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ARTICLE

Restrict Toxic Emissions from Internal Combustion Engines to Protect the Environment by Using Diesel Fuel Mixed with Vegetable Oil

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ABSTRACT

For internal combustion engines, engines installed for transport ships, cargo ships, and fishing vessels are mainly diesel engines. The number of engines is increasing due to the development of the maritime and seafood exploitation sectors. Therefore, the high demand for petroleum fuels increases environmental pollution due to engine emissions. Reducing environmental pollution from the combustion of petroleum fuels has become a concern worldwide, especially for internal combustion engines. The exhaust gases from the engine contain harmful substances such as soot and nitrogen oxides (NO_x). Fuels with higher carbon content generate more soot when burned. In contrast, biofuels have low carbon and sulfur content and supply ample oxygen, which helps to reduce soot formation. For these reasons, biofuels are encouraged as alternative fuels to petroleum. Vegetable oil is one of the primary raw materials for biofuel production. This study presents a mixture of diesel and vegetable oil utilized as fuel for fishing vessels' diesel engines. The results of experimental research on a fishing vessel's 4CHE Yanmar diesel engine when using diesel fuel mixed with coconut oil (B15, 15% coconut oil, and 85% diesel) show that increasing B15 fuel injection pressure by about 10–15% compared with diesel fuel injection pressure reduces the engine's soot emissions and increases power compared to unadjusted. This solution contributes to reducing environmental pollution from engine emissions.

Keywords: Vegetable Oil; Fuel Injection Pressure; Soot; NO_x; Environment

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1. Introduction

Environmental pollution has severe consequences, and various types negatively impact the environment. Not only health but also the living environment and the socio-economic situation are significantly affected. In particular, air and water pollution are the crucial causes of dangerous diseases. Environmental pollution deteriorates the ecosystem, leading to a biological imbalance. In addition, the manufacturing and transportation industries contribute to the greenhouse effect, leading to climate change and phenomena such as global warming, melting ice, rising sea levels, etc. Environmental pollution affects urban landscapes, water sources, and land. Environmental pollution also severely impacts human health, reducing labor productivity and potentially leading to social issues such as inequality and conflict [1, 2].

The actions of means of transport emit a large amount of smoke, dust, and toxic gases into the atmosphere due to the process of burning fuel. These substances seriously affect the environment and human health. The production activities of factories and enterprises create a lot of smoke, dust, and toxic gases such as CO, CO_2, SO_2, etc. The activities related to burning waste and using chemicals also contribute to air pollution [2, 3].

Air pollution exposes people to fine particles in polluted air. These fine particles penetrate deep into the lungs and cardiovascular system, causing stroke, heart disease, lung cancer, chronic obstructive pulmonary disease, and respiratory infections. In addition to the transportation field, industries, coal-fired power plants, and the use of solid fuels are crucial sources of air pollution. Air pollution continues to increase at a concerning pace and affects economies and people's quality of life. Air pollution threatens the health of people everywhere in the world. People have to breathe air containing high levels of pollutants. Therefore, the most effective way to overcome air pollution is to improve living habits and limit the amount of toxic emissions and dust released into the environment. Replace fuels from coal, firewood, and gas with modern electrical equipment and apply clean energy to transport to reduce emissions [2, 3].

With the rapid development of industrial sectors and the increase in the number of means of transport worldwide, the demand for petroleum fuel has increased, creating many toxic emissions during combustion. That is one cause of pollution that directly affects humans and the ecosystem's living environment. Therefore, applying biofuel helps minimize the negative impact on the environment and reduces the risk of climate change [3, 4].

To reduce exhaust pollution (mainly soot) from diesel engines of fishing vessels when switching to biofuel (diesel mixed with vegetable oil), to contribute to sustainable environmental protection, and effectively utilize renewable vegetable oil (coconut oil). The study will analyze the advantages of biofuel (vegetable oil) compared to traditional diesel fuel and engine adjustment solutions when using biofuel, including adjusting the fuel injection pressure of diesel engines to achieve the goal.

Biofuels are used as alternative fuels to traditional fuels of internal combustion engines, especially diesel engines used in vehicles and ships, because they limit dependence on petroleum fuels, burn cleaner, and are renewable. In addition, agricultural manufacturing activities that create raw materials for biofuel production have promoted the cultivation of raw material crop areas, contributing to greening barren land and hills, improving deserted ponds, preventing soil erosion, and preventing floods [5–8].

Biofuels originate from animal or plant compounds, such as cereals, animal fats, agricultural and industrial waste, sawdust, scrap wood, etc. These materials are by-products obtained from business and production processes or are available by nature. Using these by-products not only makes use of raw materials and downsizes costs but also helps manufacturing facilities save on waste disposal costs. Because biofuels have low greenhouse gas content, low polluting waste, and are renewable fuels from agricultural, forestry, and fishery production activities, biofuels have been encouraged to be used to improve their friendliness and contribute to environmental protection and in the future, biofuel is still a clean fuel source, with large reserves from many renewable materials in the fields of agriculture, forestry, and fishery [9–11].

Vegetable oil is a biofuel source extracted from the seeds and fruits of plants. In general, seeds and fruits of plants contain oil. However, vegetable oil used as fuel refers to the oil of plants with high oil amounts, such as coconut (60%) and palm (50%). The chemical composition of vegetable oil is about 95% triglycerides and 5% free fatty acids. Their molecules contain the elements hydrogen, carbon, and oxygen. Vegetable oil contains less than 10–12% carbon, less than 5–13% hydrogen, and about 9–11% oxygen compared to diesel oil. Due to its high oxygen content, vegetable oil can burn completely with a mini excess air coefficient [12–19].

Solutions for processing vegetable oils as fuel for internal combustion engines mainly to reduce viscosity and increase cetane index, such as hot drying, dilution, cracking, emulsification of vegetable oils, and esterification of vegetable oils. Depending on the method of production and use, bioenergy can be divided into three groups (solid, liquid, and gas), as shown in **Figure 1**. Among them, liquid fuel is of specific interest. Some high-oil content oils are used as fuels for engines, as shown in **Table 1** [12–19].

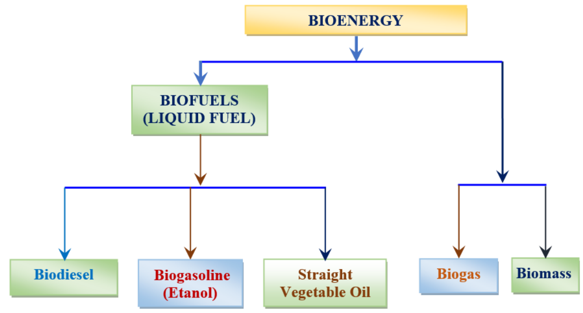

Figure 1. Bioenergy classification diagram.

Table 1. Basic properties of some vegetable oils compared to diesel oil.

Component	Cottonseed Oil	Canola Oil	Coconut Oil	Diesel Oil
Carbon	77.25	76.80	72.00	86.60
Hydrogen (%)	11.66	11.90	12.00	13.40
Oxygen	11.09	11.30	16.00	0.00
C/H density	6.63	6.45	6.00	6.46
Air/fuel ratio (A/F)	12.40	12.39	11.83	14.50

Table 1 shows that coconut oil has a high oxygen and low carbon content, so its use as a fuel will reduce soot emissions. When fuel injection parameters are adjusted appropriately for the engine, it will burn and generate greater efficiency and power than other vegetable oils. Coconut oil has a high yield. In addition to providing raw materials for food and other products, it also provides a sustainable source of biofuel (**Figure 2**) [12–19].

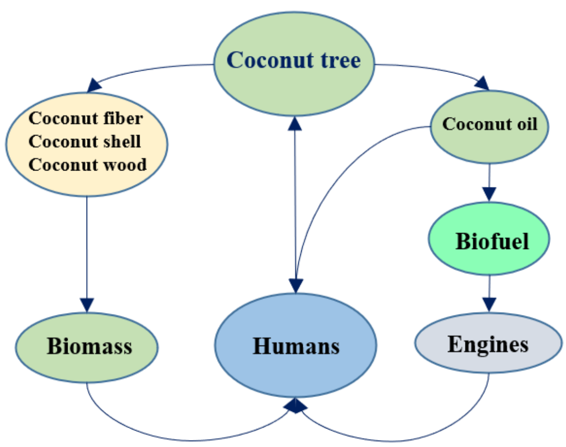

Figure 2. General overview of using coconut products.

Based on the properties of vegetable oils and solutions to use them as fuel to alternative traditional fuels, so far, more than 30 types of vegetable oils have been used directly for diesel engines without additives or chemical treatment as biodiesel. Vegetable oils are mainly extracted from rapeseed, sunflower seeds, soybeans, cottonseed, palm, coconut, peanuts, etc. [20–25]. Experimental studies have shown that diesel engines can operate with vegetable oils. However, still some problems arise in the fuel injection system, piston rings, and the stability of lubricating oil [26–31].

Diesel engines have a higher compression ratio, making them more fuel-efficient than gasoline engines. As a result, the fuel development for this type of engine has advanced significantly. In the early stages of engine production, certain machine parts were not fully optimized, resulting in low engine power, high fuel consumption, high emissions, and engine operating modes that have low efficiency during use. However, over many years of development, there have been positive impacts in improving the diesel engine's adaptation to new fuels, such as biofuels [31, 32].

The main difference between diesel and gasoline engines lies in the timing and formation of the combustion mixture. Unlike gasoline engines, in diesel engines, the compression process, fuel is injected into the combustion chamber to form an air-fuel mixture, then spontaneously ignites. Therefore, diesel fuel has specific properties such as evaporation, viscosity, and cetane index [31, 32].

In response to the increasingly stringent requirements of environmental protection laws, engine manufacturers have continuously improved their products during production. Advances in the fuel injection process and the use of new fuels for engines have contributed to reducing toxic emissions into the environment. In addition, soot filtration technology and nitrogen oxide (NO_x) removal catalysts for engine exhaust apply. However, the use of oxidation catalysts on diesel engines is only highly effective when the sulfur content in the fuel is low, and for the application of soot removal technology, that needs advancements in filter cores and the development of regeneration techniques [31, 32].

Research trends for diesel engines include internal engine treatment, meaning a priority for high performance, where fuel is injected under high pressure to increase engine torque; external engine treatment, meaning reducing injection pressure when the engine is running to reduce NO_x generation or using catalytic filters and soot filters; changing fuel composition, meaning using alternative fuels (biofuels) to reduce toxic exhaust emissions. A summary of pollution reduction solutions for diesel engines is in **Table 2** [32–34].

Table 2. Solutions to reduce pollution and improve diesel engine performance.

Solutions	Perform
Internal engine processing	• Improve engine intake. • Improve fuel injection. • Improve combustion chamber shape.
External engine processing	• Use a catalytic filter. • Use a soot filter.
Fuel composition change (alternative fuel)	• Reduce sulfur concentration in diesel fuel. • Add additives to fuel. • Use biofuels.

Optimizing diesel engines based on proposed solutions can encounter conflicts between power, fuel consumption, and emission levels. When achieving the optimal solution for one criterion, it usually causes the weakening of another criterion. Adjusting diesel engines to optimize must accept this conflict. Choosing which parameters to optimize and agree to a "loss" of engine characteristics depends entirely on the needs of use because it is arduous to have a measure that works well for all requirements. Usually, a combination of many measures is applied to compensate for each other's shortcomings. For example, increasing injection pressure reduces HC/CO and soot but must be used with EGR (Exhaust Gas Recirculation) to reduce NO_x. Therefore, in the trend of environmental protection, measures to optimize diesel engine combustion are all aimed at reducing environmental pollution [32–34].

The above analysis shows that the research on improving diesel engines is primarily related to enhancing injection technology, especially the application of electronically controlled injection technology, that can improve economic and environmental indicators. These improvements will mainly be related to injection pressure, injection timing, injection pattern, and the accuracy of the amount of fuel injected. With diesel engines using mechanical injection systems, fuel exists continuously, the burn gas pressure increases rapidly, and the maximum combustion pressure grows, leading to harsh operation, noise, and many toxic emissions [32–34].

For electronic injection systems, fuel is injected in multiple stages (layered injection). The first injection stage is also called pilot injection. In this stage, a certain amount of fuel exists, and the remaining fuel will exist in the second injection stage (main injection) or additional injection (post-injection). The pre-injected fuel burns first, and the post-injected fuel burns more gently, reducing NO_x and soot emissions. Depending on the engine characteristics and the property of the fuel used, the amount of fuel injected is adjusted appropriately in each injection stage into the combustion chamber, as shown in **Figure 3** [32–34].

Based on the theory describing the mixture formation and fuel combustion of diesel engines. In recent years, there have been significant developments in various research methods. Among them, studies on reducing harmful emissions have always been interesting. However, reducing nitrogen oxides or soot without reducing engine performance requires combining many solutions simultaneously, which increases the cost. Therefore, combining new fuels and a well-done injection process is a less expensive research direction [32–34].

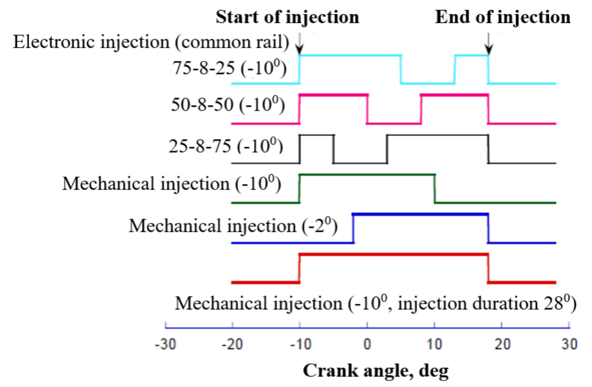

Figure 3. Description of mechanical and electronic fuel injection rules.

Thus, the biofuel used for diesel engines is still biodiesel and straight vegetable oil (SVO). Due to the advantages of being environmentally friendly and renewable, it is encouraged to use. Among the vegetable oils used as fuel for engines, coconut oil has the advantage in terms of output, especially for countries in the Southeast Asian region. Original coconut oil does not need to be synthesized into biodiesel but is mixed directly into diesel used as fuel through a mixture generator. However, coconut oil has a much higher viscosity than diesel, so when mixing coconut oil into diesel, it is necessary to heat to reduce the viscosity of the blends to close to that of diesel fuel [34, 35].

For internal combustion engines, engines installed for transport ships, cargo ships, and fishing boats are mainly diesel engines. The number of engines is increasing due to the development of the maritime and seafood exploitation sectors. Therefore, the high demand for petroleum fuels increases environmental pollution due to engine emissions. In particular, soot (smoke) and nitrogen oxides (NO_x) in engine exhaust are of specific concern due to their great harm to human health and the living environment [35, 36]. Limiting the concentration of these emissions can be done by using fuels containing less carbon (biofuels) or reducing fuel consumption, meaning increasing the economy of the engine by many measures, including implementing the fuel injection process well (adjusting the fuel injection system) or applying both measures: using biofuels combined with adjusting the engine's fuel injection system. So biofuels are encouraged to be used because they are environmentally friendly, and it is necessary to develop from many different sources of raw materials to use as petroleum alternative fuel [36, 37].

Raw vegetable oil (coconut oil) can be mixed directly into diesel oil as fuel for diesel engines. However, the different physicochemical properties compared to diesel oil, such as viscosity, calorific value, and cetane number, mean that the mixture formed when used as fuel requires adjustment of the fuel system to make the engine operate more efficiently [36, 37].

The study by Mschacon et al. [37] examined the effects of pure coconut oil and diesel-coconut oil blends on the performance indicators of a single-cylinder engine without changing the injection parameters based on load characteristics. The results showed that compared to diesel fuel, both straight coconut oil and diesel-coconut oil blends led to decreased soot emissions but increased fuel consumption.

Kalam, Husnawan and Masjuki [38] used coconut oil on diesel engines running generators, pointing out that coconut oil has a high oxygen amount and low C/H ratio, which are factors that reduce soot formation. However, the combustion mixture formation process is worse than diesel fuel, causing engine power to decrease.

Reddy, Venkanna and Wadawadagi [39] used 20% Honge oil and 80% diesel (H20) to operate a diesel engine. The results showed that thermal efficiency increased and soot emissions decreased when the injection pressure was up to 225 bar compared to unblended diesel fuel at 200 bar.

Purushothamana and Nagarjuna [40] studied the combustion process and exhaust emissions of the diesel engine when using a diesel fuel mixture mixed with orange skin powder (OSP) at injection pressures of 215 bar, 235 bar, and 255 bar. The results showed that with 30% OSP, the cylinder pressure and thermal efficiency were higher than diesel fuel, and CO, HC, and soot emissions were all reduced at a fuel injection pressure of 235 bar.

Previous studies have adjusted the engine's fuel injection system parameters when using original or diesel fuel mixed with vegetable oil. However, studies on engines using diesel fuel mixed with coconut oil have not impacted injection parameters. When the injection pressure changes, the fuel spray structure changes, leading to different combustion mixture formation processes. Therefore, when using diesel fuel mixed with vegetable oil for the engine, it is essential to implement solutions for reducing toxic emissions and enhancing engine power, such as adjusting the fuel injection pressure of the diesel-vegetable oil mixture (coconut oil) [41–49].

2. Materials and Methods

2.1. Materials

Use diesel oil fuel (DO) and a mixture of vegetable-blend diesel oil (coconut oil), with a ratio of 15% coconut and 85% diesel oil (B15). However, the viscosity of coconut oil is too great, so the mixture was heated up to 80 °C to reduce viscosity. The fuel properties were experimented with at QUATEST 3 of Vietnam, with fuel density and viscosity parameters determined according to the ASTM D6751 standard. Cetane index, flash point, and other fuel parameters are determined according to EN ISO 5165 and EN 14104 standards (**Table 3**). **Table 3** shows that B15 fuel has a higher calorific value, cetane number, and flash point compared to DO fuel. That makes the combustion of B15 fuel different from DO fuel.

The engine used in this study is a 4CHE - Yanmar diesel engine, which is the main engine of the fishing vessel. The engine parameters are as in **Table 4**.

Table 3. Properties of B15 fuel and DO.

Fuel	Density (g cm^{-3})	Cetane Number (CN)	Viscosity (mm^2 s^{-1})	Calorific Value (kcal kg^{-1})	Flashpoint (°C)
DO	0.8360	50	3.25 at 40 °C	10.478	Min 60
B15	0.8420	52	3.65 at 80 °C	10.650	75

Table 4. The parameters of the 4CHE - Yanmar diesel engine.

Type	4CHE, Unified Combustion Chamber
Number of cylinders	4
Cylinder diameter x piston stroke (mm)	105 × 125
Power (Hp rpm^{-1})	70/2300
Compression ratio (-)	16.4
Number of nozzle holes × diameter × spray direction	4 × 0.32 × 140°
Injection timing (°BTDC - Before Top Dead Center)	18
Injection pressure (bar)	205

2.2. Research Methods

The experimental study on the 4CHE - Yanmar diesel engine, using a mixture of diesel and coconut oil (B15) and adjusting the injection pressure to evaluate the effect of B15 mixture injection pressure on the engine's working characteristics compared to when the engine is using DO fuel, including power, specific fuel consumption, NO_x and soot emissions.

This research method is consistent with the theoretical analysis basis. It is the combination of using biofuel with high oxygen content, low Carbon/Hydrogen (C/H) ratio, and low sulfur content with a good setup of the injection process (injection pressure adjustment) that will bring high efficiency and emission reduction to diesel engines.

NO_x emission measuring device:

The emission measuring equipment includes the Testo 350 XL for CO, HC, and NO_x emissions analysis (**Figure 4**), which communicates with a computer via an RS 232 connection port and can store measurement data. The measurement limits of the parameters are as follows:

CO: 0–10,000 ppm; ± 10 ppm; 1 ppm

NO: 0 –3,000 ppm; ± 5 ppm; 1 ppm

NO Low: 0–300 ppm; ± 2 ppm; 0.1 ppm

NO_2: 0–500 ppm; ±10 ppm; 0.1 ppm

HC: 0–4 Vol %; ± 2 ppm; 0.001%

Figure 4. Testo 350 XL device for NO_x emission analysis.

Smoke opacity measuring device:

Msa-pc-se. nr 00601 Smoke Opacity Meter (**Figure**

5) is used to measure soot (smoke opacity), measuring soot by assessing smoke opacity as a percentage (N%), with a deviation of 0.1%. A 0% level is recognized as no smoke (smoke opacity) in the measuring chamber, and a 100% level is dark and all covered (100% opacity).

Figure 5. Msa-pc-se. nr 00601 Smoke Opacity Meter.

Hydraulic brakes:

The Dynomite 13 dual-rotor hydraulic brakes (**Figure 6**), used to load the engine, have a computer connected to the brake to record the measured values, including:

Torque measurement value (flb).

Power measurement value (Hp).

Speed measurement value (rpm).

The hydraulic brake torque (M_b) is determined[49, 50]:

$$M_b = G_w.C.(T_{in} - T_{out}) \qquad (N.m) \qquad (1)$$

The engine torque (M_e) will be equal to the sum of the torque calculated on the dynamometer and the torque in the hydraulic brake:

$$M_e = M_b + p.l \qquad (N.m) \qquad (2)$$

Engine power is determined:

$$N_e = n.M_e/9550 \qquad (kW) \qquad (3)$$

Calculate specific fuel consumption (SFC):

$$SFC = HFC/N_e \qquad g(kW.h)^{-1} \qquad (4)$$

In the above formulas: G_w- the amount of water required for the brake to work (kg); C - the specific heat of water (J $(kg.K)^{-1}$); T_{in}, T_{out} - the temperature at inlet and exit brake (K); p – dynamometer (N); l - swing arm length (m); n - test engine speed (rpm); HFC - hourly fuel consumption (g h^{-1}).

(**a**) (**b**)

Figure 6. (**a**) Dynomite 13 dual-rotor hydraulic brake and (**b**) computer.

Test conditions and procedures:

When the engine works, the high load mode generates many factors that specifically reflect the characteristics of the combustion process. Therefore, in this study, the test mode is chosen at 80% load, and the number of rounds is about 80% of the engine-rated speed[50].

On that basis, the Yanmar 4CHE engine's test speed is 1.800 rpm, and the injection pressure varies from 205 to 235 bar to evaluate their effects on power and engine emissions (soot and NO_x). Before the experiment, the devices will be adjusted according to measurement standards[50]. The engine operated in natural conditions with a temperature in the test room of about 32 °C. The ambient temperature fluctuated insignificantly and was kept stable. So, the ambient temperature did not affect the experimental results, the diagram of the test equipment layout (**Figure 7**), and the test image (**Figure 8**).

Before the experimental measurements, the engine starts and operates at no load for about 45 minutes until the engine reaches a stable state of coolant temperature and lubricating oil[50]. In this study, the engine control parameters during the test are in **Table 5**.

Table 5. Experimental parameters.

Parameters	Values
Coolant temperature (°C)	80
Lubricating oil temperature (°C)	80
The engine load (%)	80
The engine speed (rpm)	1.800
Injection pressures (bar)	205, 215, 225, 235

The data was measured when the engine operated and reached the coolant and lubricating oil temperature values and other parameters under test conditions. The data recording time for one measurement over 1.000 cycles (at a speed of 1.800 rpm), the data obtained for one measurement is the average of the values that appear most frequently during the recording time. The values presented in this study are the average of 3−5 tests. Fuel consumption is measured according to hourly fuel consumption (g h^{-1}) to calculate the engine's specific fuel consumption g $(kW.h)^{-1}$. Engine exhaust analyzers were calibrated with standard gas samples before testing. Test fuel will include DO fuel and B15.

The engine initially started using DO fuel and then switched to B15 fuel. Adjustment of the mixing ratio and fuel supply to the engine is done through a mixture generator with a flow sensor and a solenoid valve system, as shown in **Figure 9**.

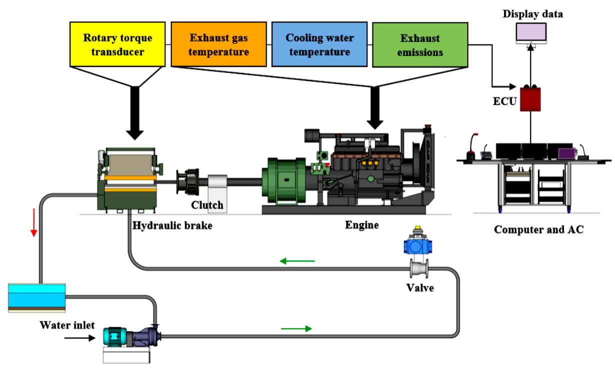

Figure 7. Diagram of the test equipment layout.

In the diagram in **Figure 7**, the water source goes into the brake to create a load for the engine, thereby determining the engine's torque.

Figure 8. Engine and experimental equipment.

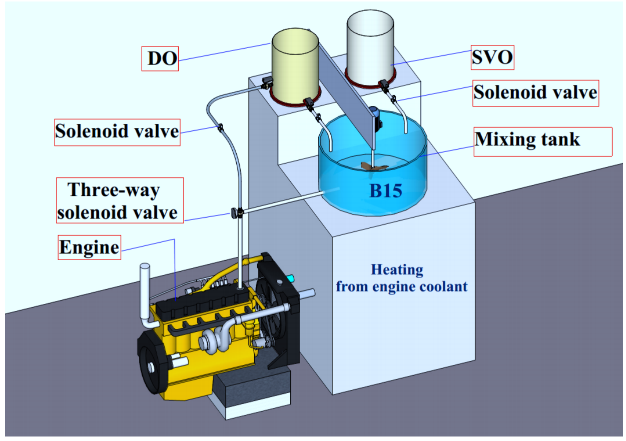

Figure 9. Fuel supply diagram for the engine.

3. Results and Discussion

3.1. Effect of B15 Fuel Injection Pressure on Engine Power and Specific Fuel Consumption

Diesel oil has a low flash point (Min 60) and cetane index (50), and B15 fuel has a flash point (75) and a high cetane index (52). In addition, B15 fuel contains more oxygen, so under the same injection conditions, B15 fuel will burn first compared to DO fuel. However, B15 has a high viscosity, and the fuel drop diameter is larger than DO, leading to incomplete combustion. When the injection pressure is augmented, the fuel drop diameter is smaller, and the process of forming a homogeneous air-fuel mixture is complete, so it burns better. If the injection pressure is augmented excessively, the spray structure may not be suitable within the combustion chamber. Combining rapid combustion when the cylinder volume is still large leads to decreased power and poor fuel efficiency.

When the fuel injection pressure changes to 205 bar, 215 bar, 225 bar, and 235 bar, the experimental results of engines using B15 mixed fuel showed changes in power and specific fuel consumption (SFC) at each injection pressure.

In **Figure 10**, the engine uses DO fuel at a standard injection pressure of 205 bar for the highest power value. When switching to B15 fuel, the engine power decreases. Adjusting the fuel injection pressure for B15, the engine power increases, and at the injection pressure of 225 bar, the power when the engine uses B15 fuel gives a higher value than other injection pressure values, which also means that the specific fuel consumption of the engine when using B15 fuel at the injection pressure of 225 bar has a low value and is approximately the same as the case of the engine using DO fuel at the standard injection pressure of 205 bar as shown in **Figure 11**. Because the higher the power, the lower the hourly fuel consumption, and the specific fuel consumption of the engine decreases (Equation 4). This result is due to the increase in injection pressure, which reduces the diameter of the fuel drops, leading to a better fuel-air mixture formation process. The combustion process occurs at the right time, the combustion pressure is high, and the mechanical work is high, increasing the engine power.

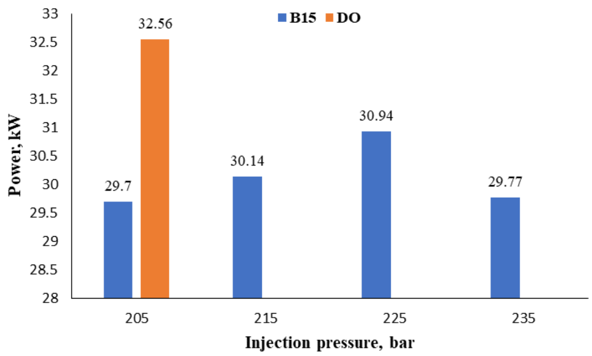

Figure 10. Engine power using B15 fuel compared to DO fuel at different injection pressures.

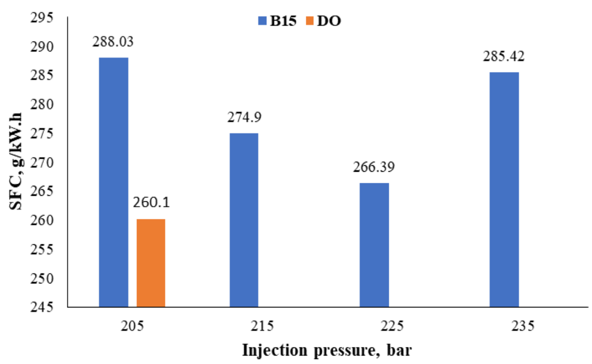

Figure 11. Specific fuel consumption of B15 compared to DO fuel at different injection pressures.

However, when the B15 fuel injection pressure is up to 235 bar, the engine power tends to decrease, causing the specific fuel consumption to increase. That is because the B15 mixture has a higher viscosity and a greater density than DO fuel. Therefore, when the injection pressure is increased too high compared to the engine's standard injection pressure, the spray structure will not be suitable for the combustion chamber structure, leading to an inconsistent combustion mixture and resulting in low combustion pressure and reduced power.

3.2. Effect of B15 Fuel Injection Pressure on the Engine Soot and NOx Emissions

Figure 12 shows the variation of soot (exhaust smoke opacity, N%) in the engine exhaust when using B15 fuel at different injection pressures compared to DO fuel at standard injection pressure. At low injection pressure, the diameter of the B15 fuel drop is sizeable, making the combustion mixture formation process less effective, leading to increased soot formation. When the B15 fuel injection pressure exceeds 205 bar, a suitable spray structure is created for the combustion chamber. The formation of a better fuel-air mixture results in low soot formation, followed by a high combustion chamber temperature, which results in better soot oxidation (the soot formed is then partially burned at high temperatures), leading to a reduction in soot emissions. Because the measured soot emission after the exhaust valve is the difference between the amount of soot formed and the amount of soot oxidized, when the injection pressure exceeds 235 bar, soot tends to increase, which is due to the structure of the spray jet not being suitable for the structure of the combustion chamber, collision with the wall, incomplete combustion, and low combustion temperature causing the amount of soot emitted to increase. Therefore, the injection pressure should not be too high.

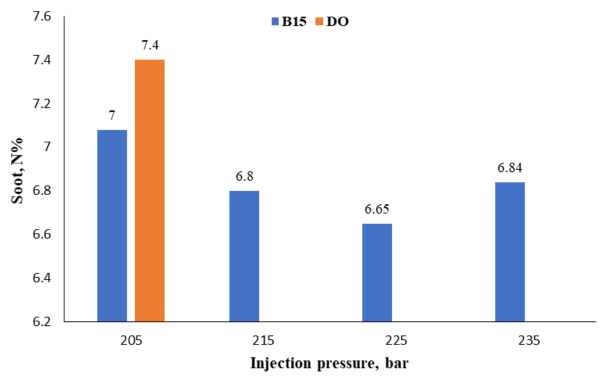

Figure 12. Soot variation of B15 fuel compared to DO fuel at different injection pressures.

The ideal combustion process of a mixture of hydrocarbons with air only produces CO_2, H_2O, and N_2. However, due to the heterogeneity of the blend in an ideal way and the complexity of the physical and chemical phenomena occurring during the combustion process, diesel engine exhaust always contains a significant amount of toxic substances. Nitrogen oxides (NO, NO_2, N_2O) are commonly called NO_x. NO accounts for the majority and is a colorless, odorless gas insoluble in water and very toxic.

The NO formation is described through the Y.B.Zeldovich mechanism, where $k_{1(-1)}$, $k_{2(-2)}$, $k_{3(-3)}$ is the reaction rate[50]:

$$O + N_2 \underset{k_{-1}}{\overset{k_1}{\rightleftarrows}} NO + N \quad (5)$$

$$N + O_2 \underset{k_{-2}}{\overset{k_2}{\rightleftarrows}} NO + O \quad (6)$$

$$N + OH \underset{k_{-3}}{\overset{k_3}{\rightleftarrows}} NO + H \quad (7)$$

Figure 13 shows the engine's NO_x emissions when using B15 fuel at different injection pressures. The reaction to create NO_x depends on the concentration of oxygen participating in the reactivity and the combustion temperature. Therefore, the NO_x concentration in the combustion products increases when the temperature and the oxygen concentration are high enough. Because NO_x depends on combustion temperature, when the heat value is high, it will develop a NO_x formation rate, increasing the amount of NO_x emissions in the engine's exhaust because the combination of nitrogen and oxygen occurs under high-temperature conditions.

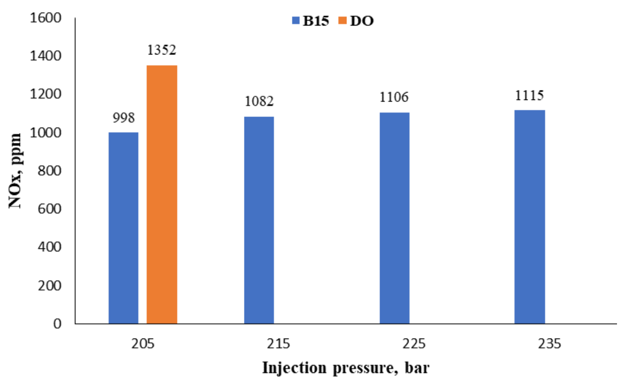

Figure 13. NOx variation of B15 fuel compared to DO fuel at different injection pressures.

At low fuel injection pressure, low combustion temperature will reduce NO_x emissions. When injection pressure increases, the combustion mixture formation process is good, and the high combustion temperature leads to high NO_x emissions. However, as analyzed in the above section, at an injection pressure of 235 bar, the increase in combustion temperature is not large, so NO_x emissions change little.

Based on experimental results, when the engine uses a mixed diesel-vegetable oil (B15), the B15 fuel injection pressure should not exceed 15% (235 bar) compared to the diesel injection pressure (205 bar).

Injection pressure affects the structure of the spray (including the spray penetration, spray cone angle, and the diameter of the fuel drop). At the phase of atomization (shred fuel drops), a conical spray jet is composed, and the tip of the spray cone is inside the nozzle holes. Dispersion begins after the spray exits the nozzle hole to create a combustion mixture. According to Mollenhauer and Tschoeke[50], this process heavily depends on the injection conditions, including the injection pressure. The change in injection pressure directly affects the structure of the jet, leading to changes in the formation of the combustion mixture[45]. B15 fuel has a high viscosity, so it is necessary to increase the injection pressure to reduce the diameter of the fuel drops. However, if the injection pressure is too high, the spray structure is inappropriate for the combustion chamber space, making the formation of the combustible mixture less effective.

Figure 14 shows the relationship between soot emissions and NO_x. The results show that the B15 fuel injection pressure adjustments from 215 to 230 bar reduce soot emissions. Similarly, **Figure 15** shows the relationship between power and B15-specific fuel consumption. When the injection pressure increases from 215 to 230 bar, the power increases and fuel consumption decreases. Therefore, the injection pressure adjustment range from 215 to 230 bar is suitable.

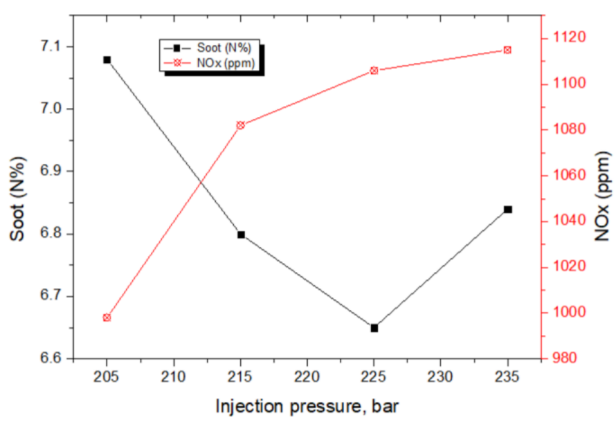

Figure 14. Variation of soot and NOx according to injection pressures when the engine uses B15 fuel.

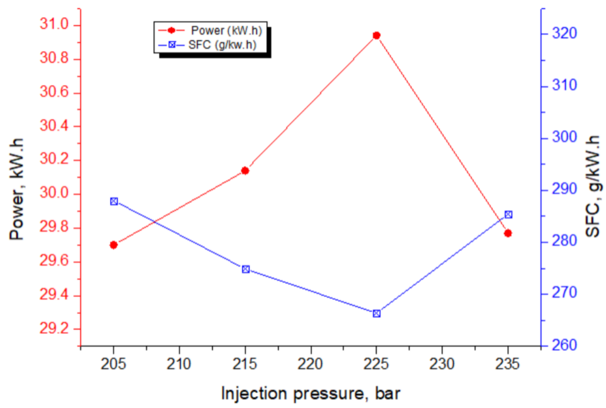

Figure 15. Variation of power and specific fuel consumption according to injection pressures when the engine uses B15 fuel.

Before and after the engine used B15 fuel, the engine's mechanical details and fuel system were thoroughly tested, and the results did not detect any abnormalities. The color of the lubricating oil did not change significantly, and there were no metal particles in the lubricating oil. When the engine used B15 fuel, it did not affect the wear and change in the properties of the lubricating oil, which showed that the technical condition of the engine did not change when using B15 fuel compared to DO fuel.

4. Conclusions

The results of the experimental study evaluating the power and emissions of diesel engines of fishing boats when using a mixture of diesel and coconut oil (B15) show that:

Engines using B15 fuel have lower power, soot emissions, and higher specific fuel consumption than DO fuel.

When the B15 fuel injection pressure increases by about 10% (225 bar) compared to the injection pressure of DO fuel (205 bar), the engine shows reduced soot emissions, increased power, and reduced specific fuel consumption.

When the B15 fuel injection pressure is up to 15% (235 bar), the fishing vessel's diesel engine power tends to decrease, and the amount of soot emitted by the engine tends to increase. Therefore, the B15 fuel injection pressure should not exceed 15% compared to the DO fuel injection pressure.

With the advantages of abundant vegetable oil resources in Southeast Asia, including coconut oil, it is possible to use a mixture of diesel oil and vegetable oil (coconut oil) mixed at a ratio of 15% coconut oil and 85% diesel oil as fuel to replace part of the traditional fuel of diesel engines and increase the injection pressure by about 10–15% compared to the injection pressure of DO fuel. The study only considered injection pressure and did not consider the effect of injection timing to optimize the combustion process and emissions of diesel engines when using diesel-vegetable oil blends. However, this solution has contributed to reducing environmental pollution from exhaust emissions of internal combustion engines.

Author Contributions

N.D.M. analyzed the research results and wrote the original manuscript. T.D.H. and T.D.P. experimented and wrote the original manuscript.

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Institutional Review Board Statement

The study does not require ethical approval.

Informed Consent Statement

Not applicable.

Data Availability Statement

The authors agree to share their research data upon request.

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Conflicts of Interest

The authors have declared no conflict of interest.

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