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Assessing Technological Feasibility of an On-shore Circular-Economy Treatment Plant for Recycling Ship-Generated Oily Waste in Peru

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Abstract

This study addresses the environmental impact of oily marine waste generated by cargo ships, oil tankers, and fishing vessels. The objective is to assess the technological feasibility of establishing a treatment facility to recover and repurpose such waste into usable fuel. A laboratory-scale process involving decantation, distillation, and condensation was designed and tested using mixed oily samples collected from maritime operations. The resulting product was evaluated based on density, calorific value, and physicochemical properties, confirming its alignment with Peruvian technical standards for diesel-type fuel. Results showed a 24% recovery rate and an average calorific value comparable to conventional diesel. This research contributes to the circular economy by offering a sustainable waste management alternative that recovers economic and environmental value. It fills a gap in the literature regarding the reuse of maritime oily waste in developing countries and presents practical implications for the hydrocarbon and logistics sectors in Latin America.

Keywords
Oily Waste Recovery, Waste-to-Fuel Conversion, Circular Economy, Thermal Treatment Technology, Marine Pollution Mitigation.

1. Introduction
The hydrocarbon sector is presently essential to the nation's development. According to the Ministry of Economy and Finance (2022), investments in this sector constitute a significant 0.7% of the Gross Domestic Product (GDP). It continues to be among the most extensively utilized energy sources by both the general public and industrial entities, with diesel, natural gas, and gasoline identified as the primary products. As reported by the Ministry of Energy and Mines (2023), 77% of the vehicle fleet utilizes gasoline, whereas 10% employs diesel; however, despite the smaller proportion of consumers, diesel accounts for 49% of energy consumption. Conversely, gasoline and petrol, which cater to a larger segment of users, contribute only 30%.

A key indicator of this situation is that Peru produces 2,226.80 thousand tons and consumes 4,727.30 thousand tons annually (Euromonitor, 2020). As a result, large quantities of crude oil are imported to meet domestic demand. According to the Ministry of Energy and Mines (2022), diesel demand is supplied at 135 MBPD, a figure met through domestic production (30%) and imports (70%). Imported fuel is transported via maritime routes using oil tankers with a cargo capacity of up to 28,000 tons. However, these vessels are the main sources of waste, which is either dumped or spilled accidentally into the sea.

As depicted in Figure 1, the hydrocarbon lifecycle commences with the extraction of raw materials, which are subsequently subjected to separation and refining processes to produce the products currently available in the market. Each phase yields solid and liquid waste. In our study, we concentrate on the distribution stage to identify potential recovery alternatives.

According to Comerma-Piña (2004), all large ships—such as cargo ships and oil tankers—consume substantial quantities of fuel, with their fuel tanks capable of storing up to 4,000 tons to operate their engines. These tanks are susceptible to accidental spills resulting from collision, sinking, or grounding. As reported by the Ministry of Transport and Communications (2022), the National Port Authority received 14,701 ships and dispatched 14,987, with Callao exhibiting the highest concentration of vessels within the maritime sector. The predominant types of vessels engaged in international trade include container ships, tankers, and bulk carriers, which constitute 26%, 28%, and 26% of the fleet, respectively (Table 1).

Table 1. Movement of ships received and dispatched nationwide

Port	Year	
	Received	Departures
Callao	2,967	3,023
Paita	596	600
Matarani	520	519
Pisco	450	449

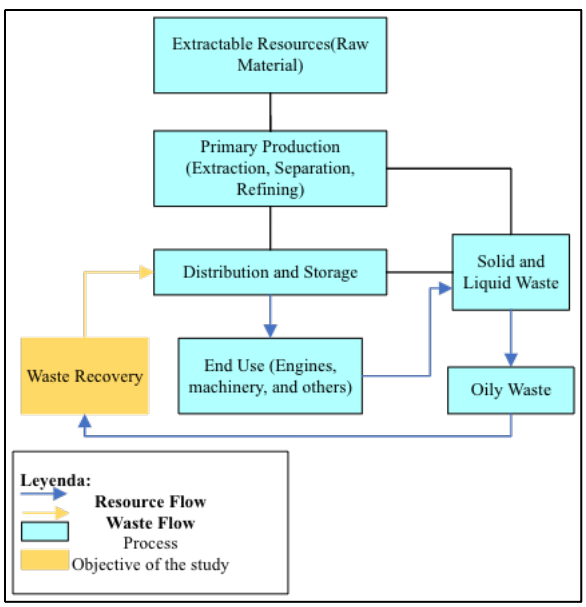

Figure 1. Life cycle of general hydrocarbons (Adapted from Al Zarkani et al. 2023)

The current situation in Peru demonstrates that these wastes are not being managed appropriately (Pulido et al. 2022), particularly those that pose a risk to the environment (Figure 1). This issue is exacerbated by the fact that the Port of Callao, Peru's largest and most significant port, lacks the necessary infrastructure for the proper disposal of oily waste generated by ships. Furthermore, it does not possess a strategic system for the management and disposal of this waste. As a result, ships are compelled to remain in port longer than scheduled, incurring additional costs (Santos and Pérez 2023).

Therefore, this research concentrates on developing a solution that involves valorizing waste via a treatment facility, the final product of which is diesel (Baskar et al. 2021).

In the pursuit of an appropriate solution, various technological alternatives have been evaluated to determine the most suitable option. This particular choice employs waste heat as the primary process for thermally decomposing organic materials and, in this instance, transforming them into valuable products while minimizing environmental impact. It is crucial to emphasize that this methodology aims to mitigate environmental effects by reusing products rather than simply disposing of them, thereby aligning with the principles of the circular economy. According to Ghisellini et al. (2016), the circular economy constitutes a strategic approach to restoring both environmental and economic equilibrium in industrial activities. Consequently, its application is gaining increasing significance in contemporary societies (Gunaratne et al. 2022).

1.1 Objectives

The objective of this research is to demonstrate the technological feasibility of implementing a treatment facility designed to recover oily waste generated by ships during their operational activities, such as movement, cleaning, loading, and unloading.

The process involves operations such as decanting, distillation, and condensation to produce a diesel-type fuel that meets the required technical specifications, including calorific value, density, and physicochemical properties.
In the initial phase, the oily waste will undergo characterization. Subsequently, the process will be designed and experimentally validated at a laboratory scale at the University of Lima. Finally, the properties of the produced fuel will be assessed, the optimal mixture ratio will be established, and concurrently, the installed capacity and technical requirements necessary to project the potential demand and market share of the final product will be analyzed.

2. Literature Review

The revised review concluded that the industry in Peru concerning waste reutilization, particularly oily waste, is experiencing stagnation. According to Juan and José (2009), despite Peru's status as an oil-producing nation, its domestic production fails to satisfy the national demand for fuels, notably gasoline and diesel. Consequently, the government encounters significant volatility in international oil prices, which has been on the rise in recent years, primarily attributable to the economic expansion in Asia over the past decades. Considering the disparity between diesel supply and demand, supported by studies presented in Figure 2 from Osinergmin (2019) reports, the findings of the aforementioned article are corroborated, indicating that fuel availability remains constrained. As depicted, a considerable gap persists between diesel supply and demand. While demand increased approximately 3% from 2014 to 2018, supply diminished by 5%. The principal distribution channel for diesel is retail outlets, accounting for 65.7% of sales. Of this, 31.9% was sold directly to consumers, 2% to retail distributors, and 0.4% to Osinergmin vessels (2019).

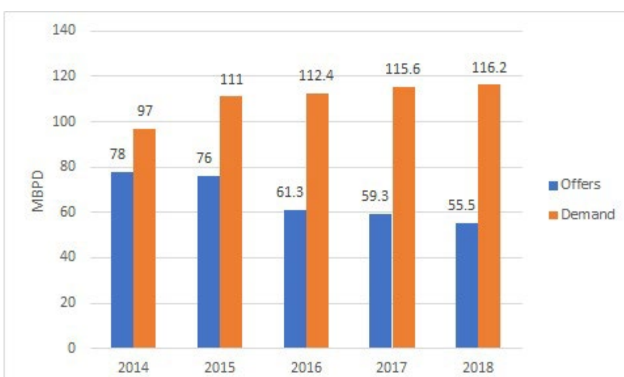

Figure 2. Balance of supply and demand for diesel

As noted in the article by Adria Pino (2014), laboratory distillation tests provided more detailed insights into the behavior of petroleum compared to industrial crude oil fractionation. The experiment was conducted in two phases. In the first phase, distillation occurred at atmospheric pressure, increasing the temperature to 400 °C. In the second phase, the residue that did not evaporate in the first stage was subjected to vacuum distillation. This approach prevented excessive heating of the sample, which could have caused unwanted thermal cracking. By following these steps, the experiment was able to analyze the oil's composition and behavior more accurately, ensuring the properties of the crude oil remained as intact as possible throughout the process. Another key point mentioned by Nuria Suárez (2024) in the journal RETEMA (Technical Journal of the Environment) highlights that waste recovery has become a critical solution to today's most urgent environmental challenges. This technology has enabled the development of innovative approaches and techniques focused on transforming traditional waste management and creating a new sector paradigm.

Historically, waste management primarily concentrated on disposal and storage, which had a considerable environmental impact. Nevertheless, with the advent of recovery initiatives, transforming waste into valuable resources such as energy or secondary raw materials has been actively promoted, thereby endorsing the principles of the circular economy and sustainability.

Despite the progress achieved, waste recovery continues to encounter substantial challenges. These encompass the necessity to enhance the efficiency of technological processes, to surmount regulatory and societal obstacles, and to guarantee the economic viability of the implemented solutions. Consequently, recovery remains a transformative alternative; however, it must still overcome obstacles to fully establish itself as the primary strategy in waste management.

3. Methods

The approach is quantitative because it aims to evaluate, compare, and interpret the data collected from tests conducted at the University of Lima laboratory on the oily waste sample, using the previously established processes. As Hernández Sampieri et al. (2014) point out, the quantitative approach is sequential and investigative, where each stage follows the previous one and no steps are skipped. The process is rigorous, although some phases may be redefined. It begins with an idea that is refined, and once defined, research objectives and questions are developed. The literature is reviewed, and a framework or theoretical perspective is built. Hypotheses are formulated, and variables are identified from the questions. A plan is then created to test these variables, which are measured in a specific context. The data collected is analyzed using statistical methods, leading to a series of conclusions.

As Vargas (2009) highlights, this type of research is distinguished by its objective to utilize existing knowledge while acquiring new insights through the implementation and systematization of research-driven practice. Within this context, technical, artisanal, and industrial innovations, along with scientific innovation itself, are regarded as applied research. Such research is pragmatic in nature, as it aims to resolve a specific issue—namely, the insufficient management of oily waste—by establishing an oily waste treatment facility, thereby offering a feasible technological solution.

The scope is descriptive because the objective is to delineate the characteristics of the samples and the final product, as well as to meticulously document the processes and final results of the experimentation conducted in the laboratory of the University of Lima.
The following procedures were used for sample treatment in the laboratory (Figure 3):

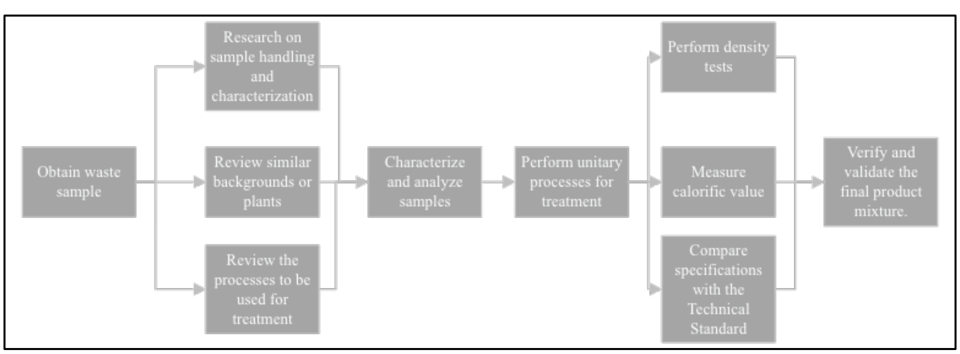

Figure 3. Construction of the experiment

First, the oily waste samples will be obtained, and their management and characterization will be investigated. According to the Comprehensive Solid Waste Management Law (2017), hazardous waste is characterized as waste that presents a substantial health hazard owing to its inherent properties. Consequently, such waste must be properly characterized, stored, and treated to diminish or eradicate its associated risks. In relation to oily waste, it is described as a blend of hydrocarbons and water generated during standard maritime operations (Aine, 2006). The subsequent table delineates the machinery utilized for each respective operation (Table 2).

Table 2. Activity related to each machine

Activity	**Machine**	**Description**
Distill	Distillation tower	Essential equipment for separating liquid mixtures according to their boiling point and density. It consists of a vertical cylindrical tower with plates with holes that, depending on density, allow specific fractions of the vapors previously heated to 350°C - 400°C to pass through. The diesel fraction is obtained in the lower middle part at a temperature between 220°C and 270°C (Seminar, 1966).
Condense	Condensers	The condenser plays a key role in the process, as the mixture leaving the distillation tower must be cooled and condensed from the mixture that has been separated according to its fraction. This is done using a tube heat exchanger where steam enters on one side and pre-cooled water on the other. Reflux is also important, as part of the condensate returns to the distillation column to improve the quality of the processing (Perez et al. 2020).
Heating	Boiler	The boiler is the main source of heat needed to reach the 350°C to 400°C required in the process to achieve the fractionation temperatures when generating the vapors that then pass to the distillation tower (Aguilar et al. 2019).
Cool	Cooling tower	Water is introduced through the dome of the tower by means of nozzles to distribute the water over the largest possible surface area. Cooling occurs when the water, as it falls through the tower, comes into direct contact with a countercurrent of air. The water is then cooled by mass transfer (Mendoza and Gallardo, 2016).

Once the characterization and unit processes are identified, the following tests are conducted on the resulting product.

Calorific value test:
As stated by Colin and Carrillo (2024), calorific value is defined as the quantity of heat released during the complete oxidation of a given mass or volume of fuel under specified temperature and pressure conditions. The energy produced in this process is expressed in the International System of Units, typically in megajoules per kilogram (MJ/kg) or per cubic meter (MJ/m^3) when referring to volumetric energy. The amount of energy obtained is influenced by both the type of fuel and the technology employed for its conversion. Calorific value is categorized into two primary types: a) Gross calorific value (PCS or gross), which signifies the maximum recoverable energy, including the heat of condensation of the water vapor produced; and b) Net calorific value (PCI or net), which excludes the latent heat of water vapor. The relationship between the higher calorific value (HHV) and the lower calorific value (LHV) can be expressed through a specific formula. Table 3 below illustrates the different calorific values of various fuel types with known consumption (Table 3).

Table 3. Calorific value and densities of known fuels

Type of fuel	**Average calorific value (kJ/kg)**	**Density ρ (g/mL)**
Diesel (automotive type A)	43	0.820 – 0.855
Renewable diesel (HVO)	4400	0.770 – 0.800
Regular gasoline	43	0.720 – 0.750
Premium gasoline	44,250	0.740 – 0.760
Ethanol	270	0.789
Kerosene (Jet A-1)	4325	0.775 – 0.840
Biodiesel (B100 – vegetable-based)	38	0.860 – 0.890
E10 blend (90% gasoline, 10% ethanol)	426	0.740 – 0.760
Light Fuel Oil	40	0.860

Physicochemical characterization test:
The physical and chemical properties of diesel are crucial in determining its effectiveness as a fuel in engines. Essential properties encompass density, which generally varies from 0.820 to 0.860 kg/L and influences the energy content per unit volume; viscosity, with typical values ranging from 2.0 to 4.5 cSt at 40°C, affecting fuel injection and atomization; and the cetane index, ranging from 40 to 55, indicating the fuel's self-ignition capability and facilitating cold start performance. The calorific value, between 42 and 46 MJ/kg, denotes the energy released during combustion. Furthermore, the color of diesel, ranging from transparent to slightly yellow, may indicate impurities or degradation, while the aromatic content, less than 35% by volume, enhances calorific value but also increases pollutant emissions. These properties reflect diesel's intricate composition, predominantly paraffinic and aromatic hydrocarbons, and its behavior in industrial and automotive applications.

4. Data Collection

The oily waste sample was taken from a vessel that collects waste produced by ships, situated in the Callao Sea within the constitutional province of Peru. As shown in Figure 4, a smaller boat is used to gather and store the waste for future treatment (Figure 4).

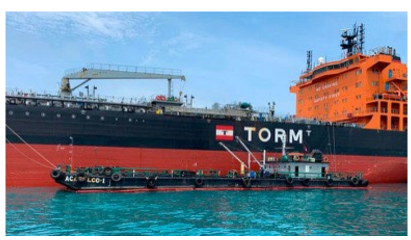

Figure 4. Collection of oily waste at sea

The samples were characterized, and tests for density and calorific value were conducted. The instruments and techniques employed are listed in the following Table 4.

Table 4. Instruments and techniques used in the experiment

Techniques	Instruments
• Laboratory tests. • Physicochemical analysis of samples and results. • Review of documents such as NTP. • Calculation of calorific value • Calculation of densities. • Simulation of final mixture	• Analytical balance • Beakers, test tubes, and funnels with stands and rings. • Digital hydrometer. • Distillation equipment. • Straight condenser. • Vacuum pump. • Thermal heating blanket

5. Results and Discussion

5.1 Numerical Results

Initially, the weights and volumes of the oily waste sample will be measured to determine its density, as shown in Table 5. This includes the weights of the materials listed in Table 6.

Table 5. Density of the unfiltered oily waste sample

Mass (g)	**Volume (mL)**	**Density (ρ)**
82.2	10	0.82
164.62	200	0.82
252.44	300	0.84
338.79	400	0.85
429.89	500	0.86

Following the preparation and determination of the waste samples' density, a 100 mL aliquot was extracted for laboratory analysis. This sample was filtered utilizing a funnel and filter paper, as illustrated in Figure 5. The objective of this process was to segregate the solid constituents from the liquid; the solids were retained on the surface of the filter paper, which functioned as a sieve, thereby permitting the liquid to pass into a 250 mL container.

Figure 5. Sample of oily waste

Given the high viscosity of the residues, the process duration would be considerably extended. Consequently, a vacuum pump was employed; when connected, it establishes a pressure differential that accelerates the movement of the liquid via suction, as illustrated in Figure 6. This procedure was conducted at 19 inHg.

Figure 6. Vacuum filtration

After filtering, 76 mL was collected. Table 6 presents the weights and densities of the sample and materials (Table 7).

Table 6. Density of the post-filtering oily residue sample

Mass (g)	Volume (mL)	Density (ρ)
65.39	76	0.86
30.61	38	0.81

Table 7. Weights of materials used

Description	Weight	Unit of measurement
Funnel	433.7	gram
100 mL beaker	137.7	gram
Clean filter	0.7	gram
Dirty filter 1	5.0	grams
Dirty filter 2	7.14	gram

Following the filtration of the residues, the distillation apparatus was assembled, as illustrated in Figure 7. A 38 mL sample of the residues was utilized, which was subsequently heated. Based on its boiling point, the components of the liquid mixture were identified.

Figure 7. Distillation and vacuum equipment

In our case, we observed that at 100 °C, the water evaporated. As the temperature increased, the water boiled thoroughly and moved to the next component, where we will now compare and describe its specifications. It should be noted that both elements are in a gaseous state, and as they pass through the distillation tube and subsequent condenser, they are transformed into a liquid state. Similarly, during this distillation phase, we also use the vacuum pump to reduce atmospheric pressure so that the liquid can boil at higher temperatures, thereby facilitating distillation, as shown in Figure 8.

Figure 8. Operating temperature

Finally, 18.5 mL of the final product was obtained, which we will now detail and characterize.

Table 8. Density of the final product obtained

Mass (g)	Volume (mL)	Density (ρ)
9.2	11.5	0.8
5.6	7	0.8

As illustrated in the aforementioned table, in addition to utilizing preceding tables as references where all weights and volumes were documented, the density determined for the final product is consistent with that of diesel in accordance with the relevant technical standards. The average density of diesel is 0.85 g/mL (García and Fernández, 2009), which, when compared to our final measurement, falls within the conventional range.

In Table 8, three samples of the final product were analyzed to ascertain the calorific value through the heat-reaction Table 9, which accounts for the temperature increase of the sample upon combustion. Furthermore, an actual reaction efficiency of 81% was employed (Table 10), leading to the calorific value being expressed in Joules per gram and subsequently converted to kilojoules per gram. The results obtained indicate a substance with medium-high calorific energy, suggesting that it aligns with the parameters of diesel, which has an average of 43,000 kJ/g (Torres et al. 2015).

Table 9. Calorific value of the samples

Table 10. Densities of the sample obtained in the laboratory

V, µL	Mass 1 (g)	Mass 2 (g)	Mass 3 (g)	ρ1, g/mL	ρ2, g/mL	ρ3, g/mL
20	0.017	0.0178	0.0169	0.8850	0.89	0.8450
20	0.0205	0.0167	0.0173	1.0250	0.8350	0.8650
20	0.0187	0.0165	0.0187	0.9350	0.8250	0.9350
20	0.0184			0.9200		
			Average	0.9413	0.8500	0.8817

5.2 Graphical Results

Finally, Table 11 shows that the recovery percentage after filtering the solid waste is 24%.

Table 11. Recovery percentage

Volume	Type	Percentage
18.5	Final product	24
10	Water	13
4	Liquid waste	63
76	**Filtered sample**	100

In Figure 9, it is observed that the volume processed correlates proportionally with the temperature, indicating that elevated temperatures lead to increased recovery. For future investigations, it is advisable to verify results using instruments capable of operating at higher temperatures.

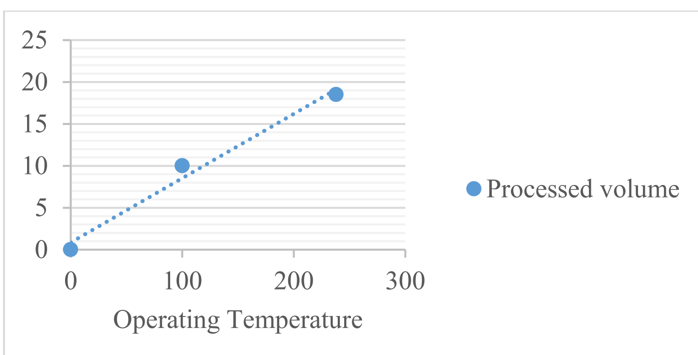

Figure 9. Processed volume according to temperature

With regard to the physical characteristics, the image below illustrates that the color is dark yellow due to its upcoming clarification process. The viscous texture has also been confirmed, demonstrating a consistency thicker than that of other fuels, as depicted in Figure 10.

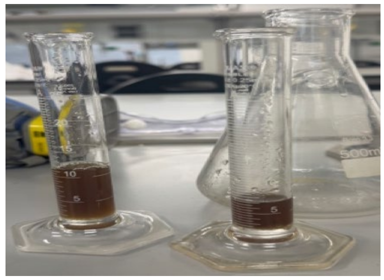

Figure 10. Final product in the laboratory

5.3 Proposed Improvements

Based on the results, we are within acceptable ranges; however, we will propose a controlled blend to standardize the quality of the final product. The proposed plan involves utilizing 80% treated product and 20% conventional diesel, which will enable us to adjust the product's quality standards and minimize the risk of potential issues. We will consistently adhere to regulatory guidelines and established standards, recognizing that conventional diesel also contains certain additives to regulate its quality.

$$Calorific\ value\ of\ the\ mixture = (0.80\ x\ 42912.78) + (0.20\ x\ 43000) = 42930.22\ kJ/kg$$

5.4 Validation

The validation of this research resides in the correlation between the deficiency of fuel supply within the national territory, indicating that an industry remains in developmental stages. The primary objective of this study is to assess the feasibility of establishing an oily waste processing facility utilizing waste from maritime vessels. This validation chapter seeks to deliver a comprehensive analysis of the findings, juxtaposing them with other research carried out within the same domain. The results demonstrate that a by-product can still be obtained from oily compounds and employed as a fuel source in diverse industrial operations.

Canacki and Gerpen (1999) indicated that this method was viewed as a sustainable alternative because it enabled the recovery and reuse of a resource with high energy content for producing a cleaner fuel. This approach helped prevent the waste of a valuable energy resource, benefiting both the environment and society overall. Additionally, it offered an opportunity to lower the environmental impact of greenhouse gas emissions, which contribute to global warming. Conversely, the research conducted by Casas Santiago and Manuel Gonzales (2024) demonstrated that, when analyzing heavy crude oil sludge, the thermal desorption technique was effective, achieving a recovery rate exceeding 50% of the hydrocarbons present. This method supported the principles of the circular economy and contributed to mitigating the environmental impact associated with hydrocarbon waste.

6. Conclusion

The study demonstrates the technical feasibility of installing a treatment facility for oily waste generated by maritime vessels, validating the process through laboratory experiments conducted at the University of Lima. The results confirm that the recycled product, obtained through decantation, distillation, and condensation, meets critical physicochemical parameters such as density and calorific value, aligning with national fuel standards. The recovery rate achieved, alongside the measured energy potential of the final product, confirms its suitability as a viable fuel alternative, reducing both waste and reliance on imported diesel.

This research highlights the significance of integrating environmental responsibility into the maritime and hydrocarbon logistics sectors. The absence of adequate infrastructure for waste disposal in major ports such as Callao has contributed to ecological damage and operational inefficiencies. Therefore, offering a locally adaptable, low-scale technological solution becomes essential. The application of thermal decomposition technologies within a circular economy framework presents a tangible path toward reducing marine pollution while generating economic value from hazardous waste.

The contribution of this study lies in its experimental validation of a decentralized and replicable treatment system for oily waste. It addresses a research gap in developing economies, where the reuse of maritime residues remains largely unexplored. By quantifying recovery outputs and comparing them to fuel benchmarks, the study bridges theoretical potential with practical implementation.

Future research may expand the scale of experimentation and integrate economic analysis, supply chain modeling, and life-cycle assessments. Furthermore, collaborative frameworks involving public and private stakeholders could enhance adoption and ensure regulatory compliance. In conclusion, this study lays the groundwork for industrial innovation that aligns with sustainability goals and national energy strategies, offering both environmental relief and operational efficiency through waste revalorization.

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