

3.2. Discussion

3.2.1. Biodiesel Yield

The yields of biodiesels obtained from the five oils studied (HR, HPm, HK, HMb, and HPL) are comparable to those reported in the literature for fatty acid methyl esters from Jatropha curcas, *Elaeis guineensis*, and Ricinodendron heudelotii [18] and from soybeans, canola, and halophytes [19] [20]. This convergence in yields, regardless of the botanical origin of the material, suggests comparable efficiency of the transesterification protocols used.

3.2.2. Density

The ASTM D6751 and EN 14214 standards specify a density of 0.86 to 0.90 g/cm^3 at 15˚C. The biodiesels synthesized in this study exhibited values ranging from 0.883 to 0.932 g/cm^3, generally consistent with current standards and previously reported results [21]-[23]. These results confirm the overall physicochemical conformity of the esters produced, although a slight exceedance of the upper limit was observed for some samples.

3.2.3. Kinematic Viscosity

More pronounced discrepancies appear regarding kinematic viscosity at 40˚C. According to ASTM D6751, this value should be between 1.6 and 6.0 mm^2/s (cSt), and according to EN 14214, between 3.5 and 5.0 mm^2/s. However, HMb123, HMb323, HPm323, HPL123, and HPL323 biodiesels exhibit viscosities significantly exceeding these ranges. This increase could be explained by the residual presence of mono- and diglycerides, byproducts of incomplete transesterification, known to increase the viscosity of the medium. Reducing the incorporation rate of these fractions in the blends is a possible technical solution.

Operationally, excessive viscosity has documented repercussions at several levels:

- it promotes polymerization, degrades combustion, and increases engine fouling [24];
- it accelerates the dilution and polymerization of engine oil [25];
- it impairs the spray pattern and particle size of injected droplets [26].

Conversely, HR123 and HR323 biodiesels have viscosities of 4.13 and 6.29 cSt at 40˚C, respectively, which are well within the limits of ASTM D-6751 and EN 14214 standards. The same is true for HK123 (5.14 cSt), HK323 (4.38 cSt), and HPm123 (4.15 cSt). These results suggest that the corresponding oils have undergone adequate refining, allowing satisfactory conversion of triglycerides into fatty acid methyl esters.

3.2.4. Pour Point

Current specifications for the low-temperature properties of biodiesel do not define unambiguous pour point limits. Indeed, the ASTM D6751 standard sets a maximum value of −15˚C, while the European standard EN14214 establishes variable requirements depending on climatic conditions. For the biodiesel samples studied, the measured pour points vary significantly according to their composition (**Table 3**):

Table 3. Comparison of HK123, HPm323, HR123, HK323 samples with the literature.

Samples	Pour point (˚C)	Comparison with literature
HK123	1	Comparable aux esters méthyliques de *Jatropha curcas*
HPm323	1	Comparable aux esters méthyliques de *Jatropha curcas*
HR123	−5	Proche de biodiesel issu de l'huile de tournesol
HK323	−5	Proche de biodiesel issu de l'huile de tournesol
HMb123	12	Comparable au biodiesel de palme

The pour points of the samples (HR323: 4˚C; HMb323: 17˚C; HPL123: 17˚C; HPL323: 21˚C) do not pose a problem for use in hot climates, the climatic factor playing a predominant role in the choice of biodiesel quality.

3.2.5. Flash Point

International standards strictly regulate the safety of biodiesel, particularly through the measurement of the flash point. According to ASTM D6751, the minimum required value is set at 130˚C, while the European standard EN14214 imposes a threshold of 120˚C. All the samples analyzed showed flash points well above these regulatory requirements, demonstrating excellent safety with regard to flammability risks during storage and transport.

The measured values are as follows: (HR123: 167˚C; HR323: 174˚C; HMb123: >200˚C; HMb323: >200˚C; HK123: 156˚C; HK323: 145˚C; HPm123: 168˚C; HPm323: 164˚C; HPL123: >200˚C and HPL323: >200˚C).

These results are consistent with data reported in the literature for biodiesels derived from various feedstocks. Indeed, similar values have been obtained for Jatropha curcas oil methyl esters, whose flash points are generally between 150 and 170˚C [27]-[29]. For soy biodiesel, flash points between 160˚C and 180˚C are commonly reported [30] [31]. Finally, biodiesels derived from palm oil frequently exhibit flash points above 180˚C, even >200˚C [32] [33], due to their high saturated fatty acid content, which confers greater thermal stability. The elevated flash point observed for some samples (>200˚C) reflects effective removal of methanol residues during the purification stages, a key factor for meeting specifications and reducing risks associated with volatile compounds. Thus, all biodiesels not only meet the normative requirements, but also exhibit performance comparable to, or even superior to, that of conventional biodiesels reported in the scientific literature.

3.2.6. Ash Content

Evaluating sulfated ash content is essential to ensuring biodiesel quality, as it reflects the presence of inorganic contaminants, metals, or residual catalysts that can damage injection systems and other components.

International standards, specifically the European standard EN 14214, set a maximum value of 0.02% (w/w) for sulfated ash. However, the ASTM D6751 standard provides almost no limits.

Analysis of the samples revealed contrasting results. Most samples had an ash content of 0.01%, a value consistent with the requirements of both standards, as observed for other biodiesels such as those derived from Ponaamia pinnata [27] [34] [35]. In contrast, three samples showed abnormally high values: HMb123: 0.2%; HMb323: 0.5%; HPL32: 0.2%.

These values, 10 to 25 times higher than regulatory limits, indicate significant contamination. This excessive sulfated ash content may result from incomplete catalyst removal during the purification stages, or from the presence of metallic soap residues and abrasive particles. These contaminants can cause premature wear of pumps, injectors, and piston rings, as well as filter fouling.

While the majority of samples meet international specifications, samples HMb123, HMb323, and HPL323 do not meet the required quality criteria, highlighting the need to optimize the purification process for these types of biodiesel.

3.2.7. Color

The analyzed samples exhibit a color intensity ranging from L.0.5 (very light) to L.4 (darker) according to the Lovobond scale. The color of the aforementioned samples falls squarely within this range. High-quality biodiesel is generally clear and bright to the naked eye, indicating good purification.

Thus, the majority of the samples meet this quality criterion, which is reassuring regarding the effectiveness of the synthesis and purification process.

3.2.8. External Appearance

External appearance is a quick but insufficient indicator for assessing the conformity of biodiesel. While the majority of samples have a clear and bright appearance (C&B), indicating good quality, samples HK323, HPm323, and HPL323 exhibit a cloudiness (e) that warrants further investigation. Analyses of water content, residual glycerol, and insoluble matter are recommended to identify the source of this anomaly and, if necessary, optimize the purification steps.

4. Conclusions

This study aimed to evaluate the quality of ten biodiesel samples, designated HR123, HR323, HMb123, HMb323, HK123, HK323, HPm123, HPm323, HPL123, and HPL323, synthesized from different vegetable oils. The main objective was to verify their compliance with the requirements of the international standards ASTM P6751 and EN 14214, with a view to their potential use as alternative fuels in diesel engines.

To this end, several physicochemical parameters were analyzed: flash point, pour point, sulfated ash content, surface appearance, and color.

The results obtained reveal contrasting performance depending on the samples and the parameters considered. Regarding the flash point, all samples exhibited values well above the regulatory thresholds set by the standards (130˚C according to ASTM D6751 and 120˚C according to EN 14214). The measured values ranged from 145˚C (HK323) to over 200˚C (HMb123, HMb323, HPL123, HPL323),

demonstrating excellent safety with respect to flammability risks and effective removal of residual methanol during the purification stages.

These results are consistent with data from the literature for biodiesels derived from Jatropha curcas oil, soybean oil, and palm oil. This study demonstrates that most of the biodiesels examined exhibit promising characteristics that meet essential regulatory requirements. However, the variability of results depending on the nature of the raw material underscores the need for rigorous characterization and process optimization for each type of oil. The perspectives opened up by this work allow for the refinement of synthesis and purification protocols, and for the development of sustainable biodiesel production adapted to local climatic and economic contexts.

Acknowledgements

The authors are thankful to the Marien Ngouabi and Northeast Normal University for providing financial support.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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