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Characterization of an Un-conventional Fuel – Residual Fuel Oil

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ABSTRACT

Despite the depleting fossil fuel reserves and growing environmental concerns, the world's energy consumption is still rising, resulting in the development of unconventional and alternative energy sources. A byproduct from the distillation of crude oil, residual fuel oil (RFO), also known as bunker fuel, finds extensive application in power generation and marine transportation. Because of its high viscosity, high Sulphur content and incomplete combustion, RFO has not gotten much attention in recent fuel research, despite its high energy content and widespread availability. This study examines RFO's physicochemical and thermal properties in contrast with standard fuels such as diesel, biodiesel and high-sulfur fuel oil. In determining RFO's suitability for combustion applications, a comprehensive laboratory investigation was performed, including viscosity, density, calorific value, cetane number, Sulphur content, and auto-ignition temperature tests. Thermal degradation patterns, combustion temperature ranges, and emission properties were also investigated. The results conclude that RFO needs to be pretreated before use, with options like heating or blending. The calorific value of RFO is found to be close to diesel, making it a potential substitute for an alternative fuel, a viable and cheaper option, for stationery and large-scale engines. There are still certain issues related to its use, such as ignition delays, particulate emissions and regulatory compliance. The study suggests that RFO has the potential to be used as fuel, when suitably modified, in areas where getting access to refined fuel is difficult. Future work on the study includes fuel upgrades, engine system modifications & long-term combustion and emission studies to improve its usability and acceptability.

Keywords: Un-conventional fuel, Kinematic viscosity, Characterization, Crude oil, Diesel engines.

1. INTRODUCTION

Thus, demand for global energy has risen as a result of population growth, fast-moving urbanization and industrialization **(Zohuri, 2023)**. The International Energy Agency: forecasts that global energy usage could increase by approximately 25% by the year - 2040,

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mainly in developing nations **(Newell et al., 2019)**. Fossil-fuels such as coal, oil and natural gas remain prevalent in the energy-mix, particularly in the heavy-duty transportation and industrial sectors, in spite of the swift growth of renewable energy options like solar, wind and hydropower **(IEA, 2023)**. It is increasingly pertinent to identify un-conventional and alternative fuels that are cost-effective, readily available and compatible with the existing combustion systems. These alternative fuels including heavy residual oils, biomass-based fuels and oils derived from waste, have the potential to bridge the gap between the slow transition to cleaner energy and the diminishing fossil fuel reserves **(Demirbas, 2016)**. However, residual fuel oil stands out amongst these alternatives due to its high-energy density, cost-effectiveness and wide accessibility. Typically obtained as the least desirable product during the fractional distillation and processing of crude oil, R-F-O is classified as a heavy fuel oil **(Speight, 2014)**. The majority of the residual fractions that do not evaporate during distillation consist of long-chain hydrocarbons, heavy aromatic compounds, asphaltenes and other high boiling point residues **(Gary et al., 2007)**. Commonly identified as fuel oil No. 5 or No. 6 in standards such as ISO and ASTM. In comparison to lighter fuels such as diesel or kerosene, RFO is denser, has higher viscosity and looks darker **(Ali et al., 2015)**.

Throughout much of the twentieth century, RFO was widely used in maritime shipping, the generation of power, and heating applications, particularly in countries with low or non-existent environmental restrictions. However, its high Sulphur content, high viscosity and the need for preheating before combustion restricted its use in smaller-scale or mobile applications such as automotive engines **(Vasquez and Bakar, 2018)**.

However, it has high viscosity, high Sulphur content, low cetane number and requires preheating before ignition. These qualities make direct deployment in standard diesel engines or in industries where clean combustion and efficiency are critically difficult **(Khedr et al., 2025)**. As refiners strive to maximize the value of each barrel of crude oil, Residual Fuel Oil has received interest not just as a low-cost fuel, but also as a potential component in blended fuels, particularly when modified to minimize the effect on the environment **(Traver et al., 2022)**. Its high calorific value, comparable to that of diesel, and abundance in oil-rich countries make it potential for further investigation as an alternative fuel source, particularly in areas where access to refined petroleum products is limited **(Zhao et al., 2016)**. In this context, determining the physicochemical and thermal properties of RFO is critical. A thorough understanding of its behavior under various combustion conditions, compatibility with the engine systems, and emission profiles could help in determining how Residual Fuel Oil can be improved or used more efficiently in modern applications **(Sani et al., 2018)**. This study aims to delve deeper into the characteristics of Residual Fuel Oil (RFO), analyzing its strengths, limits and potential role in the changing global energy scene. Stationary power generation units, naval engines and huge industrial furnaces that can handle their high viscosity and incorporate emission control technologies are prime examples of urgent application areas **(Rautiainen, 2024)**

Today, RFO is used as a primary or backup fuel in a variety of industries, including heavy industry and maritime transport. It is commonly used in:

- Marine propulsion systems as bunker fuel, as well as industrial boilers and furnaces.
- Thermal generation of power.
- Process heating in industries like steel, cement and glass industries.

Despite its affordability and high energy content, RFO has significant technical and environmental constraints which include the following:

- Requires pre-heating before combustion because of its high viscosity.
- It has low cetane number, resulting in poor ignition quality.
- It has high Sulphur and metal content, contributing to SOx, NOx, and particle matter emissions. Inefficient combustion, especially in unmodified diesel engines **(Jankowski et al., 2002)**.

As a result, while Residual Fuel Oil has potential as a fuel alternative, its direct application in conventional systems is hampered by regulatory and technical barriers. Most existing infrastructure and combustion systems are improved for lighter, cleaner fuels, making the use of RFO inefficient and environmentally harmful unless properly treated **(Kim et al., 2020)**. There is an urgent need to thoroughly characterize RFO in order to establish its feasibility, adaptability, and performance under changing operational conditions. This gap prevents its inclusion in mainstream energy initiatives, particularly in developing nations with acute energy deficits.

The key objectives of the study are:

- Analyze the physical, chemical and thermal properties of RFO and compare its performance to conventional fuels.
- Identify barriers and opportunities to improve RFO usability.
- Propose techniques for safe and efficient use in energy systems.

Residual Fuel Oil (R-F-O) has long been considered a low-value by-product of crude oil refining processes. In the 20th century, its principal application was in heavy industrial activities, particularly in the marine transportation and power generation sectors, where fuel cost-efficiency trumped environmental concerns **(Corbett, 2004)**. Studies have repeatedly shown that Residual Fuel Oil (RFO) has a high calorific value, which is often comparable to diesel, making it a desirable choice for bulk consumers of energy **(Moliere, 2002)**. However, the necessity for specialized equipment and the environmental consequences of RFO combustion have led to a reduction in its use, particularly in places with strong emission standards. RFO is chemically complex, containing long-chain alkanes, aromatic hydrocarbons, resins, asphaltenes, and various amounts of Sulphur and heavy metals like vanadium and nickel **(Speight, 2014)**. Its high molecular weight components contribute to its increased viscosity and density. Thermogravimetric and spectroscopic research has shown that RFO decomposes in multiple stages, revealing a wide range of hydrocarbon fractions. Viscosity, flash point, pour point, and Sulphur content have been identified as key characteristics influencing its handling, combustion, and emission profiles **(Ahmad and Yasin, 2019). (Sani et al., 2018)** found that without pre-heating, RFO cannot achieve optimal atomization, thereby resulting in incomplete combustion and excessive emissions. Furthermore, its low cetane number reduces ignition delay and combustion stability, particularly in diesel engines that are not designed for heavy-fuel oils.

The combustion of Residual Fuel Oil in marine engines and industrial boilers has been widely investigated. **(Jones et al., 2017)** discovered that R-F-O combustion produces high amounts of Sulphur oxides (SO_x), nitrogen oxides (NO_x), unburned hydrocarbons (U-H-C) and particulate matter (P-M). This environmental impact has driven the development of emission-control technologies such as fuel additives, scrubbers and post-treatment systems. In a study of comparability. **(Ahmad and Yasin, 2019)** found out that blending Residual Fuel Oil with lighter fuels like diesel or biodiesel can improve the efficiency of combustion and significantly reduce emissions. Other researchers **(Kim et al., 2020)** have proposed emulsification procedures in which water is diffused within Residual Fuel Oil (RFO) to reduce combustion temperatures and control NOx emissions, but these methods must be carefully controlled to ensure reliability of the engine. Several technological innovations have been proposed to enhance the usage of RFO. Fuel heating systems are required to reduce viscosity before injection into the combustion chambers **(Vasquez and Bakar, 2018)**. Preheating temperatures, ranging from 100°C to 150°C are frequently required for effective atomization. To address these heavy and diverse characteristics of RFO, advanced injection systems namely swirl atomizers and multi-stage injectors have been developed **(Jones et al., 2017)**. Furthermore, retrofitting of engine and optimization of combustion chamber designs have shown potential for enhancing RFO combustion characteristics **(Park et al., 2015)**.

Stringent global policies, particularly the International Maritime Organization's (IMO) 2020 Sulphur cap, have reduced the Sulphur content of marine fuels to 0.5% by weight, down from 3.5% **(Bilgili, 2021)**. This policy has significant implications for the future use of untreated RFO, which frequently exceeds allowable Sulphur limits **(IMO, 2019).**

To be in compliance, industries have resorted to:

- Blending RFO with low-sulfur fuels.
- Investing in desulfurization technologies.
- Using scrubbers (Exhaust gas cleaning systems).

Despite these changes, the high cost of compliance has reduced the appealing value of RFO, particularly as cleaner options such as LNG and low-sulfur fuel oils become more accessible **(Moliere et al., 2010)**.

2. MATERIALS AND METHODS

2.1 Sample Collection

Residual Fuel Oil (RFO) samples were collected from the final distillation residue of a crude oil refining process at a local petroleum refinery facility located in Port Harcourt, Nigeria. These samples show the unrefined heavy-bottom product, which is typically used in industrial boilers and marine engines. To ensure homogeneity, three representative samples were taken directly from the refinery's storage tank right after agitation. The feedstock crude oil was light-sweet with an API gravity of 32° and a sulfur concentration of around 0.8 wt.%. To assess any diurnal fluctuations, the RFO samples were labeled as RFO-1, RFO-2 and RFO-3 according to collection intervals (morning, afternoon, and evening batches), as shown in **Table 1.**

Table 1. RFO Samples

Sample ID	**Collection Time**	**Source**	**Storage Temperature (^{0}C)**	**Initial Appearance**
RFO-1	08.00 AM	Bottom Tank 01	60	Thick, dark brown
RFO-2	12.00 PM	Bottom Tank 02	65	Highly viscous, black
RFO-3	04.00 PM	Bottom Tank 03	63	Black with heavy residue

2.2 Sample Preparation

To ensure the uniformity and repeatability of results, the following sample preparation techniques were used:

1. RFO samples were pre-heated to a temperature of 80°C in a thermostatically controlled water bath to minimize viscosity and ensure uniform mixing.
2. To remove coarse particulate matter, the pre-heated RFO was filtered through a 200-micron stainless steel mesh filter.
3. To achieve homogeneity, samples were stirred using a magnetic stirrer at 200 rpm for 30 minutes.
4. Samples were stored in amber glass containers at a room temperature of 25°C to avoid photochemical degradation and appropriately labelled for analysis.

2.3 Analytical Techniques

These samples underwent a complete set of analytical methods, which is in accordance with ASTM and ISO standards, to determine their physicochemical, chemical composition, thermal, and (where appropriate) emission properties. **Table 2** illustrates the properties of the instruments used.

2.3.1 Physicochemical Analysis

The physicochemical characteristics of R-F-O were determined using standardized procedures that followed ASTM, ISO and IP requirements. These characteristics provided useful information about the fuel's combustion quality, handling characteristics, environmental impact and storage needs.

Table 2. The Used Standardized Instruments

Property	**Instrument**	**Significance**
Kinematic Viscosity	Redwood Viscometer /U-Tube Viscometer	Flow behavior under operating temperatures
Density	Digital Density Meter	Mass per unit volume affects atomization and combustion
Flash Point (°C)	Pensky-Martens Closed Cup Tester	The lowest temperature at which vapor ignites
Pour Point (°C)	Cold Chamber + Thermometer	The lowest temperature at which fuel will pour or flow
Fire Point (°C)	Open Cup Apparatus	The temperature at which sustained ignition occurs
Auto-Ignition Temp (°C)	Furnace Apparatus	Minimum temperature for spontaneous ignition without spark
Boiling Point (°C)	Simulated Distillation Unit	Temperature range of volatile components
Freezing Point (°C)	Cold Chamber Method	The temperature at which solidification begins
Calorific Value (MJ/kg)	Bomb Calorimeter	Energy content available for combustion
Ash Content (wt.%)	Muffle Furnace @ 775°C	Non-combustible mineral residues
Water Content (%)	Karl Fischer Titration / Distillation	The presence of free and emulsified water affects combustion and corrosion
Acidity (mg KOH/g)	Potentiometric Titration	Measures corrosive potential due to organic acids
Cetane Number	CFR Engine (Calculated Index also used)	Ignition quality rating; relevant for diesel engine applications

Cloud Point (°C)	Cooling Bath Observation	The temperature at which wax crystals first appear
Smoke Point (mm)	Smoke Point Lamp	Indicative of soot formation tendency during combustion
Sulfur Content (%)	X-ray Fluorescence / UV Fluorescence Analyzer	Major environmental concern due to SO_x formation
Salinity (ppt)	Conductivity Method or Chloride Titration	The presence of salts affects corrosion and emissions

2.3.2 Thermal Behavior

To assess thermal deterioration and stability, thermogravimetric Analysis (TGA) measures weight loss based on temperature.

- Instrument: Mettler Toledo TGA/DSC 1 STARe System.
- Conditions: N_2 atmosphere and heating rate of 10°C/min from 25°C to 800°C.

2.3.3 Emission Characteristics: RFO combustion testing was performed.

- Emissions were monitored with a portable exhaust gas analyzer (Testo 350).
- Monitored parameters include CO, CO_2, NOx, SO_2, and unburned hydrocarbons.
- A pilot-scale diesel engine with a preheating chamber was used for combustion tests.

Some Remarks on Measurement Conditions:

- All the Viscosity measurements were performed at 100°C in a controlled laboratory setting to simulate pre-heated operational conditions.
- Due to excessive RFO matrix interference in conductivity values, salinity was evaluated using the silver nitrate titration method.
- A Cetane Index formula based on **(ASTM D976-06, 2016)** was used in the assessment of the cetane number for cost and equipment efficiency purposes.
- A regulated smoke lamp burner was used to determine the smoke point in vertical flame height.

3. RESULTS AND DISCUSSION

3.1 Physicochemical Properties of RFO

The experimental investigation of Residual Fuel Oil (RFO) was conducted using a pilot-scale pressure-jet industrial burner system equipped with a preheating unit and precision fuel metering to ensure stable operation during tests, as shown in **Table 3.** This setup allowed accurate measurement of properties relevant to both stationary combustion applications and potential retrofit scenarios for industrial heating systems.

- The high viscosity (210cSt at 100°C) indicates poor fluidity at ambient temperatures, necessitating preheating apparatus for pumping and atomization in engines or burners.
- High density of 0.985 g/cm^3 indicates the heavy, complex molecular composition, which is typical of refinery bottom residues **(Adams et al., 2023).**
- The calorific value of 41.8 MJ/kg is comparable to standard diesel and slightly greater than Heavy Fuel Oil (HFO), indicating a significantly strong energy potential.
- The Sulfur concentration (2.68%) exceeds stipulated environmental limits, necessitating emission control technologies or desulfurization necessary for long-term use.

- Moderate acidity level and ash content pose concerns for corrosion and formation of deposits in combustion systems, respectively.

Table 3. Test Results

Property	Measured Value	Unit	ASTM Limit (HFO/Diesel)
Density @ 15°C	0.985	g/cm^3	0.820–0.890 (Diesel)
Kinematic Viscosity @ 100°C	210	Cst	1.3–4.1 (Diesel), 180–380 (HFO)
Calorific Value	41.8	MJ/kg	≥42 (Diesel), 39–41 (HFO)
Flash Point	92	°C	≥52
Pour Point	18	°C	-15 to +6
Water Content	0.28	% vol	≤0.05
Sulfur Content	2.68	% wt	≤0.5 (ULSD), ≤3.5 (HFO)
Ash Content	0.14	% wt	≤0.1
Acidity (TAN)	1.18	mg KOH/g	≤0.5
Cloud Point	20	^{0}C	5-15
Smoke Point	14	mm	≥20
Cetane Number	24	-	≥45 (Diesel)

3.2 Thermal Characteristics

3.2.1 Thermogravimetric Analysis (TGA)

TGA showed three major decomposition phases for RFO, as shown in **Table 4**. The effective combustion window is indicated by the thermal degradation, which normally occurs between 150–400°C. The residues post 650°C (roughly 15 %) confirm the presence of refractory asphaltenes and metallic impurities, which could lead to slagging and fouling in high temperature applications.

Table 4. The result of the Thermal Analysis of RFO

Stage	Temperature Range (^{0}C)	Weight Loss (%)	Description
I	30–150	5-7	Moisture and light volatiles
II	150–400	45-55	Breakdown of aliphatic compounds
III	400–650	35-40	Aromatic and resinous residue

3.3 Comparison with Conventional Fuels

Table 5 shows the comparison of R-F-O with diesel and biodiesel. The results showed that R-F-O has poor ignition properties and a higher environmental footprint due to sulfur and particulate contents. However, it aligns closely with HFO, making it suitable for industrial boilers, marine engines and power plants with adequate handling infrastructures.

Table 5. Comparison with other Conventional Fuels

Parameter	RFO	Diesel	HFO (IFO 180)	Biodiesel (B100)
Density (g/cm^3)	0.985	0.830	0.960	0.880
Viscosity (cSt)100°C	210	3.2	180	4.5
Calorific Value (MJ/kg)	41.8	42.5	39.0	37.5
Sulfur Content (%)	2.68	0.0015 (ULSD)	2.5–3.5	~0.0
Flash Point (°C)	92	62	70-100	130
Pour Point (°C)	18	-15	15-30	0-5

3.4 Combustion and Emission Characteristics

When RFO is combusted in a pilot-scale burner (with 5% excess air and preheated at 120°C), the following emission results were recorded:

Table 6. Emission Test Results of RFO

Pollutant	**Measured Value**	**Standard Limit (mg/m^3 or %)**	**Comment**
CO	1200	≤800	Incomplete combustion due to poor atomization
NO_X	640	≤500	Elevated due to combustion temperature
SO_X	2450	≤500	Directly tied to high sulfur content
Particulates	110	≤100	High ash and heavy hydrocarbon residues
Smoke Number	2.8 Bosch units	≤1.0	Indicates soot-prone combustion
O_2 (Oxygen)	3.5	3-5%	Within the expected range for excess air combustion

Note: The emission quantities are linked to the elemental composition of RFO by weight: Carbon: 85.2%, Hydrogen: 10.4%, Sulphur: 2.68%. These values vary with the crude oil source, influencing combustion emissions.

- Emission results clearly showed non-compliance with Euro VI or EPA Tier 4 standards, especially for NO_X, SO_2 and particulates.
- Preheating and blending RFO with diesel or biodiesel may reduce soot formation and improve atomization **(McGill et al., 2013)**.
- Adapting emission control strategies such as desulfurization, EGR (Exhaust Gas Recirculation) or after-treatment filters is recommended for environmental compliance **(Hefazi and Rahai, 2008).**

3.5 Applications and Modifications

3.5.1 Blending Strategies

- RFO plus Diesel (Ratio of 80:20) showed a 25% reduction in viscosity and as well 12% reduction in particulate emissions.
- Blends can be used in dual-fuel diesel generators, especially in emerging economies **(Dahake et al., 2025)**.

3.5.2 Engine Adaptation

- Fuel heating lines, bigger injectors, and modified/improved atomizers are required for combustion stability **(Pandey et al., 2012)**.
- Retrofitted boilers and Low-speed marine engines are the most compatible systems.

3.5.3 Desulfurization Options

- Hydro-treating and adsorptive desulfurization can reduce sulfur content by up to 80%, but are cost-prohibitive at small-scale level **(Song and Ma, 2003)**
- Low-cost options include activated clay filtration and oxidative desulfurization for rural or modular applications.

3.5.4 Environmental and Economic Factors in the Utilization of RFO

- RFO is 40–60% more economical than diesel per MJ of energy, offering economic incentives in large-scale thermal applications.
- Carbon intensity remains high but can be reduced by blending or carbon capture.
- Its effective utilization can also reduce waste from refinery operations, thereby promoting circular economy principles.

5. CONCLUSIONS

This study comprehensively characterized Residual Fuel Oil (RFO), confirming its classification as a heavy fuel due to its high density (0.985 g/cm^3), viscosity (210 cSt at 100 °C), and strong energy content (41.8 MJ/kg). Thermal analysis validated its usability within the 150 - 400°C combustion range, while emission tests revealed high SO_2, NO_x, and particulates, primarily attributed to its sulfur content (2.68 wt%) and incomplete combustion. Compared to diesel and biodiesel, RFO offers competitive energy output but falls short in ignition quality, flow behavior, and emission compliance, necessitating preheating, blending, or emission controls for effective use. RFO remains a viable option for large-scale applications such as industrial boilers, marine propulsion, and stationary power systems, particularly where infrastructure supports its handling. Its economic appeal lies in low cost and abundant availability as a refinery byproduct, making it attractive for energy-constrained regions. However, environmental concerns remain its major drawback, requiring cleaner utilization strategies. Future work should focus on cost-effective desulfurization, optimized blending with cleaner fuels, and burner or engine modifications. Policymakers can further support its responsible adoption by establishing emission standards, blending frameworks, and incentives for waste-to-energy recovery, ensuring RFO's role in sustainable energy portfolios.

Credit Authorship Contribution Statement

M.A Nwufo: Writing original draft, Methodology & Validation. C.O Iwenofu: Data Collection. C.M U-Dominic: Writing review & editing.

Declaration of Competing Interest

The authors declared that they have no known competing financial interests or personal relationships that would have appeared to influence the work reported in this article.

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توصيف الوقود غير التقليدي – زيت الوقود المتبقي

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الخلاصة

يستمر الطلب العالمي على الطاقة في الارتفاع في ظل تضاؤل احتياطيات الوقود الأحفوري وتزايد المخاوف البيئية، مما يخلق المعروف عادةً باسم زيت الوقود الثقيل أو وقود ،(RFO) حاجة ملحة لمصادر طاقة بديلة وغير تقليدية .زيت الوقود المتبقي السفن، هو منتج ثانوي لتقطير النفط الخام، وقد استُخدم تاريخيًا في النقل البحري وتوليد الطاقة .على الرغم من محتواه العالي ،باهتمام يُذكر في أبحاث الوقود المعاصرة نظرًا لارتفاع لزوجته (RFO) من الطاقة وانتشاره الواسع، لم يحظَ زيت الوقود المُركَّب ومحتواه من الكبريت، وعدم كفاءته في الاحتراق .تبحث هذه الدراسة في الخصائص الفيزيائية والكيميائية والحرارية لزيت الوقود مُقارنةً أدائه بالوقود التقليدي مثل الديزل والديزل الحيوي .أُجريت تحليلات مختبرية شاملة، شملت قياسات ،(RFO) المُركَّب اللزوجة، والكثافة، والقيمة الحرارية، ورقم السيتان، ومحتوى الكبريت، ودرجة حرارة الاشتعال الذاتي، لتقييم مدى ملاءمة زيت لتطبيقات الاحتراق .كما تم تحليل أنماط التحلل الحراري، ونطاقات درجة حرارة الاحتراق، وخصائص (RFO) الوقود المُركَّب يتطلب معالجة مسبقة كالتسخين أو المزج، إلا (RFO) الانبعاث .تشير النتائج إلى أنه على الرغم من أن زيت الوقود المُركَّب أنه يُظهر قيمًا حرارية تُضاهي الديزل، ويمكن أن يُشكِّل بديلاً فعالاً من حيث التكلفة للمحركات الثابتة وكبيرة الحجم .ومع ذلك، لا تزال هناك تحديات تتعلق بتأخير الاشتعال، وانبعاثات الجسيمات، والامتثال للوائح التنظيمية .خلصت هذه الدراسة إلى كمصدر طاقة فعال في المناطق التي (RFO) أنه مع إجراء التعديلات المناسبة، يُمكن إعادة توظيف زيت الوقود المُكرر يصعب فيها الحصول على الوقود المُكرر .وتشمل توصيات العمل المستقبلي تطوير الوقود، وتكييف نظام المحرك، واختبار الاحتراق والانبعاثات على المدى الطويل لتحسين قابلية الاستخدام والامتثال البيئي

الكلمات المفتاحية :وقود غير تقليدي، اللزوجة الحركية، التوصيف، النفط الخام، محركات الديزل