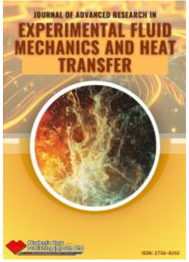
Penerbit Akademia Baru

Journal of Advanced Research in
Experimental Fluid Mechanics
and Heat Transfer

Journal homepage:
http://www.akademiabaru.com/submit/index.php/arefmht
ISSN: 2756-8202



Adjusting Fuel Injection Timing of Fishing Vessel's Diesel Engines When using Diesel-Vegetable Oil Blends to Increase Power and Reduce Soot Emissions

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ARTICLE INFO

Article history:
Received 20 February 2025
Received in revised form 1 April 2025
Accepted 22 April 2025
Available online 30 June 2025

Keywords:
Diesel engine; injection timing; vegetable oil; power; soot

ABSTRACT

Biofuels used for diesel engines can be biodiesel or vegetable oil. Vegetable oil can be mixed directly into traditional diesel fuel as engine fuel to reduce toxic exhaust emissions into the environment and limit dependence on non-renewable petroleum fuels. However, vegetable oil's physical and chemical properties are different from traditional diesel fuel, so when used for engines, the engine fuel system needs to be adjusted to increase power and reduce exhaust emissions, especially soot. This study used the experimental method on the Yanmar 4CHE diesel engine, and the fuel applied to the engine was a mixture of 15% coconut oil and 85% diesel oil (B15). The results showed that when B15 fuel injection timing is adjusted to increase by about 1-2 degrees of crankshaft angle before the top dead center (19-20^{0} bTDC) compared to traditional diesel oil (DO) injection timing (18^{0} bTDC), soot emissions are low (decrease 4.57-6.14%), power is high (increase 2.05-2.69%), and specific fuel consumption is reduced 5.14-6.25% compared to when not adjusted.

1. Introduction

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 timing of diesel engines to improve the combustion of biofuels.

Nowadays, all countries worldwide must develop their economy and society, leading to growth in the industry, transportation, maritime, marine exploitation, etc., and stations using diesel engines to provide electric energy for production and human life. Therefore, the demand for petroleum fuels increases, and combustion products create many toxic substances that pollute the environment, directly affecting human health and the ecosystem. Before this situation, multiple solutions have

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https://doi.org/10.37934/arefmht.20.1.118

been used to reduce pollution emissions, including reducing the emission of toxic substances in the exhaust of internal combustion engines to protect the environment [1-4].

Among the alternative energy sources to petroleum, such as solar, wind energy, and other types of energy, biofuels for internal combustion engines are receiving special attention due to their suitable characteristics and feasibility in finding raw materials [5-7]. According to the International Energy Agency (IEA), the world's energy development trend by 2050 will use 23% diesel oil (DO) and 27% biofuel; the rest is other types of fuels in the total fuel supply for internal combustion engines [8]. Biofuel can be biodiesel, pure vegetable oil, or waste cooking oil. Biodiesel fuel is productive from vegetable and animal oils and fats. Both biodiesel and vegetable oil can be utilized directly or blended with diesel fuel at specific ratios for engine use [9-11].

For vegetable oil, the chemical composition includes 95% triglycerides and 5% free fatty acids. Vegetable oil contains the elements hydrogen, carbon, and oxygen. Compared to diesel oil, vegetable oil contains 10-12% less carbon and 5-13% less hydrogen, and the amount of oxygen in vegetable oil is very high by 9-11% oxygen, so vegetable oil is a fuel that contains much oxygen. Therefore, vegetable oil can burn clean with a low excess air coefficient [11-13]. The solutions for processing vegetable oil as fuel for internal combustion engines mainly reduce viscosity and increase the cetane number of vegetable oil. Currently, the commonly used methods are heating vegetable oil, diluting vegetable oil, cracking, emulsifying vegetable oil, and esterification methods [13-15].

According to previous studies, biofuel used for diesel engines can be biodiesel or pure vegetable oil mixed with diesel at a suitable ratio [16]. Therefore, using vegetable oil (coconut oil) as fuel for diesel engines is necessary, and vegetable oil must be processed so that its properties are similar to diesel fuel. The difference between vegetable oil and diesel oil is viscosity. The high viscosity causes the fuel system to operate abnormally, causing poorer injection and combustion quality [16,17]. Due to poorer injection and combustion quality, engine performance decreased when using vegetable oil [17]. For the above reasons, vegetable oils must decrease viscosity before being utilized as fuel. That means mixing vegetable oil with diesel fuel in the appropriate ratio and heating the mixture. This process lowers the viscosity, resulting in diesel-vegetable oil blends that can be applied as fuel for diesel engines [18,19].

Based on the diesel engine working cycle and some measures to optimize the engine combustion process, as shown in Table 1 [20,21], no measure works well for all requirements to apply biofuel to diesel engines effectively. Increasing the injection timing will increase the combustion delay time, leading to increased NO_x due to high combustion temperature. However, it will reduce soot because high temperatures will increase soot oxidation.

Table 1
Measures to optimize the diesel engine combustion process

Measures	NO_x	HC/CO	Soot	Specific fuel consumption	Noise
Adjust the fuel injection timing	-	+	+	+	-
Exhaust gas recirculation (EGR)	-	+	+	+	-
Exhaust gas recirculation with cooling	-	+	-	-	0
Supercharging	+	-	-	-	0
Intercooling	-	+	-	-	0
Pilot injection	0	-	+	0	-
Post injection	-	0	-	+	0
Adjust the fuel injection pressure	+	-	-	-	0
Reduce the compression ratio	-	+	-	0	+

Note: Decrease (-), increase (+), not change (0)

When switching to a blend of diesel and vegetable oil (coconut oil), the fuel injection system needs to be adjusted appropriately, including injection timing, to increase power and reduce emissions for diesel engines. These parameters affect the spray structure, the formation of the combustion mixture, and fuel combustion, affecting the engine's economic and environmental targets [21].

Bari *et al*., [22] used waste cooking oil (WCO) for diesel engine-running generators. When changing the injection timing of WCO fuel compared to DO fuel at 15^0 bTDC (before the top dead center) up to 19^0 bTDC. As a result, increasing the injection timing of WCO fuel to 4 degrees of crankshaft angle (4^0 CA) improved economic and environmental targets compared to diesel fuel. Pachiannan *et al*., [23] used n-pentanol-diesel blends as fuel for engines. Experimental studies varied the injection timing of n-pentanol-diesel blends from 35 to 55^0 bTDC. The results showed that changing the injection timing improved thermal efficiency, reduced fuel consumption, and reduced CO, HC, and NO_x emissions. Adding hydrogen to n-pentanol-diesel blends improved engine combustion, resulting in lower fuel consumption and reduced soot, HC, and CO compared to diesel fuel. Hartmann *et al*., [24] used a converter to use sunflower oil for diesel engines.

The experiment studies the Yanmar YT22 diesel engine, 4-stroke, 1-cylinder at no-load characteristics with a speed of 1,300 - 2,100 rpm, an injection pressure of 200 bar, and an injection timing of 18^0 bTDC. The results showed that when the engine used a mixture at a mixing ratio of 50% sunflower oil and 50% diesel, the power decreased by more than 10%. When used with 100% sunflower oil, the engine power decreased by more than 20% compared to diesel. Siddalingappa *et al*., [25] studied the use of Karanja - diesel oil blends at the ratios K10 (10% Karanja and 90% diesel oil), K15 (15% Karanja and 85% diesel oil), and K20 (20% Karanja and 80% diesel oil) on a 1-cylinder diesel engine. As a result, the K15 ratio is most suitable. However, the injection timing needed to be increased to 5^0 CA for the thermal efficiency to grow and be equivalent to when the engine used DO fuel. Veeraraghavan *et al*., [26] the study applied mixed fuel containing biodiesel (40%), n-Heptane (10%), and diesel (50%) to the engine, changing different fuel injection timing (19^0, 21^0, and 23^0 bTDC) and injection pressure (170, 210, and 240 bar).

The results showed that injection timing at 23^0 bTDC and injection pressure at 240 bar gave the highest efficiency; however, at 19^0 bTDC, injection pressure at 240 bar reduced hydrocarbon emissions the most. The results also showed that each type of fuel applied to the engine requires reasonable injection system adjustment. Shaikh *et al*., [27] used biodiesel for Common Rail Direct injection (CRDi), an experimental study with three operating parameters at various values as injection timing (IT), injection pressure (IP), and exhaust gas recirculation (EGR). The results showed that the CRDi engine gave the best efficiency at IT of 9^0 bTDC, IP of 855 bar, and EGR of 20% when using biodiesel. Agarwal and Atul [28] conducted tests on a diesel generator engine at a constant speed of 1,500 rpm to evaluate the performance and emissions of Karanja oil blended with diesel oil without adjusting the fuel injection system and ran the test for many hours. The results showed that the mixture at a less than 20% ratio could be suitable as a fuel. However, the low thermal efficiency was the reason for the need to adjust the fuel injection system for the engine.

Winangun *et al*., [29] applied palm oil-derived biodiesel to a single-cylinder direct injection diesel engine, adding hydrogen to the biodiesel fuel. The results showed that the advantage of hydrogen addition was reduced soot emissions but increased NO emissions. However, the engine performance improved, and other exhaust pollutants were reduced. Gad and Ahmed [30] used biodiesel (B20) at a ratio of 20% biodiesel combined with nano additives as a fuel mixture for diesel engines. The results showed that the HC content was reduced by up to 36%. The engine operated stably. Some previous studies have confirmed that injection timing directly affects the formation of combustion mixtures and combustion processes, leading to changes in engine power and exhaust emissions [31-33].

Therefore, changing the injection timing of the diesel-vegetable oil blend will directly affect the spray structure and the emissions and power of the diesel engine.

Using vegetable oil as fuel for diesel engines will reduce soot emissions because vegetable oil contains a lot of oxygen and little sulfur. However, its high viscosity and density affect the formation of the combustible mixture, making the combustion process of lower quality than that of traditional diesel fuel [31-33]. In particular, no work provides complete information on the mixing ratio, viscosity reduction method, and optimal adjustment method of the fuel injection system for diesel engines to ensure the best combustion process when using coconut oil directly mixed with diesel oil as fuel for the diesel engine of fishing vessels. Therefore, the objective of the study is to use pure coconut oil, without synthesizing it into biodiesel, without using additives; coconut oil is mixed directly with diesel fuel, combined with heating to reduce the viscosity of the mixture and adjusting the fuel injection timing to create a combustion mixture formation process equivalent to the combustion mixture formation process of diesel fuel, to reduce toxic exhaust emissions and increase engine power. The study was conducted using experimental methods on a diesel engine used as the main engine of a fishing vessel.

2. Methodology

2.1 Materials

Use diesel oil fuel (DO) and a mixture of diesel oil blended with 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^{0}C to reduce viscosity. The fuel properties were experimented with at QUATEST 3 of Vietnam (Table 2). This study uses the fishing vessel's main engine, a Yanmar 4CHE diesel. The engine specifications are in Table 3.

Table 2
Properties of B15 fuel and DO

Properties	DO fuel	B15 fuel	Test method
Cetane number (CN)	50	52	TCVN 7630 (ASTM D613)
Density (g/cm^3)	0.8360	0.8420	TCVN 6594 (ASTM D4052)
Calorific value (Kcal/kg)	10,478	10,650	TCVN 7868 (EN 14103)
Viscosity (mm^2/s)	3.25 at 40^{0}C	3.65 at 80^{0}C	TCVN 3171 (ASTM D445)
Flashpoint (^{0}C)	Min 60	75	TCVN 2693 (ASTM D93)

Table 3
The specifications of the Yanmar 4CHE diesel engine

Specifications	Unit	Value
Type	-	4CHE
Combustion chamber type	-	Unified combustion chamber (ω)
Number of cylinders	-	4
Cylinder diameter x piston stroke	mm (in)	105×125 (4.13×4.92)
Cylinder capacity	L (cu.in)	4.330 (264.21)
Power	HP/rpm	70/2300
Compression ratio	-	16.4:1
Order of explosion	-	1-2-4-3
Fuel system	Injection timing (^{0}bTDC)	18
	Injection pressure (kg/cm^2)	210

2.2 Research Methods

This study uses an experimental method: The experimental study on the Yanmar 4CHE diesel engine uses a diesel-coconut oil (B15) blend. Adjusts the injection timing to evaluate the effect of the B15 mixture injection timing on the engine's working characteristics compared to when it uses DO fuel, including power, specific fuel consumption, NO_x, and soot emissions. The measured values from the experiment will establish mathematical functions describing the rule for adjusting the injection timing of diesel-coconut oil blends to reduce emissions and increase power. This research method is consistent with the theoretical analysis. It combines biofuel with high oxygen content, low Carbon/Hydrogen (C/H) ratio, and low sulfur content with an optimized injection process setup (injection timing adjustment) to bring high efficiency and emission reduction to diesel engines [31-33].

Measuring equipment and experimental layout: Viscosity measuring cup: Viscosity is an important parameter; it affects the injection process and the formation of the combustible mixture. Therefore, the control of the viscosity of the B15 mixed fuel during the experiment must be consistent with the test value at QUATEST 3 (Table 2). Table 4 and Eq. (1) show the process parameters for measuring and determining viscosity using the Zahn cup according to ASTM D4212 standards.

Table 4
Viscosity measurement parameters according to ASTM D4212 standard

Volume (ml)	Coefficient K	Time flows (s)	Coefficient C	Adjustment coefficient	Viscosity measuring range (cSt)
44	1.1	<80	29	0.95 - 1.05 at 25^0C ± 0.2^0C	1-60

The formula for calculating viscosity using Zahn cup according to ASTM D4212 standard.

$$V = K(T - C) \tag{1}$$

where V is kinematic viscosity (cSt), T is efflux time (s), K and C is constants.

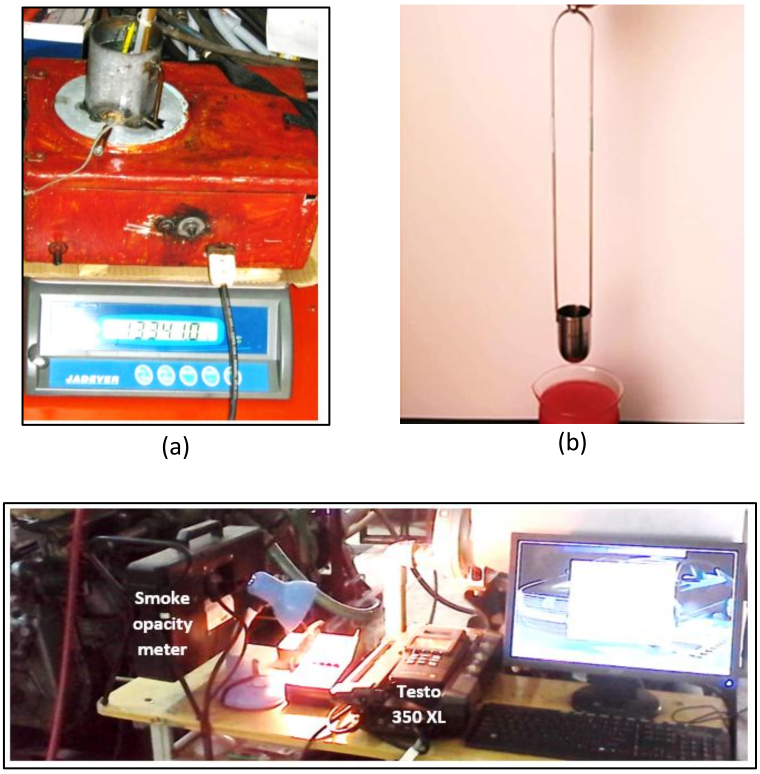
The measurement process involves using a device to mix DO oil with coconut oil in a ratio of 15% coconut oil and 85% diesel oil. A water heating system keeps the mixture's temperature at 80^0C (Figure 1a). Clean the cup before measuring, especially the cup hole. Keep the temperature stable; completely immerse the cup into the fuel mixture sample until the cup is thermally balanced with the mixture temperature. Measure when the cup's upper edge leaves the sample's surface. Stop the meter when there is a flow interruption at the bottom of the cup. Repeat the measurement 3 times. The results of the time for each measurement, the average time of the measurements, and the corresponding viscosity values are presented in Table 5. The measuring cup is shown in Figure 1(b).

The viscosity determined during the experiment is deviation negligible compared to the viscosity tested at QUATEST 3 in Table 2 (0.35%). The viscosity measurement results are reliable, which is one of the bases for discussing the research results. Smoke opacity measuring equipment: Msa-pc-se. Nr 00601 smoke opacity meter (Figure 1(c)) was used to measure soot (smoke opacity) by assessing smoke opacity as a percentage (N%), 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). NO_x emission measuring equipment: The measuring equipment is the Testo 350 XL (Figure 1(c)) for CO, HC, and NO_x emissions analysis, 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:

NO: 0 – 3,000 ppm, ± 5 ppm; NO Low: 0-300 ppm, ± 2 ppm; NO_2: 0-500 ppm, ±10 ppm.

Table 5
Viscosity measurement values of B15 fuel mixture using Zahn cup

Temperature, 80^0C, deviation ± 0.5^0	Measure for the first time, T1 (s)	Measure for the second time, T2 (s)	Measure for the third time, T3 (s)	Average measurement time, Ta (s)
Measurement time (s)	32.35	32.18	32.46	32.33
Viscosity (cSt)	3.685	3.498	3.806	3.663



(a) (b)

(c)

Fig. 1. (a) Fuel mixture temperature stabilizer (b) Zahn viscosity measurement cup (c) Soot measurement equipment and NO_x emission measurement equipment

Hydraulic brakes: The Dynomite 13 dual-rotor hydraulic brakes (Figure 3), used to create load for 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 [34]:

$$M_b = G_w.C.(T_{in} - T_{out}), \text{ N.m} \tag{2}$$

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:

$$M_e = M_b + p.l, \text{ N.m} \tag{3}$$

Engine power is determined:

$$N_e = n.M_e/9550, \text{ kW} \tag{4}$$

Calculate specific fuel consumption (SFC):

$$SFC = HFC/N_e, \text{ g/(kW.h)} \tag{5}$$

In the above formulas G_w is the amount of water required for the brake to work (kg), *C* is the specific heat of water (J/(kg.K)), T_{in}, T_{out} is the temperature at inlet and exit brake (K), *p* is dynamometer (N), *l* is swing arm length (m) *n* is test engine speed (rpm) and *HFC* is hourly fuel consumption (g/h). Figure 2 shows a diagram of the experimental equipment layout. Figure 3 shows an image of the experimental process.

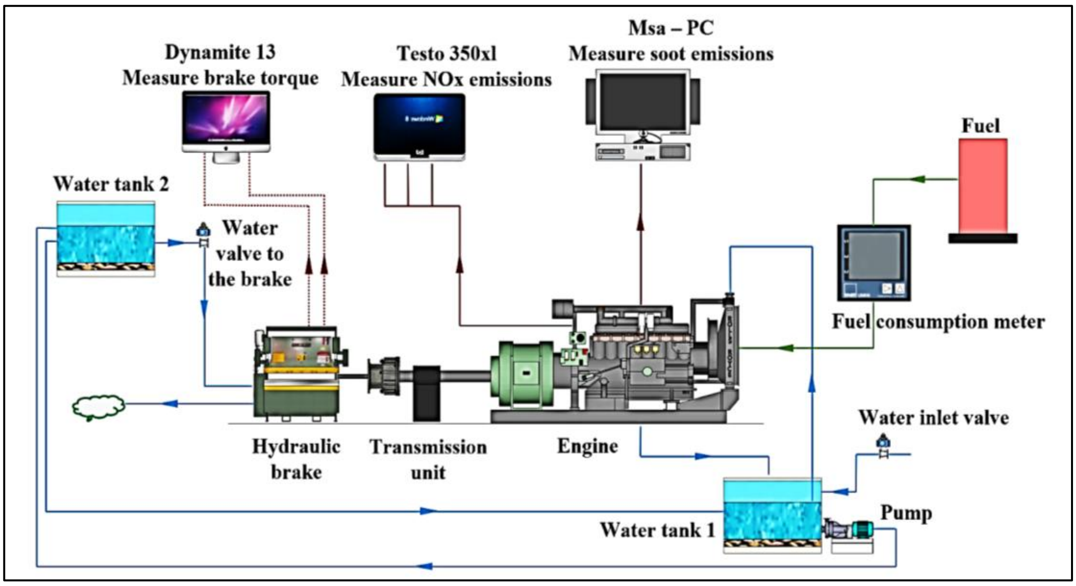


Fig. 2. Diagram of the experimental setup

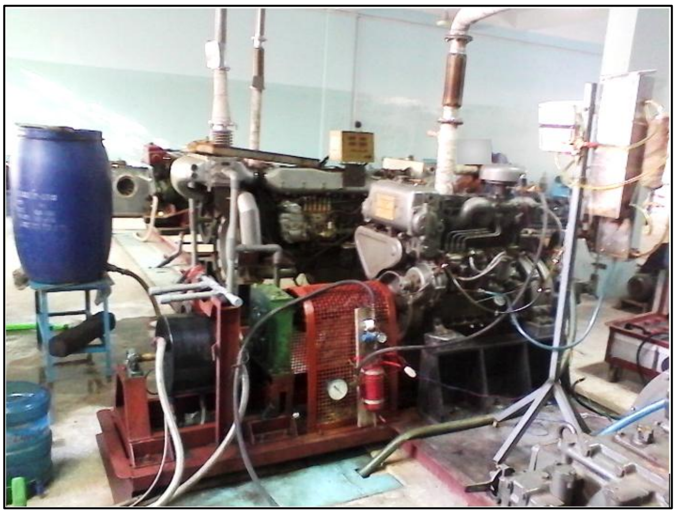


Fig. 3. Engine and equipment used for the experimental process

Fuel consumption is measured according to hourly fuel consumption (g/h) to calculate the engine's specific fuel consumption (g/(kW.h)). Engine exhaust analyzers were calibrated with standard gas samples before the experiment. Experimental fuel will include DO fuel and B15. In this study, the engine control parameters during the experiment are in Table 6.

Table 6
Experimental design

Parameters	Unit	Values
Coolant temperature	(^{0}C)	80
Lubricating oil temperature	(^{0}C)	80
The engine load	(%)	80
The engine speed	(rpm)	1,800
Injection pressures	(Kg/cm^2)	210
Injection timing	(^{0}bTDC)	18; 19; 20; 21; 22

The basis for establishing the rule for adjusting the fuel injection timing: Establish the empirical formula using the least squares method. This means finding the functional relationship between two quantities, *x* and *y* (called a regression function), where *x* represents injection timing, and *y* represents power, SFC, soot, and NO$_x$ emissions. The correlation between *x* and *y* is in Table 7 [35].

Table 7
Correlation between *x* and *y* in the empirical regression function

x	x_1	x_2…	x_i…	x_n
y	y_1	y_2…	y_i…	y_n

From Table 7, establish the empirical formula *y = f(x).* Find the function *f(x),* which means finding the approximate function of the function *f(x).* One of the approximation functions commonly used in experimental problems has the form [35]:

$$y = ax + b \tag{6}$$

$$y = ax^2 + bx + c \tag{7}$$

Error: $v_i = (ax^2 + bx + c) - y_i, i = 1, 2, \dots, n$

Create a spreadsheet as follows (Table 8):

Table 8
Method for calculating the sum of *x* and *y* in the empirical regression function with *n* pairs of data

n	x_i	y_i	x^2_i	x^3_i	x^4_i	x_iy_i	$x_iy^2_i$
1							
2							
…							
n							
∑	$\sum x_i$	$\sum y_i$	$\sum x^2_i$	$\sum x^3_i$	$\sum x^4_i$	$\sum x_iy_i$	$\sum x_iy^2_i$

To minimize the sum of the squares of the above errors:

$$S = \sum_{i=1}^{n} v_i^2 = \sum_{i=1}^{n}(a\,x_i^2 + bx_i + c - y_i)^2 \rightarrow min \tag{8}$$

Thus, *a, b,* and *c* must satisfy the system of equations:

$$\begin{cases} \frac{\partial S}{\partial a} = 0 \\ \frac{\partial S}{\partial b} = 0 \\ \frac{\partial S}{\partial c} = 0 \end{cases} \Leftrightarrow \begin{cases} \frac{\partial S}{\partial a} = 2\sum_{i=1}^{n} ax_i^2 + bx_i + c - y_i)x_i^2 = 0 \\ \frac{\partial S}{\partial b} = 2\sum_{i=1}^{n} ax_i^2 + bx_i + c - y_i)x_i^2 = 0 \\ \frac{\partial S}{\partial c} = 2\sum_{i=1}^{n} ax_i^2 + bx_i + c - y_i)x_i^2 = 0 \end{cases} \tag{9}$$

Simplify the system of Eq. (9) to get the following canonical system of equations:

$$\begin{cases} a\sum_{i=1}^{n} x_i^4 + b\sum_{i=1}^{n} x_i^3 + c\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} x_i^2 y_i \\ a\sum_{i=1}^{n} x_i^3 + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} x_i y_i \\ a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i + nc = \sum_{i=1}^{n} y_i \end{cases} \tag{10}$$

The Eq. (10) system determines the regression function for the characteristic curves, including power and SFC, environmental targets soot, and NO_x. The horizontal axis is the injection timing, *n* is the number of adjustment points (pairs of data), and x_i is the adjustment value of each injection timing. The vertical axis *y* has the value y_i corresponding to each adjustment point x_i. Experimental data will be established according to Table 8, and then the solved system of equations of the form Eq. (10) will find the coefficients *a, b,* and *c*. Substitute the values *a, b,* and *c* into the equations parabola, Eq. (7), to determine the empirical regression function. These functions reflect the engine's working characteristics. Based on that, the appropriate injection timing will be determined.

To evaluate the reliability of the regression functions found from the experimental results, use the coefficient of determination R^2 [35]:

$$R^2 = \frac{\hat{\beta}_2^2 \sum_{i=1}^{n} x_i^2}{\sum_{i=1}^{n} y_i^2} \text{ with } \hat{\beta}_2 = \frac{\sum_{i=1}^{n} y_i x_i}{\sum_{i=1}^{n} x_i^2} \tag{11}$$

The coefficient R^2 will indicate the reliability variation of *y* according to the variables *x* in the regression function.

3. Results

The combustion process is affected by fuel properties such as viscosity, cetane value, flash point, and fuel injection parameters. When fuel is injected into the combustion chamber too early, the temperature and pressure in the combustion chamber are low, causing the ignition delay time to be long, which leads to heat accumulation and intense combustion. When the combustion occurs, a lot of NO_x gas will be emitted, and the engine will be noisy. However, if fuel is injected too late, the fuel combustion time is short, leading to incomplete combustion before entering the engine's exhaust stroke, which increases soot and affects power. B15 fuel has a higher viscosity and oxygen content than traditional DO fuel, so the injection timing is adjusted to give the fuel a suitable ignition delay. This ensures the combustion process occurs at the right time, generating maximum power and optimizing emissions. The measurement results when the engine used B15 fuel at different injection timing are presented in Table 9.

Based on the data from Table 9 and the method of calculating the sum of *x* and *y* in the empirical regression function with *n* pairs of data (Table 8). Table 10 presents the *x* and *y* values in the power regression function corresponding to different injection timing. The regression values of specific fuel consumption, soot emissions, and NO_x are calculated similarly to the power regression function.

Table 9
Experimental results of engines using diesel-coconut oil blends

Injection timing (^{0}bTDC)	Value			
	Power (kW)	SFC (g/(kW.h))	Soot (N%)	NO_x (ppm)
18	29.71	288.03	7	998
19	30.51	270.02	6.57	1091
20	30.32	273.22	6.68	1118
21	29.07	300.22	6.84	1135
22	28.39	307.00	7.06	1194

Table 10
x and *y* values of the power regression function

Pairs of data	Variable *x* (injection timing)	Corresponding *y* function value (power)	Results of calculating x_i and y_i					
n	x_i	y_i	x_i^2	x_i^3	x_i^4	x_iy_i	$x_i^2y_i$	y_i^2
1	18	29.71	324	5832	104976	534.78	9626.04	882.684
2	19	30.51	361	6859	130321	579.69	11014.1	930.86
3	20	30.32	400	8000	160000	606.4	12128	919.302
4	21	29.07	441	9261	194481	610.47	12819.9	845.065
5	22	28.39	484	10648	234256	624.58	13740.8	805.992
∑	100	148	2010	40600	824034	2955.92	59328.8	4383.9

From the results of Table 10 and Eq. (10), create the following system of canonical equations, Eq. (12):

$$\begin{cases} 824034a + 40600b + 2010c = 59328.8 \\ 40600a + 2010b + 100c = 2955.92 \\ 2010a + 100b + 5c = 148 \end{cases} \tag{12}$$

Solve the system of Eq. (12):

a= - 0.285, *b* = 11.02, *c* = -75.95.

Substituting the values *a, b,* and *c* into Eq. (7), the regression function is as Eq. (13):

$$y = -0.285x^2 + 11.02x - 75.95, \text{ with reliability, } R^2 = 0.711 \tag{13}$$

Table 11 presents the results of the variance analysis of ANOVA for regression data, Eq. (13). Table 11 shows that the regression function's *P* value is less than 0.05, a power prediction factor affected by injection timing. This means that the power measurement data are reliable [36]. The regression function, Eq. (13), represents the rule for adjusting injection timing and its effect on diesel engine power when using diesel-coconut oil blends (Figure 4).

Figure 4 shows the power variation rule of the engine when using B15 fuel. When the temperature and pressure conditions in the cylinder do not change, the fuel injected into the combustion chamber will have an ignition delay before the mixture combustion and increase in temperature. Chemical kinetic reactions control this delay period; ignition delay times are also related to the design of many types of engines and depend on the temperature in the combustion chamber at the time of fuel injection. In addition, the ignition delay time also depends on the density of the mixture of substances participating in the chemical reaction [37]. At the engine's standard injection timing (18^0 bTDC), the combustion chamber temperature is high, which is optimal for DO fuel. However, keeping the injection timing at 18^0 bTDC when switching to B15 fuel with higher oxygen content and cetane number than DO fuel shortens the ignition delay time. Fuel evaporation had not yet been completed before combustion, leading to decreased power. When the injection timing is too early, the combustion process occurs when the cylinder volume is still significant, leading to low maximum combustion pressure and reduced power. According to the record, the most suitable ignition delay time for the combustion process to occur at the right time leads to increased engine power engine's power, that is, at the injection timing of $19\text{-}20^0$ bTDC.

Table 11
ANOVA analysis results for the power regression function

Summary output								
Regression statistics								
Multiple R	0.948333							
R square	0.899335							
Adjusted R square	0.86578							
Standard error	0.579268							
Observations	5							
ANOVA								
	df	SS	MS	F	Significance F			
Regression	1	8.993346	8.99334	26.8017	0.013988			
Residual	3	1.006654	0.33555					
Total	4	10						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	64.18867	8.346375	7.69060	0.00456	37.62678	90.75056	37.6267	90.75056
Power	-1.47191	0.284314	-5.17704	0.01398	-2.37672	-0.56709	-2.37672	-0.56709

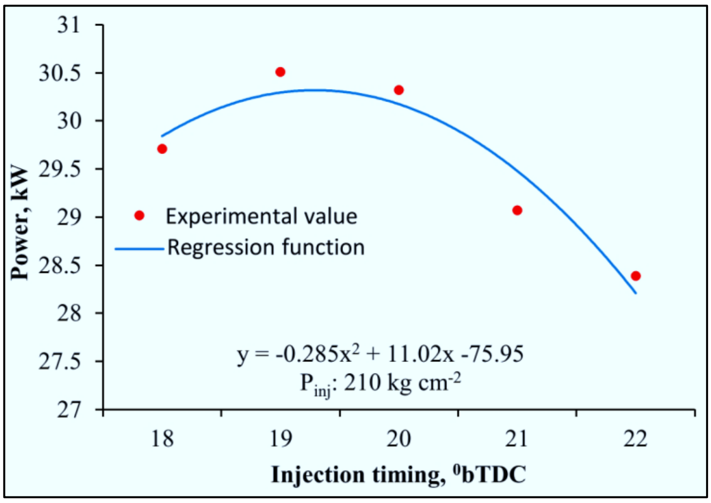


Fig. 4. Power characteristics of diesel engine using diesel-coconut oil blends

Establish a similar to Eq. (13), the regression function as Eq. (14) for specific fuel consumption:

$$y = 5.2414x^2 - 24.635x + 303.95, \text{ with reliability, } R^2 = 0.807 \tag{14}$$

Table 12 presents the results of the variance analysis of ANOVA for regression data, Eq. (14). Table 12 shows that the regression function's P value is less than 0.05. The data for the specific fuel consumption is reliable. The regression function, Eq. (14), represents the rule for adjusting injection timing and its effect on a diesel engine's specific fuel consumption when using a diesel-coconut oil blend (Figure 5). Figure 5 shows that when increasing the injection timing 19-20^0 bTDC compared to the standard injection timing when using DO fuel (18^0 bTDC), the B15 specific fuel consumption decreases because the power increases (Figure 4). When increasing injection timing exceeds 20^0 bTDC, specific fuel consumption increases because the power tends to decrease.

Table 12
ANOVA analysis results for specific fuel consumption regression function

Summary output								
Regression statistics								
Multiple R	0.952754							
R square	0.90774							
Adjusted R square	0.876987							
Standard error	0.554556							
Observations	5							
ANOVA								
	df	SS	MS	F	Significance, F			
Regression	1	9.077402	9.077402	29.51687	0.01224			
Residual	3	0.922598	0.307533					
Total	4	10						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-1.55026	4.158055	-0.37283	0.734057	-14.783	11.68253	-14.783	11.68253
SFC	0.077097	0.014191	5.432943	0.01224	0.031936	0.122258	0.031936	0.122258

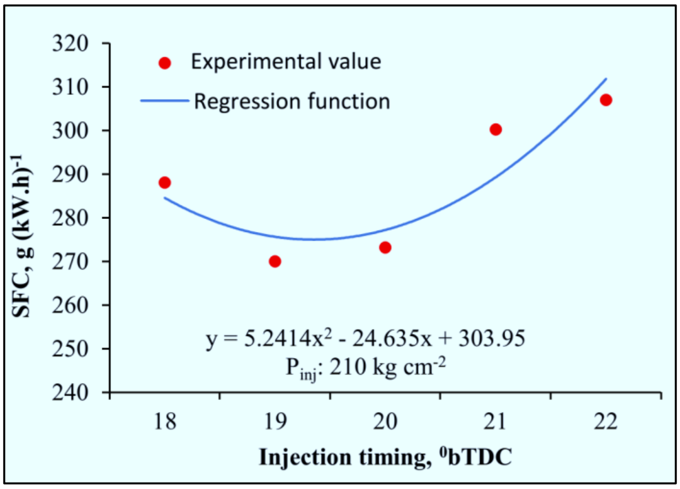


Fig. 5. Specific fuel consumption characteristics of diesel engines using diesel coconut oil blends

B15 fuel has a viscosity and high temperature, which reduces the spray penetration and decreases the spray cone angle, leading to an inefficient combustion mixture formation. This is one of the differences between B15 fuel and DO regarding physical and chemical properties. Therefore, it is necessary to adjust the fuel B15 injection timing. Establish a similar to Eq. (14), the regression function as Eq. (15) for soot emissions. This function represents the rule for adjusting injection timing and its effect on diesel engine soot emissions when using a diesel-coconut oil blend (Figure 6).

$$y = 0.0964x^2 - 0.5396x + 7.388, \text{ with reliability, } R^2 = 0.8453 \quad (15)$$

Table 13 presents the results of the variance analysis of ANOVA for regression data, Eq. (15). Table 13 shows that the regression function's *P* value is less than 0.05, which means that the data for the soot emissions are reliable. Changing the fuel injection timing means changing the ignition delay time. Ignition delay time is one of the most essential criteria, significantly impacting the combustion process, mechanical stress, engine noise, and exhaust [38]. Under the same injection conditions, fuel with high oxygen content and cetane value will reduce the ignition delay time. Therefore, when the engine uses B15 fuel, it is necessary to increase the injection timing compared to DO fuel to increase the ignition delay time.

Figure 6 shows that soot emission is significant at the injection timing of 18^0 bTDC and low at 19 - 20^0 bTDC; when the injection timing exceeds 20^0 bTDC, it tends to increase. This is because soot is formed from an inefficient combustion mixture and incomplete combustion. At the time of late injection (injection near the top dead center), the short combustion delay time and low combustion temperature reduce the oxidation process, causing the amount of soot emitted to increase. When the injection is too early, the temperature and pressure in the cylinder are low, combined with the high viscosity and density of B15 fuel, which affects the formation of the combustion mixture and the incompletely evaporated fuel, causing a significant amount of soot to form.

Table 13
ANOVA analysis results for the soot regression function

Summary output								
Regression statistics								
Multiple R	0.988787							
R square	0.9777							
Adjusted R square	0.96655							
Standard error	0.236114							
Observations	4							
ANOVA								
	df	SS	MS	F	Significance, F			
Regression	1	4.8885	4.8885	87.68647	0.011213			
Residual	2	0.1115	0.05575					
Total	3	5						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-20.2125	4.349323	-4.64728	0.043316	-38.9261	-1.49889	-38.9261	-1.49889
Soot	5.99816	0.640548	9.364105	0.011213	3.242104	8.754216	3.242104	8.754216

B15 fuel has the advantage of high oxygen content; when burning, it reduces the amount of soot formation. However, adjusting the fuel injection timing properly will create suitable conditions of temperature and pressure in the combustion chamber and appropriate ignition delay time, ensuring the formation of the mixture, good combustion, and reducing soot emissions.

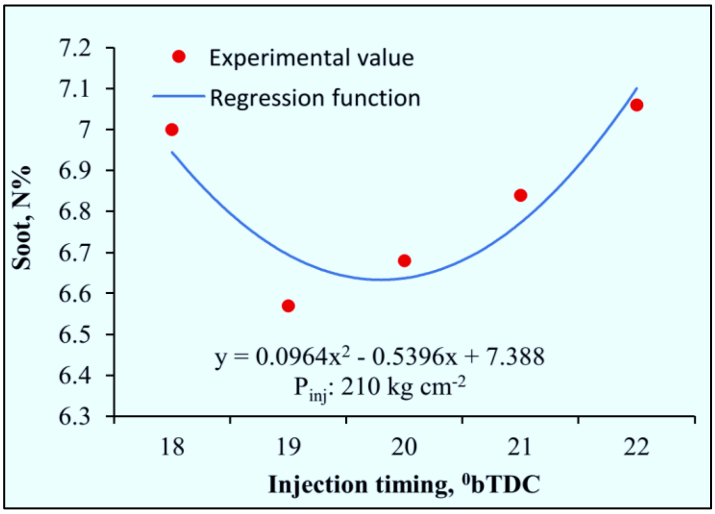


Fig. 6. Soot emissions characteristics of diesel engines using diesel-coconut oil blends

The regression function, Eq. (16), represents the rule for adjusting injection timing and its effect on diesel engine NO_x emissions when using a diesel-coconut oil blend (Figure 7).

$$y = -5.5714x^2 + 77.029x + 937.4, \text{ with reliability, } R^2 = 0.9434 \qquad (16)$$

Table 14 presents the results of the variance analysis of ANOVA for regression data, Eq. (16). Table 14 shows that the regression function's *P* value is less than 0.05. Figure 7 shows that NO_x emissions increase as the fuel injection timing increases (early injection). This occurs because early fuel injection results in a longer ignition delay and intense combustion, leading to increased combustion temperatures. In addition, the diesel-coconut oil blend has a high oxygen content, which leads to increased NO_x emissions because NO_x develops when nitrogen combines with oxygen at high temperatures.

Table 14

ANOVA analysis results for the NO_x regression function

Summary output								
Regression statistics								
Multiple R	0.957617							
R Square	0.917031							
Adjusted R Square	0.889375							
Standard error	0.525893							
Observations	5							
ANOVA								
	df	SS	MS	F	Significance, F			
Regression	1	9.170311	9.170311	33.15811	0.010407			
Residual	3	0.829689	0.276563					
Total	4	10						
	Coefficients	Standard error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-3.01217	4.176631	-0.7212	0.522912	-16.3041	10.27974	-16.3041	10.27974
NO_x	0.020654	0.003587	5.758308	0.010407	0.009239	0.032069	0.009239	0.032069

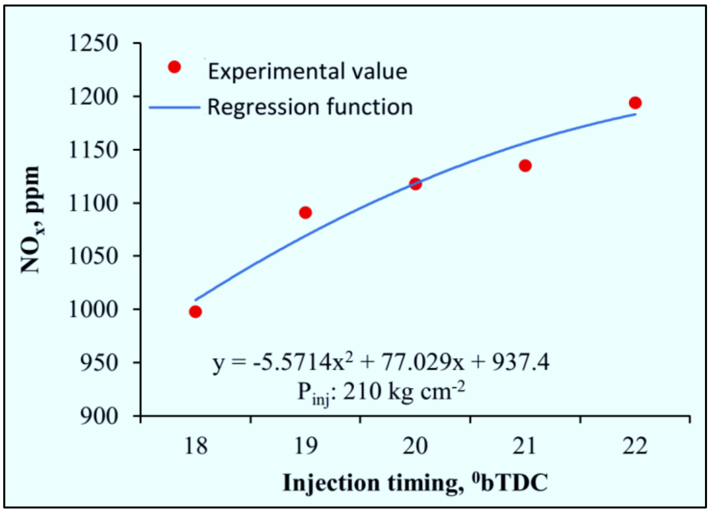


Fig. 7. NO_x emissions characteristics of diesel engines using diesel-coconut oil blends

The above observation is consistent with the observations of many previous studies [39]. In which, according to Kumar *et al.*, [39]. The ignition delay is the time between the start of fuel injection into the combustion chamber and the beginning of the combustion process. It determines the ignition quality according to the cetane number and the time required to mix the fuel with air and vaporize. When the injection is too early, the temperature in the combustion chamber is low, resulting in the fuel mixture being unable to ignite immediately but taking a while. This is the increase in the ignition delay, which leads to an increase in the formation of the fuel-air mixture, so the ignition process will be intense, causing the combustion temperature to increase.

Based on established mathematical functions, the injection timing is appropriate for the Yanmar 4CHE diesel engine when using a diesel-coconut oil blend at 19-20^0 bTDC. The research results of a diesel engine using B15 mixed fuel combined with injection timing adjustment are compared with some studies on biofuels presented in Table 15.

Table 15
Comparison of diesel engine characteristics when using B15 fuel with other biofuels

Fuel	Results when used for diesel engines	Conditions	Note
Waste cooking oil.	Improved economic and environmental indicators compared to diesel fuel.	Adjust IT to increase 4^0 CA compared to IT of DO fuel.	Bari *et al.*, [22]
K15 (15% Karanja and 85% diesel oil).	Thermal efficiency to grow and be equivalent to when the engine used DO fuel.	Adjust IT to increase 5^0 CA compared to IT of DO fuel.	Siddalingappa *et al.*, [25]
Mixed fuel contains biodiesel (40%), n-heptane (10%), and diesel (50%).	Reduced hydrocarbon emissions the most.	Adjust IT and IP to increase compared to DO fuel.	Veeraraghavan *et al.*, [26]
20% Honge oil and 80% diesel (H20).	Soot emissions decreased.	Adjust IP to increase compared to DO (12.5%).	Belagur *et al.*, [40]
Diesel fuel mixture mixed with orange skin powder (30% OSP).	CO, HC, and soot emissions were all reduced.	Adjust IP to increase compared to IP of DO fuel.	Purushothamana and Nagarajan [41]
15% Coconut oil and 85% diesel (B15).	Soot emissions and specific fuel consumption decreased.	Adjust IT to increase about 1 - 2^0 CA compared to IT of DO fuel.	

4. Conclusions

Diesel fuel mixed with vegetable oil (coconut oil) at a ratio of 15% coconut and 85% diesel oil can made as fuel for diesel engines. However, this requires an increase in the engine's fuel injection timing to improve the formation of a better combustion mixture. The experimental research results have established mathematical functions describing the rule of adjusting the injection timing of diesel-vegetable oil blends and the influence of injection timing on diesel engines' economic and environmental targets.

When a fishing vessel's Yanmar 4CHE diesel engine increased the injection timing by about 1-2 degrees of crankshaft angle (19-20^0 bTDC) compared to traditional DO fuel injection timing (18^0 bTDC) to use a diesel-vegetable oil blend (B15), the power increased (2.05-2.69%), the specific fuel consumption reduced (5.14-6.25%), and soot emissions decreased (4.57-6.14%) compared to not adjusted. That has contributed to reducing environmental pollution and improving economic targets for diesel engines. Other diesel engines with similar characteristics to the Yanmar 4CHE diesel engine can apply this research result when transitioning to using diesel-vegetable oil blends.

Acknowledgement

This research was not funded by any grant.

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