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ARTICLE

Small-scale thermal distillation reactor for producing distillate oil from waste lubricant oil

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ABSTRACT

Waste lubricant oil is produced when petroleum-based or synthetic lubricants degrade and become contaminated during engine operation. Because its composition is complex and it contains impurities, it requires treatment before disposal to limit environmental pollution. This study investigated the recovery of a distillate oil and a residue from waste lubricant oil by thermal distillation in a small batch reactor. The aims were to design, fabricate and test a small-scale reactor and to evaluate the mass yields and selected physicochemical properties of the distillate oil and the residue. A descriptive-developmental research design was used. The fabricated system, built from locally available materials, consisted of a cylindrical reactor with a cover and screw locks, a heat exchanger, a water reservoir with a centrifugal pump, and an LPG burner. The reactor was 25 cm in diameter and 35 cm high, with a 1.5 mm wall and an internal volume of about 17 L. In duplicate trials at five loadings (800-4000 g), the mean distillate yield ranged from 6.21% to 25.00% and the mean residue yield from 65.00% to 90.00%, with total recovery of 89.13-96.22%. The distillate had a flash point of 90 °C (ASTM D92), kinematic viscosities of 4.16 and 1.57 mm²/s at 40 and 100 °C, and a density of 831 kg/m³. Flash point, viscosity at 40 °C and density of the distillate were within the ranges specified for automotive diesel, but other fuel properties were not determined, so the suitability of the distillate as a diesel substitute remains to be shown.

INTRODUCTION

Lubricating oil, an important product of crude oil refining, reduces friction, wear, and heat generation in mechanical systems. It consists mainly of high-molecular-weight hydrocarbons such as paraffins, naphthenes, and aromatics, and it is made either from refined petroleum fractions or by synthetic processes (Rațiu et al. 2022). Lubricating oils are generally classified, by composition, production method, and intended application, as mineral, synthetic, semi-synthetic, or biodegradable (Islam Sazzad et al. 2024). In typical formulations, about 80-90% of the mixture is base oil and the remaining 10-20% is additives that improve viscosity, prevent corrosion, and extend service life (Rincón et al. 2005). These oils are widely used in automotive and marine engines, industrial machines, turbines, compressors, and hydraulic systems, where efficient lubrication is critical for reliability and energy efficiency (Pinheiro et al. 2017). Over time, however, lubricating oils are exposed to high temperatures, oxidation, and contamination by dust, soot, and metallic wear particles. This exposure causes chemical breakdown, higher acidity, viscosity changes, and the accumulation of sludge or varnish, which degrade the oil's lubricating properties (Hong and Jang 2023). Once lubricating oil has deteriorated, it becomes waste lubricant oil (WLO), also called used lubricating oil or waste engine oil. The disposal of WLO is a serious environmental problem. It contains harmful components such as heavy metals, polycyclic aromatic hydrocarbons, and chlorinated compounds (Lam et al. 2010), and exposure to them can cause serious health problems, including lipid pneumonia and some cancers.

To address these problems, the waste hierarchy favors recycling and recovery, with safe disposal as the last resort (European Parliament and Council 2008). Recycling is preferred because it uses less energy than refining crude oil and substantially reduces air, soil, and water pollution (Jafari and Hassanpour 2015). Various re-refining processes have been developed, such as acid-clay treatment, solvent extraction, vacuum distillation, hydrogenation, membrane separation, and catalytic processing (Sarkar et al. 2023). Industrial-scale processes such as Vaxon, CEP, Ecohuile, Cyclon, STP, Interline, and Propak combine several of these techniques to achieve higher efficiency (Boadu et al. 2019). However, such

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KEYWORDS

Distillate, Physicochemical, Residue, Reactor, Waste lubricant oil

technologies are often complex, costly, and unavailable in developing regions, which creates a need for simpler, local solutions.

Thermal distillation has been investigated as a practical approach for recovering useful hydrocarbon fractions from WLO through boiling-range separation (U.S. Department of Energy 2020). In this process, waste oil is heated, ideally in the absence of oxygen, to produce a distillate, gases, and a residue, which can be used as fuel substitutes, chemical feedstocks, or precursors of activated carbon (Al-Rumaihi et al. 2022). Previous studies have shown that blending distilled waste oil with biodiesel, such as Jatropha biodiesel, can improve combustion because of the biodiesel's favorable cetane number (Sharma et al. 2020). However, most existing oil treatment systems are designed for large volumes and are not suited to local collection points such as motor pools, so small-scale equipment for local treatment of waste oil needs to be developed.

This study therefore designed and fabricated a small-scale thermal distillation reactor to produce distillate oil from WLO collected from the official service vehicles of the Motorpool of Camarines Norte State College (CNSC), Daet, Camarines Norte, Philippines. Specifically, it aimed to (1) design and fabricate a small-scale thermal distillation reactor from locally available materials; (2) evaluate its performance in terms of the mass yields of distillate oil and residue and the total recovery; and (3) determine the flash point, kinematic viscosity (at 40 and 100 °C), viscosity index, and specific gravity of the distillate and the residue, and calculate their density and API gravity. This study did not examine the effects of loading and temperature on the yield; five loadings were run in duplicate to characterize the reactor, not to model the process.

MATERIALS AND METHODS

Feedstock Collection

WLO was collected from CNSC service vehicles consisting of diesel-powered minibuses, pickup trucks, vans, and a boom truck. The feedstock was a mixture of used engine, gear, and transmission oils. The oils were combined according to their available collected volumes, without predetermined proportions. After collection, the WLO was immediately transferred into clean plastic containers with threaded caps to prevent leakage and contamination. The containers were stored in a secure place away from direct sunlight, rain, and excessive heat. About 30-40 kg of WLO was collected and divided into 10-kg per container, of which only three batches were used for the experiments. The WLO was used as collected, without pretreatment.

Fabrication of the equipment

The system developed in this study is a small-scale batch unit for processing WLO. Its main component is the reactor, which holds the feedstock and in which the oil is heated and vaporized. During operation, the oil is separated into two products: a distillate and a residue and non-condensable gas, which was not collected.

The reactor was fabricated from 1.5-mm-thick stainless-steel 316 plate at a local fabrication shop in Daet, Camarines Norte. The material and thickness were judged adequate for operation at atmospheric pressure, with good thermal stability, corrosion resistance, and durability. The reactor has a cylindrical body 25 cm in diameter and 35 cm high, which gives an internal volume of about 17 L ($\pi \times 12.5^2 \times 35 = 17.2$ L, excluding the collar and the cover). The reactor has a conical (frustum-shaped) stainless-steel cover with gasket, which carries three screw locks, a handle, and a combined temperature and pressure gauge. The dimensions and configuration were chosen according to the capabilities of local machine shops and the availability of materials in the province, which kept fabrication costs low while meeting the functional requirements. Heat was supplied by a single liquefied petroleum gas (LPG) burner, chosen for its availability, ease of operation, and controllable output. Distillate vapors are condensed in a counter-flow, single-shell, two-pass tube heat exchanger made of stainless steel with 30 cm long and 3.81 cm diameter. Cooling water was circulated continuously through the condenser by a 0.3-hp centrifugal pump at rated 13.2 L/min from a 50-L plastic reservoir.



Figure 1. Experimental setup of the small-scale thermal distillation system: (1) reactor with collar, (2) reactor cover, (3) screw lock, (4) heat exchanger, (5) centrifugal pump, (6) reservoir, and (7) burner.

The assembled equipment (Figure 1) was then operated as described below. Performance was evaluated from the mass yields of the recovered distillate and residue.

Preparation of feedstock

Before each run, the required mass of WLO (0.8–4.0 kg) was weighed using a digital balance with a maximum capacity of 30 kg and a readability of 1 g. The measured WLO was then transferred into a clean plastic container before being loaded into the reactor. The WLO was used as collected: it was not filtered, dehydrated, or chemically treated to test whether untreated WLO can be separated into a distillate and a residue.

Experimental setup and safety measures

The setup consisted of the cylindrical reactor, the LPG burner, a water-cooled heat exchanger (condenser), a cooling-water reservoir with a circulating pump, a pressure gauge, a temperature gauge, connecting pipes, and a product collection vessel. Before each run, all pipe connections and fittings were inspected for leaks of distillate vapor. Operators wore a face mask, heat-resistant gloves, and safety goggles throughout the experiments. A portable dry-chemical fire extinguisher was kept within reach. During operation, the burner flame, the reactor temperature, and the pressure reading were monitored continuously. After each run, the reactor was kept closed until it had cooled to near ambient temperature, and was opened only then, to reduce the risk of ignition of residual vapors on contact with air.

Schematic diagram

Figure 2 shows the process flow of the system. In the process (Figure 2), an LPG burner heats the oil in the reactor, the vapors are condensed in a water-cooled heat exchanger, and the condensate is collected in a container, while the cooling water is recirculated from the reservoir.

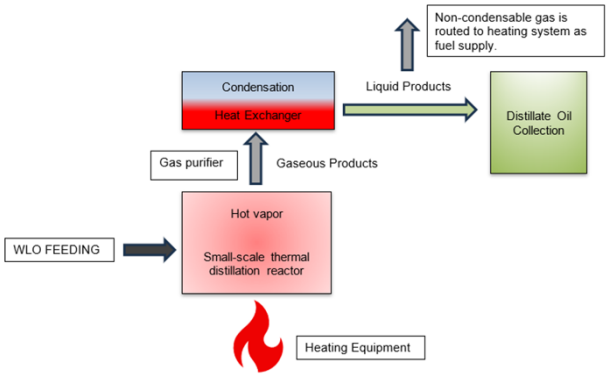


Figure 2. Process flow diagram of the small-scale distillation system.

Operating procedure

The experiments were carried out in the batch reactor at atmospheric pressure. Each of the five feedstock loadings (800, 1600, 2400, 3200, and 4000 g) was run in duplicate in increasing order to estimate the repeatability of the recovered masses.

The reactor was heated with the LPG burner at a fixed setting for 3 h. The maximum temperature recorded in the vapor headspace was about 80 °C, and each batch was run for 3 h from ignition of the burner. The operating conditions are summarized in Table 1.

Table 1. Operating conditions of the thermal distillation experiments.

Parameter	Operating condition
Reactor type	Batch stainless-steel reactor
Feedstock	Vehicle WLO
Feedstock loading (g)	800, 1600, 2400, 3200, and 4000
Heating source	Single LPG burner
Operating pressure	Atmospheric pressure
Maximum vapor headspace temperature (°C)	80
Batch time (h)	3
Cooling water flow rate	13.2 L/min
Number of trials per loading	2

Note: Heating rate, LPG consumption, ambient temperature, and relative humidity were not measured, because the study aimed to determine only the recovered masses, mass yields, and physicochemical properties. The same reactor, burner, procedure, and run time were used in all experiments, but without temperature or fuel records the consistency of the heating cannot be checked.

The procedure for each run was as follows:

a. Weigh the required mass of WLO.
b. Transfer feedstock into the reactor.
c. Secure the cover with screw locks.
d. Inspect for leaks in the reactor and heat exchanger.
e. Ignite burner and begin heating.
f. Maintain the experiment for 3 hours while ensuring continuous cooling water circulation.
g. Collect the distillate from the condenser outlet.
h. Turn off the burner and let the reactor cool to ambient temperature.
i. Stop the pump and release the screw locks.
j. Remove cover and collect residue.
k. Clean the reactor before next run.

Product recovery and measurement

The distillate collected from the heat exchanger and the reactor collar and the residue left in the reactor were weighed and recorded. The products were stored in clean, sealed containers until analysis.

The percentage yield was calculated using the Total mass recovery (Y_R) was calculated as:

$$\text{Total Recovery Yield } (Y_R) = \left(\frac{md + mr}{mf}\right) x\ 100\%$$

where:
- md = mean mass of distillate oil (g)
- mr = mean mass of residue oil (g)
- mf = initial mass of feedstock loaded into the reactor (g)

The mass yields of the distillate (Y_d) and the residue (Y_r) were calculated with Equations (1) and (2):

$$Y_d = \frac{m_d}{mf} x\ 100$$

eq. (1) for distillate mean mass yield

$$Y_r = \frac{m_r}{mf} x\ 100$$

eq. (2) for residue mean mass yield

Product characterization

The distillate and the residue were analyzed at the Standards and Testing Division of the Industrial Technology Development Institute, Department of Science and Technology (DOST-ITDI), Taguig City, Philippines. The following ASTM methods were used:

- Flash point (ASTM D92)
- Kinematic viscosity at 40 °C and 100 °C (ASTM D445)
- Specific gravity (ASTM D1298)
- Viscosity index (ASTM D2270)
- Density and API gravity were calculated from the specific gravity with Equations (3) and (4):

$$\rho_f = \left(\frac{SG_f}{SG_w}\right)\rho_w$$

eq. (3)

$$°API = \frac{141.5}{SG_f} - 131.5$$

eq. (4) *American Petroleum Institute*

where;

ρ_f = density of the substance
ρ_w = density of the water = 1000 kg/m^3 at 4°C
SG_f = substance specific gravity
SG_w = water specific gravity = 1.0

Data analysis

The mean masses of the distillate (m_d) and the residue (m_r) were calculated from the two trials with Equations (5) and (6):

$$m_d = \frac{m_{d1} + m_{d2}}{2}$$

eq. (5)

$$m_r = \frac{m_{r1} + m_{r2}}{2}$$

eq. (6)

Where;

m_{d1} = mass of distillate recovered in trial 1 (g)
m_{r1} = mass of residue recovered in trial 1(g)
m_{d2} = mass of distillate recovered in trial 2 (g)
m_{r2} = mass of residue recovered in trial 2 (g)

No standard deviation or range was reported, as the experimental results were based on two replicates (n = 2).

RESULTS AND DISCUSSION

Heating the WLO vaporized its light, volatile fractions, which condensed as the distillate oil; the heavier, less volatile components remained in the reactor as residue. This section presents the mass yields (Tables 2 and 3) and the physicochemical properties of the distillate and the residue (Tables 4 and 5).

Yield of the products

Table 2. Masses of distillate and residue recovered in duplicate trials at five feedstock loadings.

Loading	Feedstock (g)	Distillate oil (g)		Residue oil (g)		Mean recovered mass (g)	
		m_{d1}	m_{d2}	m_{r1}	m_{r2}	m_d	m_r
1	800	196.0	204.0	560.0	480.0	200.0	520.0
2	1600	207.2	194.4	1280.0	1360.0	200.8	1320.0
3	2400	152.0	226.4	2160.0	2080.0	189.2	2120.0
4	3200	331.2	252.8	2480.0	2640.0	292.0	2560.0
5	4000	221.6	275.2	3680.0	3520.0	248.4	3600.0

Note: Note: Values are the results of two independent trials per loading. The mean masses are the averages of the two trials (Equations 5 and 6). The process loss was calculated as the feedstock mass minus the combined mass of distillate and residue. It may include non-condensable gases, vapors not condensed, and holdup in the reactor, collar and condenser; its size (80-348 g) was not measured separately.

Table 2 lists the recovered masses. The mean distillate mass varied little with loading (189-292 g), while the mean residue mass increased from 520 to 3600 g. The mean masses were used to calculate the mass yields in Table 3.

Table 3. Mean mass yields (%) of distillate oil and residue, and total recovery, by feedstock loading.

Feedstock (g)	Distillate oil yield (%)	Residue oil yield (%)	Loss (%)	Total recovery yield (%)
800	25.00	65.00	10.00	90.00
1600	12.55	82.50	4.95	95.05
2400	7.88	88.33	3.78	96.22
3200	9.13	80.00	10.88	89.13
4000	6.21	90.00	3.79	96.21

Note: Yields are the mean recovered masses in Table 2 divided by the feedstock mass (Equations 1 and 2). Total recovery is the sum of the mean distillate and residue masses divided by the feedstock mass.

The mean distillate yield ranged from 6.21% to 25.00% and the mean residue yield from 65.00% to 90.00%. Total recovery was 89.13-96.22%, so 3.8-10.9% of the feed (80-348 g) was not recovered as liquid.

The 800 g loading gave the highest mean distillate yield (25.00%) and the lowest mean residue yield (65.00%). At 1600 and 2400 g, the distillate yield fell to 12.55% and 7.88% and the residue yield rose to 82.50% and 88.33%. At 3200 g, the distillate yield rose to 9.13% and the residue yield fell to 80.00%, because the distillate mass was higher (292.0 g) while the residue mass increased less than the loading. At 4000 g, the distillate yield fell again to 6.21% and the residue yield reached its highest value, 90.00%. The distillate yields therefore decreased with loading, although not monotonically. Because the distillate mass was nearly constant (189-292 g), the decrease is mostly a result of dividing a similar mass by a larger feed mass. The data do not show why. A larger charge has a larger thermal mass and needs more heat to reach vaporization temperature. A fixed 3 h run may have been too short for the larger charges to reach vaporization temperature; this should be tested by temperature-time records.

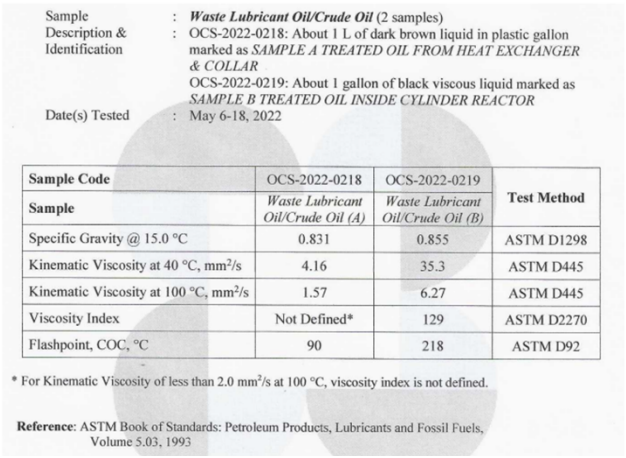
Characterization of the distillate and the residue

Table 1: Physicochemical properties of the recovered distillate and residue.

Parameters	Distillate Oil	Residue	Test Method
Flashpoint, ºC	90	218	ASTM D92
Kinematic viscosity at 40 ºC (mm^2/s)	4.16	35.3	ASTM D445
Kinematic viscosity at 100 °C (mm^2/s)	1.57	6.27	ASTM D445
Density at 15°C (kg/m^3), calculated	831	855	-
Viscosity index	Not defined	129	ASTM D2270
ºAPI gravity, calculated	38.8	34.0	-
Specific Gravity	0.831	0.855	ASTM D1298

Note: Flash point, viscosity, viscosity index and specific gravity were determined by the Standards and Testing Division, Industrial Technology Development Institute, Department of Science and Technology (DOST-ITDI), Taguig City, Metro Manila, Philippines. Density and °API gravity was calculated from the specific gravity (Equations 3 and 4). Viscosity index is not defined when the viscosity at 100 °C is below 2.0 mm^2/s (ASTM D2270)

The distillate had a flash point of 90 °C, kinematic viscosities of 4.16 mm^2/s at 40 °C and 1.57 mm^2/s at 100 °C, a density of 831 kg/m^3, a specific gravity of 0.831, and a °API gravity of 38.78; its viscosity index is not defined because the viscosity at 100 °C is below 2.0 mm^2/s. The residue had a flash point of 218 °C, kinematic viscosities of 35.3 mm^2/s at 40 °C and 6.27 mm^2/s at 100 °C, a density of 855 kg/m^3, a specific gravity of 0.855, a °API gravity of 34.0, and a viscosity index of 129. The laboratory report is shown in Figure 3.



Sample : ***Waste Lubricant Oil/Crude Oil*** (2 samples)
Description & Identification : OCS-2022-0218: About 1 L of dark brown liquid in plastic gallon marked as *SAMPLE A TREATED OIL FROM HEAT EXCHANGER & COLLAR*
OCS-2022-0219: About 1 gallon of black viscous liquid marked as *SAMPLE B TREATED OIL INSIDE CYLINDER REACTOR*
Date(s) Tested : May 6-18, 2022

Sample Code	OCS-2022-0218	OCS-2022-0219	Test Method
Sample	*Waste Lubricant Oil/Crude Oil (A)*	*Waste Lubricant Oil/Crude Oil (B)*	
Specific Gravity @ 15.0 °C	0.831	0.855	ASTM D1298
Kinematic Viscosity at 40 °C, mm^2/s	4.16	35.3	ASTM D445
Kinematic Viscosity at 100 °C, mm^2/s	1.57	6.27	ASTM D445
Viscosity Index	Not Defined*	129	ASTM D2270
Flashpoint, COC, °C	90	218	ASTM D92

* For Kinematic Viscosity of less than 2.0 mm^2/s at 100 °C, viscosity index is not defined.

Reference: ASTM Book of Standards: Petroleum Products, Lubricants and Fossil Fuels, Volume 5.03, 1993

Figure 3. Test report of the DOST-ITDI Standards and Testing Division for the distillate (OCS-2022-021) and the residue (OCS-2022-022) conducted last May 6-18, 2022.

Table 5. Properties of the recovered distillate compared with the requirements of PNS/DOE QS 004:2017 and EN 590.

Parameters	Distillate Oil	PNS/DOE QS 004:2017*[1]	EN 590:2025*[2]
Flashpoint, ºC	90	≥ 55	≥ 55
Kinematic viscosity at 40 ºC (mm^2/s)	4.16	*2.0–4.5*	*2.0–4.5*
Density, kg/m^3	831	*820–860*	*820–845*

Note: ****1*** *PNS/DOE QS 004:2017: Philippine National Standard for automotive diesel oil, with coconut methyl ester (CME) blend* ****2*** *EN 590:2025, automotive diesel fuel specification.*

Table 5 compares the flash point, viscosity at 40 °C and density of the distillate with the Philippine diesel specification (PNS/DOE QS 004:2017) and the European one (EN 590:2025). The flash point of the distillate, 90 °C, exceeded the minimum of 55 °C in both PNS/DOE QS 004:2017 and EN 590, but it was measured by the open-cup method (ASTM D92), while the specifications refer to a closed-cup method, so the values are not directly comparable. A flash point well above the minimum may also mean that few light ends were collected, which affects cold starting and ignition. The kinematic viscosity at 40 °C, 4.16 mm^2/s, is within the 2.0-4.5 mm^2/s range of both standards, close to the upper limit. The density, 831 kg/m^3, is within the ranges of PNS/DOE QS 004:2017 (820-860 kg/m^3) and EN 590 (820-845 kg/m^3). Although the flash point, the viscosity at 40 °C and the density meet the corresponding limits, compliance with either standard cannot be established from these data. Compliance would require post-treatment and further testing, since cetane number, sulfur content, distillation range, lubricity, and water and sediment were not determined (acid number, carbon residue, ash and metals would also be needed for a WLO-derived product).

CONCLUSION

A small-scale batch reactor was fabricated from locally available materials and separated WLO into a distillate and a residue, with a mass recovery of 89-96% (mean values, five loadings, duplicate runs). The results show that a small-scale unit can be built with accessible fabrication methods to separate WLO into two oil fractions. Such units might be useful for decentralized waste-oil handling; this requires a cost analysis and a test of the distillate quality.

The mean distillate yield decreased as the loading increased from 800 to 4000 g (25.00% to 6.21%), although the distillate mass was about the same (189-292 g); the reason was not investigated. The residue was the main product at every loading (65.00-90.00% of the feed), and its mass increased with the loading. Total recovery ranged from 89.13% to 96.22% (mean of two trials per loading). The unrecovered 3.8-10.9% of the feed was probably gas and holdup, which were not measured (Table 3). Optimizing the operating conditions (temperature profile, heating rate, loading) might improve the distillate yield and quality; this was not examined here.

The distillate had a lower flash point, density, and viscosity than the residue, which shows that it is the lighter fraction. The two fractions differ in flash point, viscosity and density, which shows that the process separated the oil into a light and a heavy cut. The distillate might be used as a blending component after further treatment and testing; the suitability of the residue for any use was not tested. Table 5 shows that the flash point, viscosity at 40 °C and density of the distillate are within the limits for automotive diesel. However, conformity with the Philippine and European diesel specifications cannot be established, because cetane number, sulfur content, distillation range, lubricity, and water and sediment were not determined. Further work should (i) record temperature-time profiles and fuel use, (ii) characterize the feed, (iii) measure gas losses and close the mass balance, (iv) test the distillate against the full diesel specification, and (v) use more replicates.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

CONTRIBUTIONS OF INDIVIDUAL AUTHORS

P.C. Lamadrid conceptualized the study, designed and fabricated the reactor, carried out the experiments, and wrote the first draft. **F.D. Siacor** contributed to the interpretation of the data, reviewed the data analysis, and helped revise the manuscript. Both authors reviewed and approved the final manuscript.

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