

EFFECT OF FUEL INJECTION ON EMISSIONS OF DIESEL ENGINE FUELED WITH WASTE COOKING OIL BIODIESEL PRODUCED BY ULTRASONIC TRANSESTERIFICATION

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This study aimed to examine effect of injection timing on the use of biodiesel fuel from waste cooking oil processed with ultrasonic transesterification technology on exhaust emissions of diesel engine. Several variations of injection timing were applied to evaluate their impact on exhaust gas characteristics and engine emissions. Engine was run at a constant speed of 2,400 rpm with standard injection timing (17° CA BTDC), advanced at an angle of 3° and 6° CA (20° and 23° CA BTDC), followed by retardation at 3° and 6° CA (14° and 11° CA BTDC). The results showed that the standard injection timing of 17° CA BTDC provided optimal performance with an EGT of approximately 250°C at B10. Advancing injection timing increased the EGT to 320°C but reduced CO and UHC emissions by 11.11% and 26.30%, respectively. However, there was a significant increase in smoke opacity emissions and NOx by 14.58% and 31.1%, respectively. The retardation in injection timing decreased EGT to 220°C as well as increased CO, UHC, and smoke opacity emissions, with NOx rising by 10.4%. These results showed that ultrasonic transesterification technology produced high-quality biodiesel with better combustion characteristics. Meanwhile, increasing biodiesel content (B20-B100) tended to cause a rise in NOx emissions due to higher oxygen content.

Keywords: biodiesel, waste cooking oil, ultrasonic transesterification technology, injection timing, emissions

1. Introduction

The current global energy challenges are attributed to increasing energy demand, limited fossil fuel resources, and the negative environmental impacts of conventional fuel combustion [1]. These phenomena significantly contribute to the search for alternative and sustainable energy sources. An additional issue that requires attention is managing production waste, suggesting the need for efficient and environmentally friendly processing method [2]. Biodiesel offers a promising solution to fossil fuel dependency because it is derived from renewable feedstocks and produces significantly lower emissions than conventional diesel [3, 4].

The production of biodiesel through ultrasonic transesterification technology has shown higher efficiency compared to conventional methods [5]. Biodiesel from ultrasonic processing exhibits viscosity values within 3.46-3.51 mm²/s range and flash point reduction to 158°C, properties that directly affect engine combustion performance [6]. Although biodiesel has the potential to reduce emissions, the effect of altered viscosity and flash point properties on diesel engine performance requires further investigation and exhaust emissions still needs further analysis in terms of optimal injection timing [7]. Ultrasonic transesterification has become a promising biodiesel production method due to the high efficiency and shorter reaction time [8]. This method uses ultrasonic waves to enhance mass and heat transfer during transesterification process, leading to higher biodiesel yields with lower energy consumption [9]. Ultrasonic transesterification can increase the reaction rate and produce cleaner biodiesel, which affects engine performance [10].

Fuel injection timing is one of the important parameters capable of influencing the performance and efficiency of diesel engine [11]. Previous studies reported that proper injection timing could increase engine power and torque, as well as reduce fuel consumption [12, 13]. However, effect of injection timing on diesel engine using biodiesel from ultrasonic transesterification has not been fully explored. By understanding the interaction between injection timing and biodiesel characteristics, engine performance can be optimized to reduce emissions.

Appropriate injection timing significantly influences in-cylinder combustion, directly affecting fuel efficiency, engine performance, and emissions formation [14, 15]. One important aspect in optimizing diesel engine performance is fuel injection timing setting. Previous study showed that optimal injection timing could increase combustion efficiency as well as reduce NO_x and particulate emissions [16]. The differences in physical and chemical characteristics between biodiesel and conventional diesel fuel require adjustments to engine operating parameters to achieve optimal performance and lower emissions

Optimization of injection timing for biodiesel produced by ultrasonic transesterification technology should consider various engine operating conditions, including partial and transient loads [17]. This is important to ensure that the adjustments made are effective in various practical usage scenarios. Additionally, the potential use of dynamic injection timing strategies, which can adapt to fuel characteristics and operating conditions, offers a promising study direction to improve performance and reduce overall emissions [18]. This research employs experimental methods to analyze particular combustion characteristics in diesel engines, contributing to the understanding of selected aspects of the combustion process.

Based on the description, this study aimed to examine effect of fuel injection timing on exhaust emissions from biodiesel produced through ultrasonic transesterification technology. Biodiesel produced through ultrasonic transesterification technology could have different stability characteristics compared to conventional methods, thereby affecting engine performance and emissions over the life of fuel [19]. The results were expected to provide practical recommendations for the automotive industry in adopting biodiesel as an environmentally friendly alternative fuel. A proper understanding of injection timing on engine performance was recommended due to the increasing use of biodiesel.

1.1. Ultrasonic Transesterification

Ultrasonic transesterification is used to convert vegetable oil or fat into biodiesel through a chemical reaction between triglycerides and alcohol, with the help of a catalyst [20]. The use of

ultrasonic waves in this process aims to increase reaction efficiency by creating an acoustic cavitation effect, namely the formation of microbubbles in a liquid that explodes at high pressure [21]. This effect accelerates the mixing of reactants, increases mass transfer, and accelerates the reaction rate compared to conventional methods. Additionally, ultrasonic transesterification allows for reduced reaction time and energy consumption, which is considered more economical and environmentally friendly. This makes ultrasonic transesterification an attractive method for both large and small-scale biodiesel production [22].

Transesterification is a chemical reaction including oil or fat with alcohol (methanol or ethanol) to produce biodiesel and glycerol as a by-product. Meanwhile, ultrasonic transesterification is biodiesel production method that uses ultrasonic waves to accelerate and increase the efficiency of transesterification reaction [23]. Ultrasonic waves can help mix oil and alcohol better, increase the contact surface area, and accelerate the dissolution of the catalyst [24]. This allows transesterification reaction to take place faster than the conventional method and can be carried out at lower temperatures, thereby reducing energy consumption. The ultrasonic process demonstrates 85% reduction in energy consumption and 25% less methanol usage while maintaining comparable conversion efficiency. Several studies have shown that ultrasonic transesterification can produce biodiesel with higher yields in a shorter time [25].

The advantages of ultrasonic transesterification technology lie not only in its efficiency but also in flexibility in handling low-quality raw materials, such as waste cooking oil or high free fatty acid content [26]. This technology can reduce the formation of by-products such as soap, which is often a problem with conventional methods. The use of ultrasonic is capable of reducing the need for catalysts by approximately 50%, which has an impact on lowering overall production costs [27]. Therefore, ultrasonic transesterification offers an innovative solution to meet the need for sustainable alternative energy.

2. Methodology

2.1. Experimental Design

Table 1 shows the specifications of the Yanmar TF 105 MR-di test engine, which is a horizontal, air-cooled, 4-stroke diesel engine. This engine has 1 cylinder with a bore of 88 mm and a stroke of 96 mm, thereby the total volume displacement is 583 mm. The Yanmar TF 105 MR-di test engine has a maximum power of 7.83 kW at 2400 rpm, and a continuous power of 7.08 kW at 2400 rpm. The maximum torque (Max Torque) is 41.5 N.m at 1,600 rpm, with specific fuel consumption of 249 g/kWh and compression ratio of 17.9:1. The engine employs a radiator for cooling and direct injection for fuel delivery.

Table 1. Test Machine Specification

ITEM	SPECIFICATION
Brand	YANMAR
Model	TF 105 MR-di
Type	Horizontal, water-cooled 4-cycle diesel
No. of cylinder	1
Bore x stroke	88 mm x 96 mm
Displacement	583 mm

ITEM	SPECIFICATION
Max power	7.83 kW @ 2400 rpm
Continuous power	7.08 kW @ 2400 rpm
Max Torque	41.5 N.m @ 1600 rpm
Specific Fuel Consumption	249 g/kWh
Compression ratio	17.9: 1
Cooling system	Radiator
Combustion system	Direct injection

Figure 2 shows the experimental study design conducted to analyze effect of various concentrations of waste cooking oil biodiesel processed by ultrasonic transesterification technology on diesel engine performance and other operational parameters. Diesel engine used was the Yanmar TF 105 MR-di engine, equipped with several sensors to monitor operational conditions. Water, oil, and engine temperature sensors functioned to measure temperatures at various points in the system. Meanwhile, a voltmeter was connected to an electric generator to measure power output.

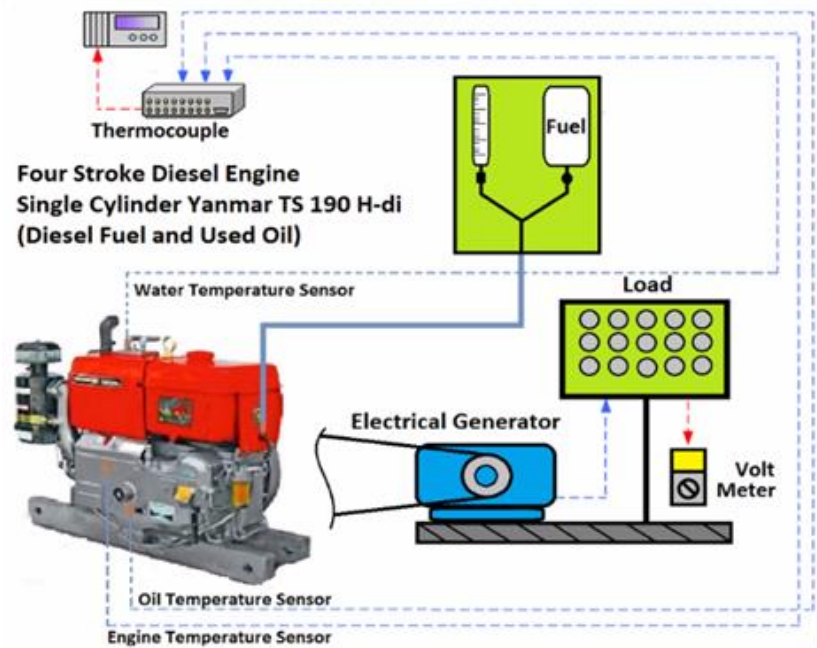


Figure 1. Experimental Design

This design allowed the testing of various concentrations of biodiesel mixture with diesel, providing accurate data on combustion efficiency and exhaust emissions. The analysis was to optimize the use of biodiesel as an environmentally friendly alternative [28].

Table 2. Operating Conditions

Engine speed	2400 rpm
Injection Timing	17° CA BTDC
Engine load	10%; 20%; 30%; 40%; 50%; 60%; 70%; 80%; 90%, 100%
Fuel	B0, B20, B40, B60, B80, B100

In this study, the engine was operated at a constant speed of 2,400 rpm while varying fuel injection timing settings: standard 17° Crank Angle (CA) Before Top Dead Center (BTDC), advanced by 3° and 6° CA (corresponding to 20° and 23° CA BTDC), and retarded by 3° and 6° CA (corresponding to 14° and 11° CA BTDC). Engine load was regulated using a water brake dynamometer, ranging from low load (10%) to full load (100%). The fuels tested included fossil diesel, waste cooking oil biodiesel produced via ultrasonic transesterification, and their volumetric blends. Details of the operational conditions are presented in Table 2.

3. Results and Discussion

3.1. Exhaust Gas Temperature (EGT)

Figure 2 shows a comprehensive analysis of the relationship between EGT and injection timing for various biodiesel mixtures derived from waste cooking oil through ultrasonic transesterification technology. At the standard injection timing of 17° CA BTDC, the EGT for the B10 reached approximately 250°C, showing relatively efficient combustion for low biodiesel blends. That optimal injection timing produces a balanced trade-off between performance and thermal efficiency, and that standard timing yields optimal atomization across biodiesel blends [29, 30]. Increasing biodiesel concentration from B10 to B100 at standard injection timing showed a consistent trend of higher EGT. Ultrasonic transesterification process used in biodiesel production positively contributed to the combustion quality at standard timing [25, 26]. Biodiesel produced via ultrasonic transesterification exhibited a kinematic viscosity of 3.48 mm²/s, a density of 0.885 g/cm³, and a cetane number of 52.3 values that together support improved atomization and spray characteristics in the combustion chamber [27]. The combustion stability at standard timing showed the success of ultrasonic transesterification process in producing high-quality biodiesel [27, 31].

When injection timing was advanced by 3° and 6° CA from the standard angle of 17° CA BTDC to 20° and 23° CA BTDC, an increase in EGT was observed. Byrne & Seamus [31] explained that the increase in temperature occurred due to longer combustion times, allowing for more optimal energy release. This increasing pattern was consistent for all biodiesel mixtures, showing more efficient combustion with better preparation. The data showed that at 20° CA BTDC timing, the EGT increased to 260-300°C, and reached 270-320°C at 23° CA BTDC. This increase was consistent in all variations of biodiesel, showing more efficient combustion.

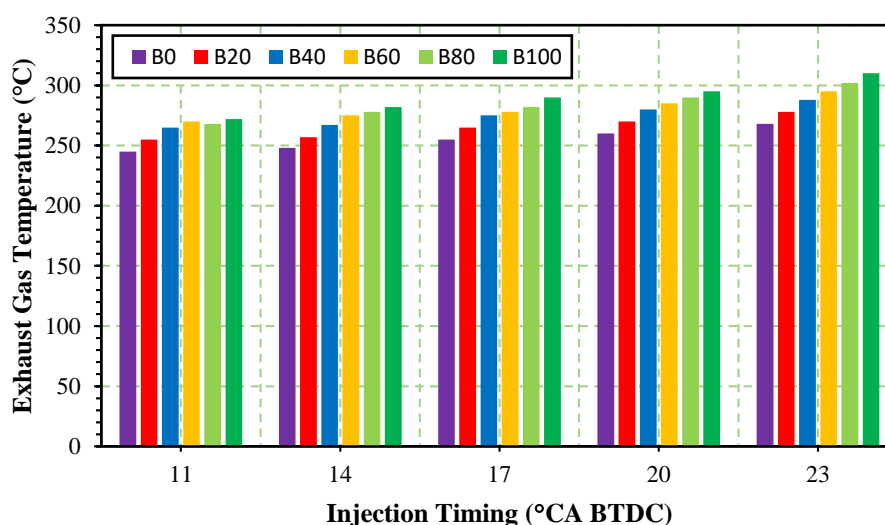


Figure 2. EGT againsts Injection Timing

When injection timing was retarded by 3° and 6° CA from the standard angle of 17° CA BTDC to 14° and 11° CA BTDC, a decrease in EGT was observed. Prakash et al. [32] explained that the decrease in temperature occurred because the combustion time was shorter, causing some energy not to be released when the exhaust gas exited. The decrease pattern was consistent for all biodiesel mixtures, with B100 still showing the highest temperature. This phenomenon showed less than optimal combustion due to preparation time. The data showed that at timing of 14° CA BTDC, the EGT decreased to 230-270°C, reaching 220-260°C at 11° CA BTDC.

The use of biodiesel with a higher percentage (B50 and B100) consistently showed greater EGT across all injection timing variations. This was due to the higher oxygen content in biodiesel, which caused more complete combustion with greater temperatures [33]. The data showed that the temperature difference between B10 and B100 was consistently approximately 20°C at each injection timing. Furthermore, the characteristics of B10 and B100 were influenced by the higher cetane number of biodiesel, which accelerated the combustion process. The use of ultrasonic transesterification technology could produce biodiesel with consistent combustion quality under various operating conditions [33, 34].

3.2. Carbon Monoxide (CO) Emissions

Carbon Monoxide (CO) is a dangerous compound that needs to be limited in its formation. Fuel combustion process, either directly or indirectly, can produce CO gas. When combustion occurs under ideal conditions, the carbon element (C) will react with oxygen (O₂) to form carbon dioxide (CO₂). However, at incomplete combustion, CO gas will be formed due to the reaction. Based on previous studies [34], the formation of CO occurs due to inadequate oxygen availability during the combustion process to produce CO₂.

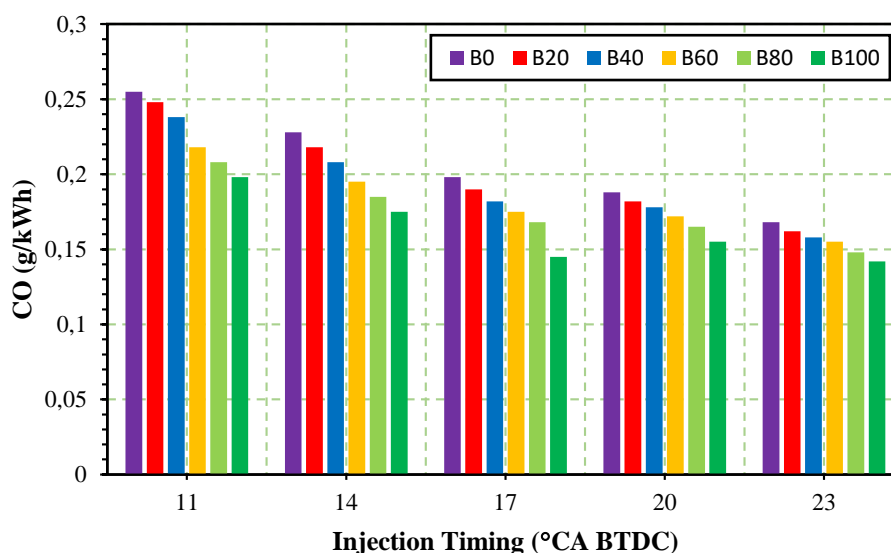


Figure 3. CO Emissions against Injection Timing

Figure 3 shows the relationship between CO emissions in gr/KW.h units with variations in injection timing for various waste cooking oil biodiesel mixtures processed using ultrasonic transesterification technology. Therefore, this study conducted tests with various injection timing settings at 2400 rpm. The visible trend showed that CO emissions decreased when injection timing was accelerated. In tests with B40 fuel and 40% load, acceleration of injection timing by 3° and 6° CA from

the standard angle of 17° CA BTDC to 20° and 23° CA BTDC successfully reduced CO emissions by 11.11%. This phenomenon occurred because earlier injection timing increased EGT, as shown in Figure 3. Therefore, the oxidation reaction between carbon and oxygen becomes more optimal, which has an impact on reducing CO emissions [35]. When injection timing was retarded by 3° and 6° CA from the standard angle of 17° CA BTDC to 14° and 11° CA BTDC, CO emissions increased by 33.33% under the same test conditions. The results were supported by Sahu et al. [10], where advancing injection timing created better fuel atomization and air mixing. This condition caused higher turbulence and adequate combustion duration, thereby allowing efficient conversion of CO to CO₂.

The most significant reduction in CO emissions occurred due to the combination of advanced injection timing and increased content of waste cooking oil biodiesel processed with ultrasonic transesterification technology. All variations of biodiesel mixtures recorded the lowest CO emissions when injection timing was set at 23° CA BTDC and B100 biodiesel. Ultrasonic transesterification technology used in biodiesel processing contributed significantly to combustion quality and CO emissions reduction. Increasing biodiesel content led to stable CO emissions across all injection timings, a trend consistent with Maleki and Mansouri's observation of reduced CO with ultrasonic-derived biodiesel. This stability reflects the combined influence of the fuel's optimized viscosity (3.48 mm²/s), density (0.885 g/cm³), and cetane number (52.3), which enhance atomization and combustion efficiency under our test conditions [8, 13, 18]. Optimal biodiesel viscosity and density allowed for better atomization during injection. The stability of the CO emissions showed an efficient combustion process [19, 36].

3.3. Unburned Hydrocarbon (UHC) Emissions

Figure 4 shows the relationship between unburned hydrocarbon (UHC) emissions and variations in fuel injection timing. This graph shows UHC data in grams per kilowatt-hour (g/kWh) for various biodiesel mixtures. Standard injection timing at 17° CA BTDC shows optimal performance for B20 to B100 biodiesel blends compared to advanced timing (20° or 23° CA BTDC) or retarded (14° or 11° CA BTDC). At advanced injection timing (20° or 23° CA BTDC), UHC emissions were significantly reduced, indicating more efficient combustion of waste cooking oil biodiesel produced by ultrasonic transesterification technology. This phenomenon occurred because the higher oxygen content in biodiesel molecules improved the combustion process [36].

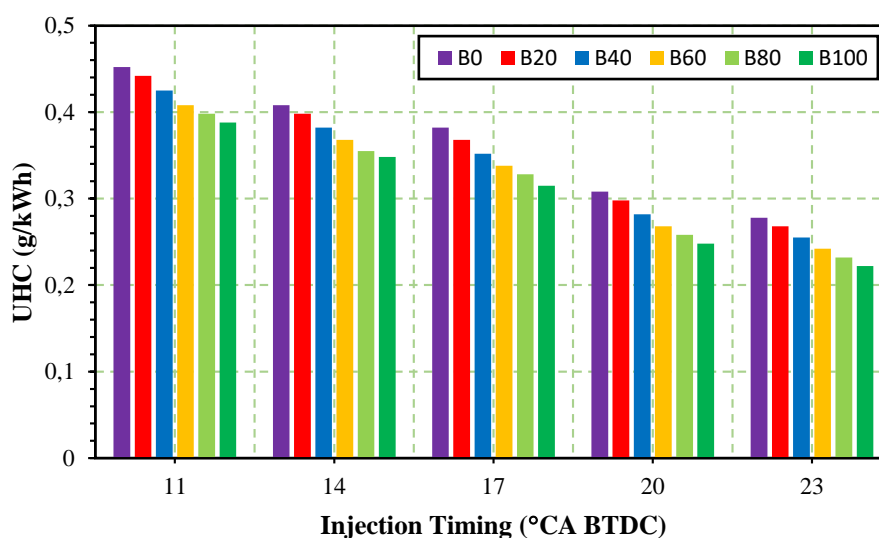


Figure 4. UHC Emissions against Injection Timing

When injection timing was advanced by 3° and 6° CA from the standard angle of 17° CA BTDC to 20° and 23° CA BTDC under test conditions on the B40 mixture with 40% engine load, there was a significant decrease in UHC emissions of 26.30% for all biodiesel mixtures. This decrease occurred because of the availability of a longer combustion time, allowing for better fuel-air mix [21]. The quality of biodiesel processed with ultrasonic technology positively contributed to fuel atomization process. Improved physicochemical characteristics of biodiesel specifically reduced kinematic viscosity, optimized density, and increased cetane number enhance combustion quality by promoting finer fuel atomization [37]. Longer combustion time also allows oxygen in biodiesel to react more optimally. Smaller fuel droplets increase the air fuel contact surface area, thereby improving combustion efficiency.

At the same test parameters, retarding injection timing by 3° and 6° CA from the standard angle of 17° CA BTDC to 14° and 11° CA BTDC increased UHC emissions significantly by 20.45% for all variations of biodiesel mixtures. This increase was caused by a shorter combustion time, leading to less complete combustion [14]. Although biodiesel is produced using ultrasonic technology, suboptimal injection timing causes higher UHC emissions. The time available for fuel-air mixing becomes shorter, contributing to sub-optimal characteristics of the spray pattern at late injection timing. Lower combustion temperatures reduce the level of HC oxidation [38]. This shows that biodiesel mixtures processed with ultrasonic transesterification technology have the potential to improve combustion efficiency. Technology produces biodiesel with lower viscosity and higher ester content, which contributes to more complete combustion. Therefore, the use of biodiesel can significantly reduce UHC emissions, serving as an important indicator of better quality [39].

3.4. Smoke Opacity

Figure 5 shows the relationship between smoke opacity (%) and the variation of injection timing (CA) in various waste cooking oil biodiesel mixtures processed using ultrasonic transesterification technology. At the standard injection timing of 17° CA BTDC, all biodiesel mixtures showed lower smoke opacity values compared to advanced or retarded against. This phenomenon showed that combustion at standard injection timing was more optimal due to proper combustion preparation. The results of Kombe [5] showed that biodiesel produced using ultrasonic technology had a more uniform viscosity and density, leading to better atomization when injected. These characteristics contributed to more complete combustion and lower particulate emissions.

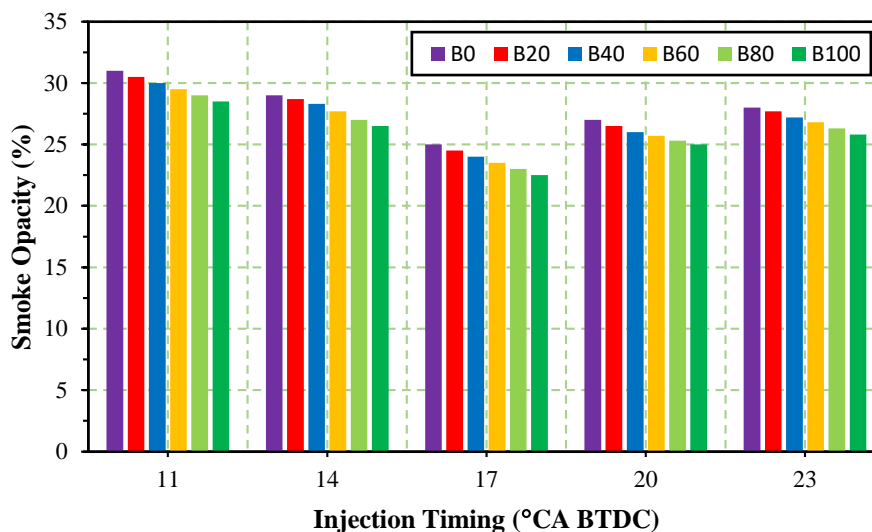


Figure 5. Smoke Opacity Emission against Injection Timing

Advancing injection timing by 3° and 6° CA from the standard angle of 17° CA BTDC to 20° and 23° CA BTDC causes a relatively smaller increase in smoke opacity when compared to the retarded injection timing, which only increases by 14.58% for B40 at 40% engine load. Fayad [40] stated that ultrasonic transesterified biodiesel had a higher cetane number, beneficial for advanced injection timing. However, the limited fuel-air mixing time remains a limiting factor, as shown in all biodiesel mixtures. Excessively advanced injection timing can reduce combustion efficiency even though biodiesel quality is very good.

Retarding injection timing by 3° and 6° CA from the standard angle of 17° CA BTDC to 14° and 11° CA BTDC causes smoke opacity to increase by 25.0% for B40 at engine load 40. This increase occurs because the combustion preparation period is excessively long causing larger fuel accumulation in the combustion chamber. Rajendran et al. [41] reported that biodiesel from ultrasonic transesterification had better oxidation stability, but required proper injection timing for optimal combustion. This suggested that early injection timing could also cause combustion chamber pressure and sub-optimal temperature, leading to higher soot formation.

Based on a comprehensive analysis, the combination of optimal injection timing (17° CA BTDC) and the use of high-concentration biodiesel produced through ultrasonic transesterification technology provided the best results in controlling smoke opacity emissions. Sun et al. [42] confirmed that ultrasonic technology produced biodiesel with superior characteristics compared to conventional methods. These advantages included more suitable viscosity, optimal oxygen content, and better stability. The use of high-quality biodiesel combined with proper injection timing was effective in reducing particulate emissions. The results provided an important perspective in developing more effective emissions control strategies. This study also showed the potential of ultrasonic technology in improving the quality of biodiesel from waste cooking oil. According to Simsek et al. [43], ultrasonic waves can increase the rate of transesterification reactions 5-10 times faster than conventional methods. Ultrasonic process also produces biodiesel with more consistent physical-chemical characteristics.

3.5. Nitrogen Oxide (NO_x) Emissions

Figure 6 shows the relationship between NO_x emissions in gr/kW.h units and the variation of injection timing (CA BTDC) for various mixtures of waste cooking oil biodiesel processed with ultrasonic transesterification technology. At the standard injection timing of 17° CA BTDC, the B20 to B100 biodiesel mixtures showed higher NO_x emissions compared to pure diesel fuel (B0). This increase in emissions was related to the chemical nature of biodiesel, which had a higher oxygen content than pure diesel [44]. The oxygen content facilitated more complete combustion, increasing the combustion temperature and NO_x emissions [45].

Advancing injection timing by 3° and 6° CA from the standard angle of 17° CA BTDC to 20° and 23° CA BTDC causes NO_x emissions to increase by 31.1% for B40 biodiesel at 40% engine load. These NO_x emission increases significantly for all fuel types, particularly at higher mixture percentages (B80 and B100). The increase is due to earlier combustion in the high-pressure cycle, which causes higher peak temperatures and increased NO_x formation [46]. Therefore, although advancing injection timing can improve thermal efficiency, the side effect is increased NO_x emissions [47].

Retarded fuel injection timing by 3° and 6° CA from the standard angle of 17° CA BTDC to 14° and 11° CA BTDC causes a relatively smaller increase in NO_x emissions, which is only 10.4% for B40 biodiesel at 40% engine load. The decrease in NO_x emissions occurs for all types of fuel. Retarding

injection timing causes combustion to occur in the pressure cycle, thereby lowering the maximum combustion temperature. Zhao et al., [48] stated combustion efficiency also decreased, leading to higher HC and CO emissions. In the context of biodiesel processed with ultrasonic technology, retarding injection timing is a strategy to reduce NO_x emissions. However, there is a need to consider the compromise on combustion efficiency.

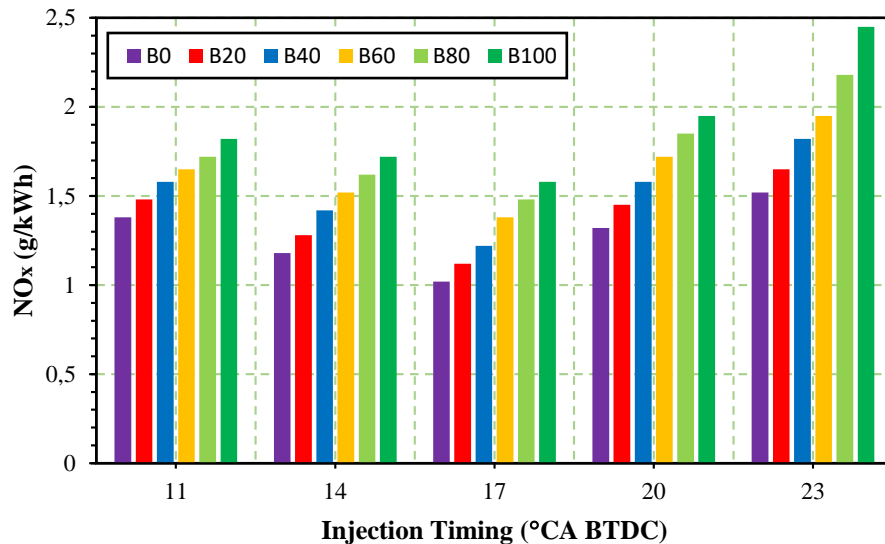


Figure 6. NO_x Emissions against Injection Timing

Ultrasonic transesterification technology plays an important role in improving the quality of biodiesel by accelerating the reaction process and production with higher purity [43]. The resulting biodiesel has better combustion properties, such as higher cetane numbers and sufficient oxygen content [45]. These properties contribute to increased NO_x emissions, particularly at more advanced injection timings. Therefore, proper injection timing settings are needed to optimize engine performance with minimal emissions.

4. Conclusions

In conclusion, this study showed the significant impacts of using waste cooking oil biodiesel processed with ultrasonic transesterification technology on exhaust emissions in stationary diesel engine. The results obtained were as follows:

- Ultrasonic transesterification technology provided a significant contribution to producing high-quality biodiesel with low viscosity and high oxygen content. These efficient combustion properties produced more environmentally friendly exhaust gases.
- Injection timing and biodiesel concentration affect the EGT. At standard timing of 17° CA, B10 shows efficient combustion with EGT of approximately 250°C. Earlier injection timing increased EGT to 320°C, while late timing decreased EGT to 220°C. High biodiesel (B50-B100) consistently increased EGT due to its high oxygen content and cetane number. This suggested that ultrasonic transesterification technology supported optimal combustion.
- CO emissions can be decreased by advancing injection timing and increasing the proportion of waste cooking oil biodiesel produced via ultrasonic transesterification technology. The combination of these two factors caused more efficient combustion, better fuel atomization, and a significant reduction in CO emissions.

- d. UHC emissions decreased when injection timing was advanced and increased after retarding from the standard angle of 17° CA. The use of waste cooking oil biodiesel processed with ultrasonic transesterification technology contributed to the decrease in UHC due to its better physical-chemical characteristics.
- e. The lowest smoke opacity occurred at the standard injection timing of 17° CA BTDC. When injection timing was advanced and retarded at B40 and 40% engine load, the smoke opacity increased by 14.58% and 25.0%, respectively. The use of high-concentration biodiesel produced with ultrasonic transesterification technology contributed to the control of smoke opacity emissions.
- f. NO_x emissions increased in B20-B100 biodiesel compared to pure diesel due to the higher oxygen content in fuel. Advancing injection timing by 6° CA increased NO_x by 31.1% at B40 and 40% engine load. Meanwhile, retarding injection timing at the same conditions only increased NO_x by 10.4%. These results showed that ultrasonic transesterification technology improved biodiesel quality but did not reduce NO_x.

5. Acknowledgment

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