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Published by the Faculty of Engineering, Khon Kaen University, Thailand

Utilization of waste transformer oil for alternative fuel: Design of combustion system model, economic feasibility, and performance test

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Received 2 February 2024
Revised 24 July 2024
Accepted 13 August 2024

Abstract

The utilization of waste transformer oil (WTO) for combustion applications can offer significant potential to generate thermal energy and reduce industrial waste disposal. This study focuses on the development of a burner system designed to utilize WTO as an alternative fuel blended with 30% biodiesel and 70% diesel (B30) to produce thermal energy for various applications in industrial processes. Moreover, the economic feasibility and performance test were explored to provide an overview of the economically designed burner system and inform that WTO blended with B30 is suitable for an environmentally friendly alternative fuel. The development combustor consists of a vertical metal tube cylinder supplied with pressurized air from a blower. Secondary air flow was also provided at the tip of the burner for complete combustion of the fuel. Various test scenarios were conducted to optimize combustion and emission performance. The combustion temperature of the fuel was measured at the tip of the burner, while the emissions gases were recorded at 150 cm above the burner tip. Based on the experimental results, it is shown that the developed burner system can effectively burn the WTO blended B30 to produce thermal with low emissions gases. The maximum combustion temperature reached by the burner is 979°C, achieved with a combustion mixture consisting of 30%:70% WTO/B30 (v/v). The economic feasibility of the developed burner system was very useful and inexpensive to be developed at household or industrial scales and emissions from the combustion process are relatively low, with no significant environmental or health risks. Future studies may explore different fuel blends, system improvements, and broader industrial applications.

Keywords: Waste transformer oil, Burner, Development, Combustion, Emissions

1. Introduction

The rapid growth of the human population, industrialization, and transportation have increased energy demand, raising concerns about the depletion of fossil fuels [1, 2]. The utilization of fossil fuels poses environmental issues, such as pollution emissions and greenhouse gases [3, 4]. A prudent step to mitigate environmental damage is to explore alternative energy sources that are technically feasible, economically viable, and environmentally sustainable [5]. Several recent studies have revealed that the use of biofuels plays a pivotal role in reducing our dependence on fossil fuels, offering an effective solution to address the energy crisis and combat climate change [6-8]. Unfortunately, it is not yet feasible for biofuels to entirely replace fossil fuels due to competition between food and energy needs (first-generation fuels) [9, 10]. Therefore, the introduction of various alternative fuels is essential to meet the global petroleum demand and improve future fuel utilization and exploration.

One potential step towards alternative fuels involves the reutilization of used oil and reducing the impact of hazardous waste by utilizing waste transformer oil (WTO) as a viable alternative fuel source [11, 12]. In electrical transformers, transformer oil is primarily used for insulation purposes. With prolonged use, the physicochemical properties of the oil change, rendering it as waste oil that requires replacement. Transformer oil that has lost its insulation function within the transformer is typically disposed of without further use [13, 14]. Transformer oil is an industrial compound composed of hydrocarbons, solvents, heavy metals that are toxic to the atmosphere and impossible to extract or handle (soot, polycyclic aromatic hydrocarbons (PAHs), chlorinated paraffins, and polychlorinated biphenyls (PCBs) [12]. Improper disposal of waste transformer oil on land or in water can lead to environmental problems [15]. Inadequate disposal of waste can result in environmental pollution because it often contains carcinogens and other heavy metals that have the potential to contaminate the soil [16, 17]. Elevated levels of various metals in WTO components are detrimental to human health, such as iron, copper, aluminum, lead, tin, silver, and zinc [15]. A literature review indicates that individuals exposed to carcinogens may experience adverse health effects, including cancers of the liver, gastrointestinal tract, and urinary tract, as well as respiratory diseases [18, 19]. Therefore, it is imperative to find an environmentally friendly way to reuse this hazardous waste oil as a substitute for fossil fuels.

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doi: 10.14456/easr.2024.56

Several researchers have actively explored the use of WTO in diesel engine applications as part of their efforts to harness vital energy sources from industrial waste products. Lee et al. [20] conducted a study to investigate the impact of temperature on the melting heat desorption treatment and heating duration on the pollutant removal efficiency of diesel-contaminated soil from WTO. However, the combustion performance of these fuel blends in a trash burner still needs to be constructed and analyzed in depth. Belkhode et al. [12] and Behera et al. [21] directly mixed waste transformer oil with diesel fuel without any prior treatment and used it as fuel in the diesel engine. They observed a reduction in smoke density at maximum brake power and temperature stability. They found that this treatment is very effective in improving engine performance. In addition, Belkhode et al. [22] also reported that transformer oil can be used as a renewable fuel source in compression ignition engines, potentially reducing fuel costs through the utilization of waste oils. In contrast, different results reported by Yadav et al. indicated that the use of a higher proportion of WTO in the fuel mixture decreased performance and increased exhaust emissions (smoke) [23].

The identification of references to the WTO on the Scopus website reveals recent studies focusing on the utilization of WTO, primarily as a diesel fuel. This is closely associated with research on the impact of smoke and exhaust emissions resulting from WTO utilization. Therefore, this research addresses a significant and sustainable concern in utilizing WTO for alternative fuels, as evidenced by the Scopus publication data (Figure 1), which showcases WTO studies dating from 2020 to the present, featuring keywords such as "diesel fuels," "biodiesel," "emission," "smoke," and "transesterification.". Numerous researchers have explored the re-utilization of WTO for biodiesel synthesis [24], the conversion of waste into diesel fuel [11, 12], and the assessment of contamination in WTO waste [25]. These findings collectively suggest that waste transformer oil holds the potential to serve as a biodiesel feedstock. Biodiesel produced from waste transformer oil demonstrates superior performance and lower carbon monoxide emissions in comparison to conventional diesel fuel.

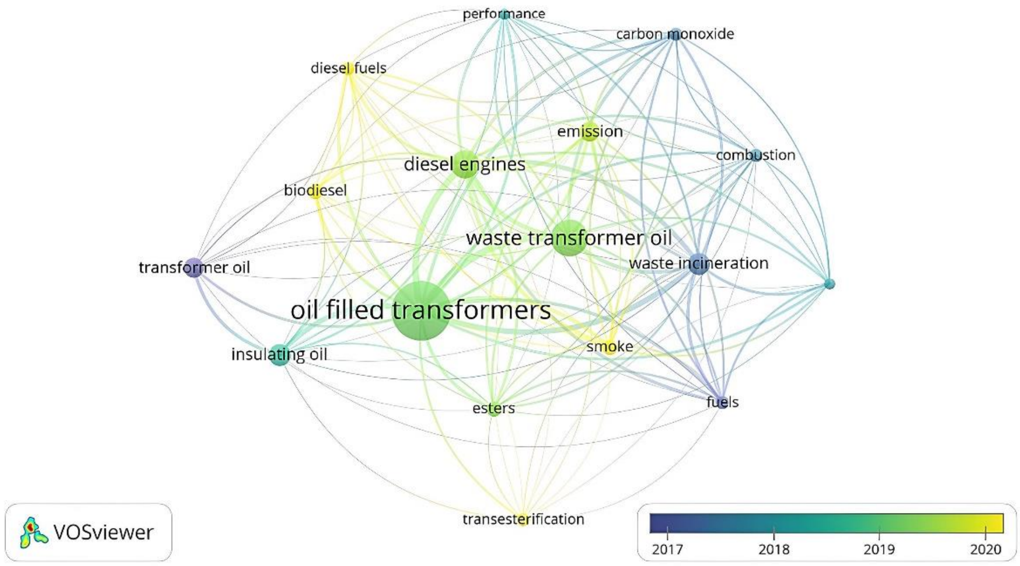

Figure 1 VOSviewer analysis based on Scopus database for WTO keywords

To address the challenges associated with using WTO, a modified burner device with compressed air was developed to reduce emissions by utilizing WTO blended with diesel fuel in various compositions. A burner with a secondary air supply into the combustion system was fabricated to ensure clean combustion of WTO in diesel fuel. Incomplete combustion can produce CO gas and black smoke plumes, stemming from WTO material containing n-paraffin compounds with varying degrees of oxidation depending on the carbon chain chemistry [26]. To overcome this issue, a modification of the compressed air supply model was developed, where combustion with excess O_2 gas supply assists in the combustion of the diverse carbon chains present in WTO, resulting in complete combustion (CO_2 and H_2O) [27]. This study presents the design and performance test of a developed burner system equipped with compressed air to utilize waste transformer oil as an alternative fuel. The key findings of this research include the utilization of WTO as sustainable fuels, the model burner system, and the performance evaluation WTO combined with fuels. This paper provides a schematic model of the design, construction, and performance test to demonstrate the successful utilization of WTO, resulting in different flames and heat generation.

2. Materials and methods

This research refers to primary and secondary data approaches based on the reverence database from Scopus (VOSviewer) to observe the urgency of this research (Figure 1) and secondary data from Rajan et al. to complexify scientific studies [28]. Experimental engineering approaches such as modeling the combustion system were developed, cost estimation was adjusted in Indonesia, and the utilization of WTO as an environmentally friendly fuel was applied.

2.1 Material feedstocks

This research endeavors to construct and advance a burner system specifically designed for utilizing WTO blended with diesel oil (B30) as a prototype for the development of environmentally friendly industrial fuel. The WTO utilized in this study was sourced from a prominent mining company, PT. ANTAM, Tbk., located in Kolaka, Southeast Sulawesi, Indonesia. The retrieval of WTO involved the identification of irreparable transformers and the extraction of unused oil. To enhance the quality of the WTO, a decanting process was employed to obtain oil free from impurities and water, ensuring its suitability for the intended application.

2.2 WTO burner development

The burner was fabricated using a cylindrical metal combustion chamber with a diameter of 25 cm. The airflow into the combustion chamber is regulated by a damper positioned within the supply pipe, and this air supply is facilitated by a compressor. Initially, about 100 cc of diesel fuel is poured into the base of the burner and ignited to initiate the heating of both the fuel and the air pipe within the burner. This process is essential for vaporizing the fuel injected from the burner, ensuring complete combustion, and adhering to the fundamental combustion principle of liquid fuel in any burner type, with appropriate oxygen supply from a blower. The burner was conceived as a small-scale thermal production technique for the efficient utilization of waste materials. The technological innovation developed is the ability to adjust capacity to control the fuel-air ratio within the muffler controller and the secondary air supply at the top of the burner. These modifications allow for the optimization of heat production and emissions gases. Data collection is performed once the fuel combustion has stabilized. For a visual reference, the developed burner is presented in Figures 2 and 3.

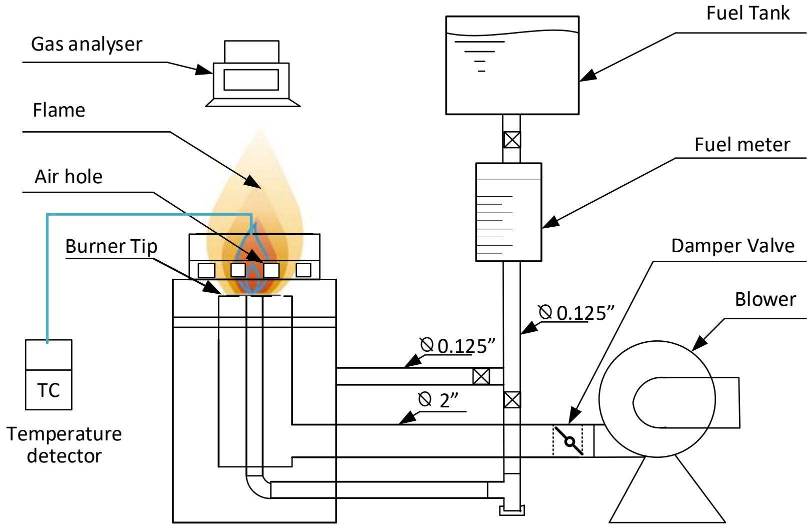

Figure 2 A schematic view of the developed burner system

2.3. Performance evaluation of the burner

The burner's performance was evaluated during each combustion trial by adjusting the volumetric airflow rate while maintaining a consistent fuel consumption rate. The combustion temperature was monitored using a K-Type thermocouple located at the tip of the burner, and emissions were recorded with a gas analyzer (IBRID-MX6) placed above the flame. Additionally, the fuel consumption rates were documented for each fuel composition and damper position. To measure fuel consumption on the burner, a flowmeter and stopwatch were utilized during the combustion process. The innovative burner equipped with air pressure was constructed and tested for the combustion application of WTO and diesel fuel in various phases of fuel compositions.

3. Results and discussion

3.1 Physicochemical of waste transformer oil

In this research, the WTO was obtained from a power plant and subjected to settling and filtration processes. Transformer oil (TO) gradually loses its insulating properties over time, rendering it unusable and necessitating proper disposal. Typically derived from petroleum, TO exhibits robust and stable electrical insulation properties at elevated temperatures, serving as a cooling, insulating, and moisture-protecting agent. When TO is no longer suitable for its intended purpose, it demands careful management, as it may contain contaminants or pollutants harmful to the environment and human health if disposed of improperly. In this study the WTO was repurposed to create a safe and valuable fuel product.

The WTO consists of chemical compounds that include a benzene ring and a lengthy active carbon chain ($C_{12}H_{26}$), endowing it with properties akin to diesel fuel ($C_{12}H_{23}$). Moreover, its cetane number is marginally higher than that of diesel fuel. Notably, Rajan et al. [28] reveal that WTO possesses notably higher viscosity, approximately four times that of diesel fuel. This higher viscosity requires a complementary use of diesel fuel to enhance the heat generated by WTO. Table 1 presents the findings of Rajan et al. [28], elucidating that WTO's properties tend to surpass those of diesel fuel because it is influenced by the cetane number value which is similar to diesel fuel. Therefore, there is a compelling need for a comparative study exploring various applications of WTO in conjunction with diesel fuel as an alternative source of energy.

Table 1 Properties of WTO and diesel by Rajan et al. [28]

Properties	Testing Method (ASTM)	Diesel	WTO	WTO30
Density @15°C (kg/m^3)	D1298	830	890	850
Kinematic viscosity at 40°C (cSt)	D445	2.6	11	5.0
Flash point (°C)	D92	52	144	89
Fire point (°C)	D92	60	152	96
Gross calorific value (kJ/kg)	D240	42500	40000	41750
Calculated cetane index	D976	48	53	50

3.2 The economic feasibility of a developed burner system

The burner design illustrated in Figure 3 comprises simple components, including an oil tank, fuel regulator, damper, air compressor, fuel and air connecting pipes, and a burn point. The tool's design utilizes recycled materials, such as cylindrical iron pipe frames connected through a welding process. The design ensures a 70 cm distance between the wind pump and the combustion system to reduce heat transfer from the combustion system. Positioned above the pump are a fuel tank and a fuel indicator. The combustion mixture is directly fed into the fuel tank, allowing the tool to be flexible and accommodate various types of fuels. This device was fabricated with a low-cost estimate, encompassing specific circuit requisites such as iron pipes, fuel tanks, fuel meters, and compressors. The estimated cost of constructing this burner, which measures 1.5 cm × 0.5 cm and boasts a 5-liter fuel tank capacity, is US$289, with detailed information provided in Table 2. The findings from the cost analysis of the developed burner system hold great significance in estimating the feasible cost for the community to manufacture an environmentally friendly burner. The entire set of equipment was assembled to optimize the combustion process using WTO. The role of the compressor is pivotal as it ensures the efficient distribution of clean air to the burner system, thereby augmenting the supply of oxygen (O_2) during the combustion process.

Table 2 Cost estimation for economy feasibility of burner system

Components	Materials	Total of requirements	Cost estimation
Burner Air line Fuel line	Pipe (diameter of 0.1 inch – 2.0 inch)	4 meters	32$ USD
Fuel Tank	Aluminium plate	2 meters (200 cm × 50 cm)	32$ USD
Fuel meter	GPI Aluminium Turbine Fuel Meter	1 unit	22$ USD
Damper	Fire damper control	1 unit	38$ USD
Compressor	Wind blower	1 unit	100$ USD
Manufacturing cost	Welding, design, operation		65$ USD
Total estimation cost			**289$ USD**

Figure 3 The original view of a developed burner system

3.3 Flame characteristics

The performance of combustion process has been examined from various WTO content combined with B30 diesel. Figure 4 shows the flame produced with various WTO and B30 fuel blends under fully open-throttle damper conditions (10%, 20%, and 30%). The composition containing 30% WTO/B30 produced a higher and more uniform flame during combustion when compared to 10% and 20%. The higher the WTO composition in the fuel, the better the flame produced by the burner. Several studies have concluded that higher WTO content in diesel fuel reduces the quality of the flame produced by the burner. In fact, it provides a real experiment with 30% WTO in Diesel B30 giving a very large flame. This is also aligned with the research by Rajan et al. [28] explaining that 30% WTO is very good for producing an optimal flame. This factor can also be influenced by the thrust of the compressor to supply clean air into the burner system. The rotational speed of the compressor fan of 2800r/min is considered in the combustion process. Chemically, the addition of WTO in B30 diesel fuel will also affect changes in cetane value, either by increasing or decreasing the cetane value. The cetane number in WTO refers to a measure of the combustion quality of fuel in diesel engines to ensure that this alternative fuel can be used safely, efficiently, and environmentally friendly in the combustion process. The processing and refurbishment of used transformer oil needs to consider increasing or maintaining the cetane value in order to meet quality standards [28]. The addition of hydrocarbon compounds to the fuel affects the quality of the flame and the air supply is increased to reduce the soot produced due to incomplete combustion.

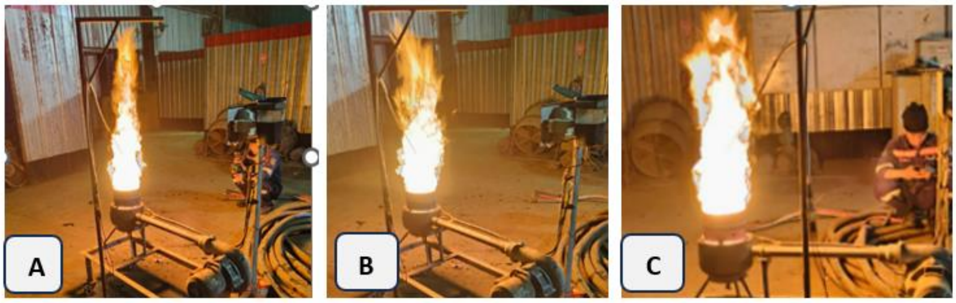

Figure 4 Combustion flame of fuel with various compositions of WTO in diesel fuel; (A) 10% WTO/B30, (B) 20% WTO/B30, and (C) 30% WTO/B30

The influence of the air supply on the flame process was examined to validate the role of air in shaping the flame. As depicted in Figure 5, the experimental results depict the flames generated by the burner under varying blower throttle damper settings—specifically at 50%, 75%, and 100%—while utilizing a 30% WTO/B30 blend. These outcomes underscore that the quantity of airflow directed to the burner significantly affects the flame's characteristics. Notably, when the throttle damper is opened wider, it leads to the production of a more robust flame. The blower throttle damper operates as a valve designed to regulate the airflow directed toward the burner. Consequently, the wider the throttle damper opening, the greater the volume of air entering the burner, thereby increasing the oxygen available for combustion. This augmentation of available oxygen facilitates more comprehensive combustion, resulting in enhanced energy production and reduced exhaust emissions. This observation emphasizes the imperative need for an adequate air supply to enable complete combustion.

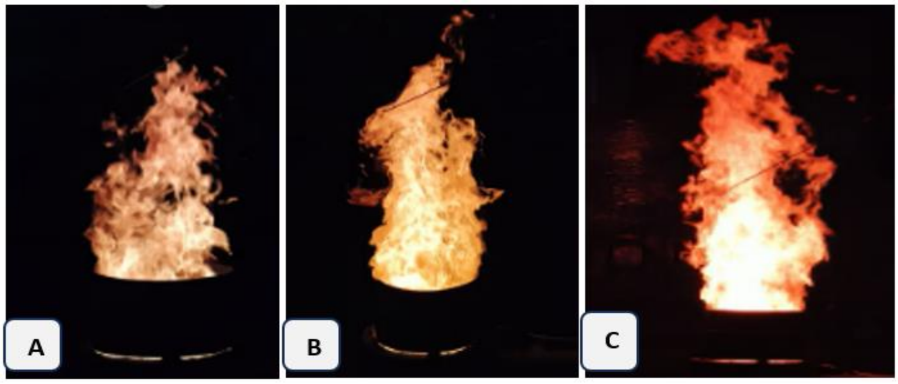

Figure 5 Combustion Flame of fuel at various supply of air into the combustor using 30%WTO/B30, (A) 50% open throttle, (B) 75% open throttle, and (C) 100% open throttle of the damper

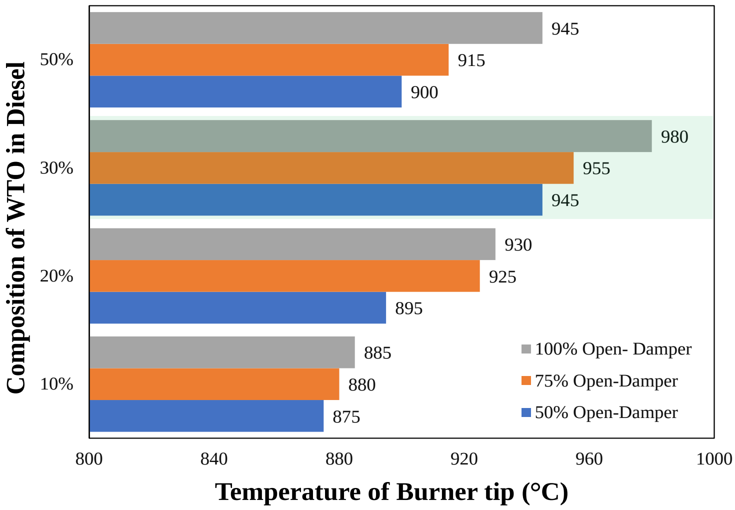

Figure 6 Maximum temperature generated on the burner

3.4 Temperature of combustion

The effect of WTO composition in diesel fuel and the degree of damper openness on combustion temperature is illustrated in Figure 6. Burner tests were conducted using fuel blends consisting of 10%, 20%, 30%, and 50% WTO in diesel, with varying degrees of damper valve openness set at 50%, 75%, and 100%. The results showed that the maximum temperature was achieved with a 30%

WTO/B30 blend, followed by 20%, 50%, and 10%. The 10% and 50% WTO/B30 blends produced similar results for 75% and 100% wide open valve positions, but the 50% wide open valve position resulted in higher temperatures. These findings indicate that the addition of WTO improves combustion performance such as for diesel fuel or combustion performance. The optimum combustion temperature was characterized by 30% WTO composition in diesel fuel with air supply increasing by 100% damper openness. The 30% WTO/B30 blend produced the highest combustion temperature among all the blends tested.

The fuel consumption rate was identified to observe the fuel efficiency using WTO and 30B diesel. Table 3 displays the fuel consumption rate during combustion for various compositions and openness levels of the damper valve. The results show that as the proportion of WTO in diesel increases, the fuel consumption rate decreases. The same trend is also seen with increased valve openings for 10% and 20% WTO/B30 blends, but the wide-open damper variation is not significant for 30% and 50% WTO/B30 compositions.

Table 3 The fuel consumption rate of the burner during combustion

Damper Valve	**Consumption Rate of WTO in Diesel Fuel Blended (mL/sec)**			
	10%	**20%**	**30%**	**50%**
50% Open-Damper	1.03±0.028	1.16±0.019	1.63±0.023	1.03±0.011
75% Open-Damper	1.17±0.028	1.27±0.018	1.36±0.021	1.17±0.023
100% Open-Damper	1.24±0.022	1.74±0.030	1.24±0.019	1.24±0.021

3.5 Emissions of combustion

Figure 7 displays the carbon monoxide (CO) emission resulting from the combustion of blended fuels with varying compositions of WTO in diesel fuel (10, 20, 30, and 50% BTO/B30 by volume). This study employed air flow into the burner with the damper valve set at 50%, 75%, and 100% open-throttle positions. The experimental finding revealed that the blend of 30% BTO/B30 resulted in lower pollution emissions at all open-throttle valve positions during combustion. The Highest CO emissions, reaching 20 mg/L, were observed at 50% open-damper position, indicating a lack of oxygen in the fuel. Other emission gases such as NO_2, SO_2, and H_2S were not detected. Fortunately, the CO emissions resulted from all experiments are still below the Indonesian standard for CO emissions, which allows for a maximum of 25 mg/L for CO emissions [29].

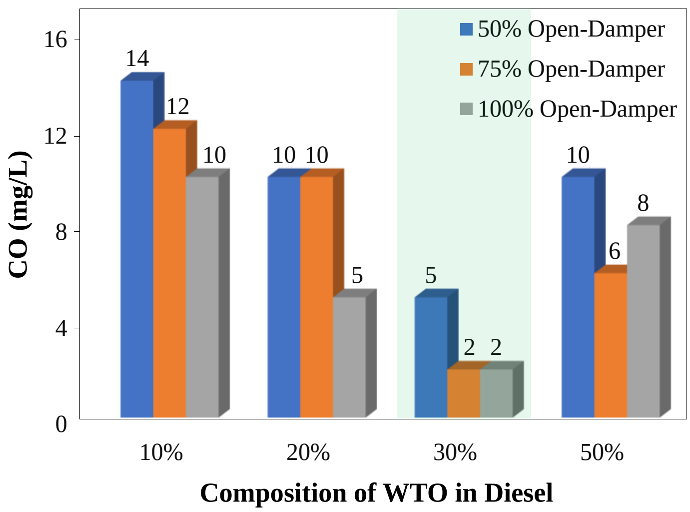

Figure 7 Emission of CO at different composition of WTO in Diesel fuel

The addition of WTO to fuels is an effective way to learn about the combustion process in biofuel engines. The unique research by Shelare et al. [30] explains that additives such as WTO has the potential to improve biodiesel fuel properties, to create favorable economic environment, and to develop policies that encourage biodiesel fuel production. In addition, this utilization can be simulated in valuable internet of things, artificial intelligence and machine learning technologies to optimize effective fuel production processes. These advancements can help promote WTO and fuel as a cleaner and renewable energy source, thereby lowering fossil fuel consumption. This research suggests that further development of biofuels can improve efficiency, expand feedstock options, create policy support, develop infrastructure, and increase public awareness.

Based on Table 4, which summarizes the research related to the utilization of WTO for fuel based on Scopus data, 12 validated and credible papers were obtained. The background of the main study is the reuse of WTO oil that is combined with diesel fuel so that they can synergize to produce environmentally friendly fuel for diesel engine use. The utilization of WTO as a diesel engine fuel has been widely studied by several researchers as a mixture to reduce combustion emissions. Based on the results of the study by Sethuraman et al. [31], it was found that WTO leads to a decrease in emissions from biodiesel materials. In addition, Prasanna Raj Yadav et al. [32] explains that increasing fuel injection will reduce emissions. Therefore, the relevance of the study in this research is that increasing the clean air injection in the burner system will result in a reduction in the level of emissions produced. A good ratio for blending WTO with diesel fuel is between 20-30% to optimize the combustion process.

Table 4 The novelty of this research compared with the several papers

No.	Research Aims	Research Finding	Years	Ref.
1	WTO is used as a diesel fuel aimed at waste utilization and reducing diesel fuel costs.	TWTO-diesel blending in diesel engines improves performance and combustion process. In addition, CO, smoke, and NOX gas emissions were in good agreement with B25 and diesel.	2020	[23]
2	Utilization of waste-derived fuel (RDF) with waste transformer oil (WTO) as diesel fuel.	There is both brake thermal and mechanical efficiency using RWTO blends. Combustion results also showed higher levels of CO, NO, HC, and CO_2 emissions. They suggested modifying the engine and adding additives.	2021	[33]
3	Improved performance of Transesterified Waste Transformer Oil-25 (TWTO25) blends with high fuel injection pressure in diesel engines.	The use of 22-88MPa injection pressure resulted in a 6.67% increase in brake thermal efficiency and a decrease in CO, HC, and smoke emissions.	2022	[32]
4	Separation of water in transformer waste oil with natural adsorbent of waste tea factory.	WTO showed that it contains water and needs to be purified with natural adsorbent (waste tea factory) if used as fuel, giving a water removal percentage of 98.6%.	2022	[34]
5	Utilization of WTO as a fuel in diesel fuel by analyzing its physiochemical properties.	They found that the brake thermal efficiency of the WTO blend was 20% WTO with a brake specific fuel consumption in the range of 0.30KJ/Kwhr.	2022	[12]
6	Role of heterogeneous trans-esterification catalyst from coconut shell activated carbon to produce biodiesel from used cooking oil, WTO, and methanol.	A comparison between waste cooking oil and waste transformer oil showed that WCO tended to perform better in the engine test. WCO40 is better than WTO20 with low emissions of HC, NOx, and smoke.	2023	[31]
7	Utilization and quality improvement of waste electrical transformer oil through pyrolysis-catalyst process to achieve low exhaust emissions.	Blending WTO with a variety of ZnO and CeO_2 catalysts reduces the high exhaust pollutants when using only WTO in diesel fuel.	2023	[11]
8	The utilization and exploration of waste transformer oil (WTO) combined B30 for fire combustion performance.	The burner can achieve the maximum combustion temperature of 979°C, which was achieved with a combustion mixture comprising 30%WTO/B30	2024	This Study

4. Conclusion

The WTO burner has been developed to utilize waste of transformer oil as a substitute fuel for Biodiesel Fuel (B30) in various thermal and heat applications. The results show that the developed burner can effectively combust the WTO in diesel fuel with low emissions production. Secondary air introduced to the burner can enhance the combustion system of the fuel. The burner can achieve the maximum combustion temperature of 979°C, which was achieved with a combustion mixture comprising 30%WTO/B30 (by volume). The economic feasibility of the developed burner system is very useful, and it is inexpensive to be developed at household or industrial scales with the estimation cost of US$289. In addition, the CO and CO_2 emissions from the fuel burner meet industry standards when the damper is open between 50% and 75%. This damper setting also affects fuel consumption during the combustion process. An effective combustion system should identify the amount of acid number, water, and viscosity. The effectiveness of this combustion system must also consider the acid number, water, and viscosity of the fuel which can affect the combustion process and the effect of soot generation. This research supports efforts to utilize waste transformer oil as a sustainable alternative fuel that can reduce the use of fossil fuels.

5. Acknowledgments

The support of the Mechanical Engineering Laboratory of Engineering Faculty, Universitas Halu Oleo, and PT. Aneka Tambang, Kolaka, Indonesia are all gratefully acknowledged.

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