Egyptian Sugar Journal (2022), 19: 44 - 59
https:// doi.org/ 10.21608 / esugj. 2022.158636.1020

RESEARCH ARTICLE

Experimental investigation of the effects of using biofuel blends with conventional diesel on the performance, combustion, and emission characteristics of an industrial burner

Medhat Elkelawy[1], Ali Kamel Abdel-Rahman[2], Ahmed Abou-Elyazied[3], Saad Mostafa El-malla[4]*

Received: 13 September 2022 / Revised: 10 December 2022 /Accepted: 12 December 2022 / Published online: 20 December 2022

Abstract

liquid biofuels are one of the most widely utilized today, bioethanol and biodiesel are essential to the development and advancement of the industry. In this research, an experimental investigation of the effects of biofuel blends with diesel on pollutant emissions and combustion characteristics of a 350-kW industrial burner. Tested fuel blends were D100, D50B50 (50% diesel and 50% biodiesel by volume), D50B50E15 (50% diesel, 50% biodiesel, and 15% bioethanol by volume), and D50B50E25 (50% diesel, 50% biodiesel and 25% bioethanol by volume). The equivalence ratio was adjusted to five values by varying the air flow rate and maintaining the fuel flow rate constant at 0.14 l/min.CO, HC, soot, and NOx were measured. Also, flame temperatures were recorded at different positions. The result indicates that utilizing the fuel blends D50B50, D50B50E15, and D50B50E25 reduces CO by (about 19, 69, and 65%), HC by (about 18, 37 and 28%), and smoke opacity emissions by (about 8, 50, and 30%) respectively, compared to diesel fuel. On the other hand, NOx emission significantly rises at D50B50E15 and D50B50E25. In terms of combustion characteristics. Biofuel mixture D50B50, D50B50E15, and D50B50E25 increase exhaust gas temperatures by (about 2, 3 and 1%), and maximum gas flames (about 5, 9 and 4%) respectively, compared to diesel. The ethanol percentage of more than 15% in the blends lowers the maximum flame temperature within the furnace and reduces the length and area of the flame. It is evident from this research that biofuel for industrial burners can produce optimum combustion characteristics and lower emissions.

Keywords: Biofuels; Industrial burner; Temperature; Emission.

Introduction

Due to the depletion of fossil fuels and their major negative impacts on the environment through emissions that affect human health, there is an urgent need to discover alternatives to fossil fuels, especially in the industrial sector, which requires energy-intensive consumption. One of the most promising fuels to replace conventional fuels is biofuel, such as biodiesel and bioethanol. The sustainability of biofuels and their use as a substitute for renewable energy sources is one of its most important advantages (Szulczyk and Tan 2022).

It is considered that finding a sustainable and renewable alternative to solve the production of part of the energy is a challenging and ambitious goal. To stabilize and control the price of energy, which affects the price of the finished product in industries that depend on energy during the manufacturing process, like the beet sugar industry, as well as the sharp rise in energy prices and the risk of conventional fuel depletion. The use of biomass-based fuels has the potential to reduce reliance on petroleum and decrease greenhouse gas emissions (Krishnan et al. 2022). Biodiesel and ethanol are liquid biofuels that are produced commercially.

Biodiesel is a liquid alternative fuel for diesel engines and industrial burner combustions, which is produced chemically from organic oils and fats and has similar properties to diesel fuel (Cerveró et al. 2008; Venu et al. 2019b). By 2025, biodiesel production is expected to exceed 41.4 billion liters, according to the organization for economic cooperation and development and the UN’s Food and agriculture organization (Tabatabaei and Aghbashlo 2018).

Biodiesel (Fatty Acid Methyl Esters) is a monoalkyl ester of long-chain fatty acids produced from renewable sources such as edible and non-edible vegetable oils, animal fat, and waste cooking oils by the transesterification process. Vegetable oils are composed of triglycerides, which are tri-esters consisting of three long hydrocarbon chains (fatty acids molecules) which may have up to three double bonds in each chain, with each chain also containing an ester group (RCO2R′) (Gerpen 2005).

---

[1] Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Egypt.
[2] Mechanical Power Engineering Department, Faculty of Engineering, Assuit University, Egypt.
[3] Horticulture Department, Faculty of Agriculture, Ain Shams University, Egypt.
[4] Faculty of Sugar and Integrated Industries Technology, Assuit University, Egypt.

*corresponding author : saad_pg1230149@sit.aun.edu.eg

By treating these compounds through transesterification, the triglycerides are broken down into smaller alkyl esters. In the transesterification process, the original molecular structure of triglycerides is changed to produce biodiesel. The goal of the conversion transesterification process is to reduce the viscosity of the oil.

The reaction with alcohol takes place in many consecutive, reversible reactions, and in this process, the fatty acids of vegetable oil exchange are placed with the (OH) groups of the alcohol-producing glycerol and methyl, ethyl, or butyl ester depending on the type of alcohol used (Pinto 2012).

The cost of production of biodiesel is one of the most significant barriers to the manufacture of biodiesel and its usage as an alternative fuel to replace traditional fuels in industries and transportation. Waste cooking oil is a key component in reducing biodiesel production costs by 60–90 percent. Talebian- Kiakalaieh et al. (2013).

Waste cooking oil is a major source of biodiesel fuel production, and it is produced locally wherever food is cooked or fried in oils. In many regions of the world, waste of cooking oil and fats generate waste problems Tashtoush et al. (2003). Waste cooking oil is considered the most practical source for biodiesel production. It not only reduces costs but also decreases waste disposal problems. Singh et al. (2021). By properly utilizing and managing waste cooking oil as a fuel substitute, these problems could be transformed into both economic and environmental benefits Mandolesi de Araújo et al. (2013). Several studies have been conducted to enhance the yield of biodiesel from waste cooking oil by optimizing the traditional alkali-catalyzed transesterification reaction factors Elkelawy et al. (2019). The main factors affecting the alkali-catalyzed transesterification reaction and biodiesel yield are the molar ratio, the type and quantity of catalyst, the reaction time and temperature, and the amount of free fatty acids (FFAs). Rashid et al. (2008). Phan and Phan (2008) investigated the effects of methanol/waste cooking oils ratio, potassium hydroxide concentration, and temperature on the biodiesel conversion from waste cooking oil WCO. The result shows that a Biodiesel yield of 88–90% was obtained at the methanol/oil ratios of 7:1–8:1, temperatures of 30–50Co, and 0.75 wt % KOH. Issariyakul et al. (2007) yielded up to 97% ethyl ester from waste cooking oil using a two-stage transesterification process that was acid and alkali catalyzed. (Leung and Guo 2006) produced biodiesel from the conversion of waste cooking oil using alkaline-catalyzed transesterification, and the maximum biodiesel yield is approximately 86%. There are several characteristics that biodiesel and conventional diesel fuel have in common. Furthermore, High oxygen-content biodiesel provides improved combustion properties and a higher cetane number compared with conventional diesel Elkelawy et al. (2022). Due to the comparable characteristics of biodiesel and petroleum fuels that allow them to be blended, biodiesel can be used in diesel engines and industrial liquid burners as a pure fuel or a blend with diesel fuel without requiring significant modifications (Ghorbani and Bazooyar 2012).

The general function of a burner is to maintain a consistent operation and an adequate flame pattern. under a specified set of operating conditions. Biodiesel combustion in an industrial burner is practical and achieves relatively higher results than conventional diesel combustion. Due to the oxygenated form of biodiesel, offers many advantages, including fewer exhaust pollutants (except for NOx emissions), higher temperature, and more complete combustion of the fuel Pourhoseini et al. (2021).

In an industrial burner system, several studies investigated the combustion and emission characteristics of biodiesel and diesel.

The findings revealed that carbon dioxide, carbon monoxide, and particulate matter emissions improved while nitrogen oxide emissions increased. Additionally, the temperature of the exhaust gas has also significantly increased, indicating that biodiesel has a strong potential for usage in industrial burners. Ahmad et al. (2020) investigated the performance and emissions of conventional diesel and biodiesel fuel mixes in a liquid fuel burner.

The results show that as the biodiesel content increased the emission Significantly reductions in CO and SO_2 emissions except for the NOx emission. Norwazan et al. (2018) investigated the characteristics of combustion and emission of jatropha oil biodiesel blends with diesel B5, B10, B15, B20, and B25 in swirl burner, they found that significant reduction in HC, CO_2, and CO emissions. conversely, NOx emissions for all blends of biodiesel were increased due to the high oxygen content in biodiesel fuel. B25 helps to significantly improve CO, SO_2, and UHC emissions by 42, 33, and 50% respectively. (Macor and Pavanello (2009) carried out an experiment on the performance and emissions of a pure biodiesel-fueled fire-tube boiler. When compared to diesel fuel oil, the results showed a reduction in CO and PM emissions and an increase in formaldehyde. Both fuels had relatively low volatile organic compounds (VOCs). Bioethanol is produced biologically by the fermentation of sugars derived from a variety of raw materials. Slathia et al. (2020).

There are three primary categories of raw materials:1- Sucrose-containing feedstocks (such as sugar cane, sugar beet, and fruits), 2-lignocellulosic materials (such as wood, straw, and grasses), and 3- starch-based materials (such as corn, wheat, rice, potatoes, and sweet potatoes).

Sugar beets provide an abundant source of sucrose which can be easily converted into ethanol by the industrial processes of molasses which is the by-product of the sugar beet production process. However, commercial ethanol production from sugar beets has not been implemented in most of the country. Bušić et al. (2018).

After sugar cane, sugar beet is the crop that is grown most extensively in the world to produce white sugar for human consumption. Sucrose is present in large amounts in sugar beet (between 16 percent and 20 percent on a fresh weight basis) (Garcia Gonzalez and Björnsson 2022).

The sucrose-based substrates of sugar cane and sugar beet have several advantages, including being comparatively plentiful and renewable. Molasses, a non-crystallizable residue of a byproduct of sucrose purification is the last byproduct created during the process of producing sucrose by repeatedly evaporating, crystallizing, and centrifuging the juices from sugar cane and sugar beets. Molasses is easily fermented by yeast to make ethanol and is a commonly available, competitively priced raw component (Ergun and Ferda Mutlu 2000). Molasses is one of the main raw ingredients utilized to produce industrial ethanol through fermentation. Non-crystallized syrup Molasses makes up to 50% of the sugar generated from sugar beet processing. Duraisamy et al. (2017).

The global market for bioethanol production was 110 BL (billion liters) in 2018 and is predicted to increase to 140 BL in 2022 Sharma et al. (2020). Bioethanol may be used as blends with diesel without modification of industrial burner. It also contains a high amount of oxygen, which aids in combustion. El-Sheekh et al. (2022).

Few research has been conducted on the practical application of biofuel blends with diesel in the industrial aspect, such as the industrial burner used in furnaces. Despite the need to develop an alternative biofuel due to the depletion of traditional fuel reserves and the harmful emissions from it. Asfar and Hamed (1998) investigated the performance and emission of conventional diesel and bioethanol fuel blends in a continuous-flow combustor.

They found that blending alcohol with diesel results in improved combustion quality, a reduction in pollutants emission and soot mass concentration in the exhaust, as well as a minor rise in NOx emissions. Beyond 10%, the amount of alcohol in the mixture does not appear to enhance combustion or further reduce pollutants and soot. Prieto-Fernandez et al. (1999) investigated the combustion performance and emission of a water-cooled combustion furnace fueled with different ratios of light diesel and ethanol blends. The results show that the amount of unburned gas hydrocarbons and solid particles in the exhaust gases is decreased when ethanol is added to light oil. Contrarily, adding up to 15% of ethanol to light oil causes a minor reduction in the production of nitrogen oxides, but at higher ethanol percentages, nitrogen oxide emissions exceed that of pure light oil. Barroso et al. (2010) studied the numerical and experimental performance and emission of using bioethanol or its blends with gas oil in heating or industrial boilers. Combustion tests demonstrated significant differences between bioethanol and gas oil. Soot, NOx, and SO_2 emissions are significantly lower with ethanol, whereas this fuel can produce higher amounts of CO. The burner and boiler operation should be readjusted or modified as a result of the change of fuel and also the results showed that the switch to bioethanol is technically feasible and has some benefits for reducing pollution. Switching the fuel in the boiler can affect how heat is transferred, which has an impact on how much steam can be produced. Due to the poor heating value of bioethanol, the proportion of gas oil in the blend should not be less than 50% to maintain the production of useful heat at acceptable levels. Motamedifar and Shirneshan (2018) used a variety of radial air swirlers connected to a cylindrical combustion chamber to study the effects of biofuel blends with conventional diesel on emission and combustion characteristics. There were six different types of air swirlers, each with a different vane angle (15°, 25°, 35°, 45°, 60°, and 90°). According to the findings, the lowest CO, HC, and NOx emissions were produced at swirl numbers of 15°, 45°, and 60°, respectively. The lowest CO2 emissions were found at swirl air vane angles of 35° and 90°. The results showed that the mean temperature of combustion gas increases when the percentage of biodiesel in the fuel mixture increases and decreases when ethanol is blended to the fuel mixture.

The findings demonstrate that the proper design of the air swirler has a significant impact on the mixing process, and consequently on combustion and pollution. Choi et al. (2016) nvestigated the effect of blending biocrude and ethanol on flame stability and emission characteristics by using a 30,000 kcal/h burner system .They found that a stable flame could be achieved with up to 90% bio-crude oil.CO emissions in bio-crude-oil/ethanol blends were lower than in pure ethanol, whereas CO concentration in pure bio-crude-oil increased significantly due to incomplete combustion. The pollutant NO emissions increased as the bio-crude-oil mixing ratio increased. Researchers and industrial institutions are working to meet the growing demand for alternative fuels made from commonly available renewable elements such as waste cooking oil and fermentation processes for sugar industry byproducts such as molasses, and to use them as an important source of energy production and pollution reduction due to the lack of reserves and the high price of fossil fuel. The present research aims to compare diesel fuel and biodiesel fuel derived from waste cooking oil WCO, its blends with diesel, and bioethanol fuel in terms of how they affect the combustion and pollutant emission characteristics in industrial oil burners installed in boilers or furnaces in an attempt to contribute further knowledge in this field. Additionally, the present study has focused on utilizing biofuels with diesel in industrial burners. The experiments were carried out at varying equivalence ratios of 0.6, 0.7, 1,1.4, and 1.6. The presented data shows include the emissions of Co, HC, soot, and NOx. Also, the temperature to identify the combustion characteristics within the flame zones. In the case of biofuel blends with diesel, experimental findings demonstrated acceptable and effective results in reducing emissions, except NOx, and enhancing combustion performance when compared to conventional diesel fuel.

Experimental test setup

Figures 1 and 2 show a schematic diagram of the arrangement. A laboratory-scale furnace is designed and built to study chemical reactions to react multi biofuel by an industrial burner and to investigate the reaction flow, flame, and exhaust that works in the combustion system.

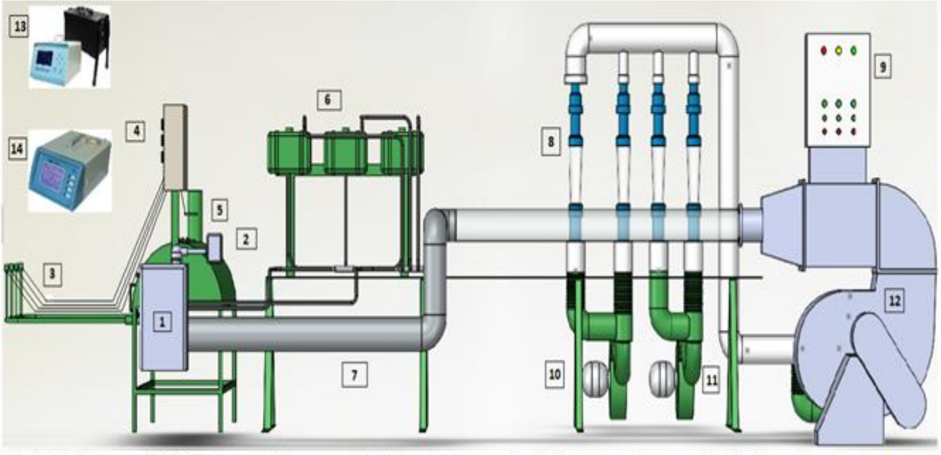
All experiments were conducted in a horizontal steel test chamber coated on the inside with refractory bricks and using a swirl atomizer type diesel oil fuel burner

(CUENOD, France Manufacturing) with a maximum heat capacity of 350 KW. The burner used for the experiment was housed within the chamber at its center and the front. The furnace had a length of 1500 mm and a diameter of 500 mm. The wall of the chamber contained a movable window measuring 96 cm x 25 cm to allow optical access and is provided with four measuring holes at equal distances for measuring temperature with a thermocouple, each having a diameter of 2.5 cm. They were 0, 0.3, 0.6, and 0.9 meters apart from the burner's inlet. Radial temperature profiles were measured at three axial locations, 25%, 50%, and 75% of the visible flame height. A chimney was also installed at the end of the furnace, measuring 2500 mm in length and 12.7 mm in diameter, to suck and exhale the combustion products. A burner blower and three independent blowers with an air intake pipe and an orifice meter for airflow measurement make up the combustion air supply system. The air blower's flow rate is regulated by valves and an on/off electronic control panel, and the fuel was fed by gravity from three tanks above the burner and a fuel pump that is operated by the burner's motor.

The fuel flow rate was maintained constant at 0.14 liters per minute while the airflow rate was changed to create five different equivalent ratios. R-type thermocouple with a wire diameter of 0.12 mm and a bead diameter of 6 mm and a length of 70 cm was used to measure the flame temperature profiles.

On a multi-dimensional linear traversing mechanism, four thermocouples were placed.

In addition, R-type thermocouple installed in the exhaust pipe was used to record the exhaust temperature. Temperature data was collected with the use of a controller. A guided traverse mechanism was used to position this thermocouple along the length of the flame. To provide an overall view of the temperature in the flame environment, temperature profiles were collected at various axial and radial positions in the flame. Temperature values were recorded averaging over 60 seconds, with losses for radiation, conduction, and convection taken into account.



1-Industrial burner. 2-A laboratory-scale furance. 3-A R-type thermocouple. 4-Thermocouples panel. 5-Exhaust temperature sensor. 6-Fuel system. 7-Air pipe lines. 8-Rotameters. 9-Electric motors control panel. 10,11,12-Electric motors. 13-Opacity meter. 14-Emission gas analyzer.

Figure 1. A schematic diagram of the test rig

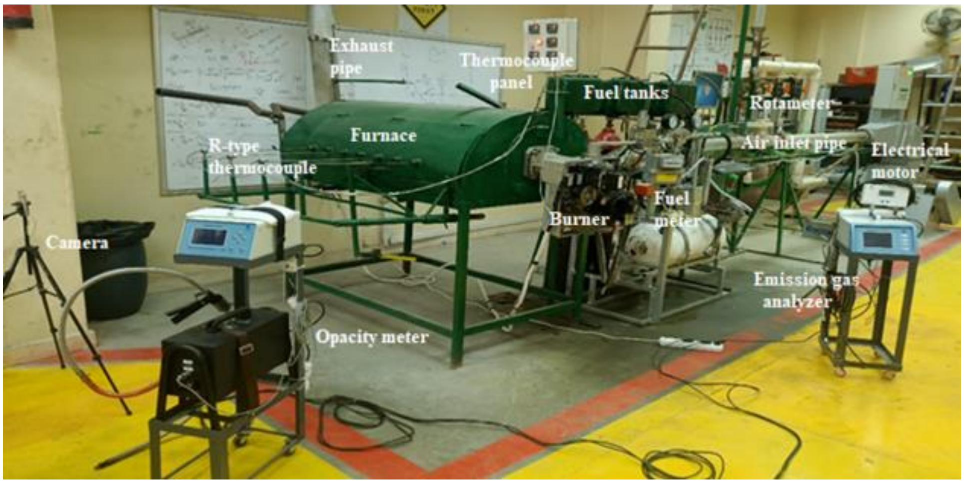


Figure 2. Direct photo of the testing apparatus in the laboratory

Garboard—5020 emission gas analyzer can be used for measurement of the concentration of emission gas CO, CO2, HC, O2, and NOx. Gasboard-6010 Opacity Meter provides a simple and accurate way to detect and measure the opacity of smoke emitted from the burner. This model can measure the complete opacity spectrum from 0-100% in either continuous or free acceleration tests.

The levels of emissions and combustion performance of D100, D50B50, D50B50E15, and D50B50E25 were all measured. The experiment began with diesel fuel being used to bring the burner to a steady state. The fuel was then changed to a new type of fuel without interrupting the burner's operation. The burner was turned on for long enough to guarantee that the fuel had been flushed out of the system and that a steady state with another fuel had been attained.

Analysis of Experimental Uncertainty

The instruments and sensors used in experiments cause some errors in the experimental result, so the uncertainty analysis was performed to ensure the accuracy of the results. Many variables affect uncertainty. The repeatability of experiments and the accuracy of the apparatus are the two most influential factors. Uncertainty calculations focused on burner operating parameters such as the flow rate of fuel and flow rate of air as well as an emission (CO, UH, smoke opacity, NOx, and temperature. Tables 1 and 2 present data on the experimental value range and precision of instrumentations and sensors. The root-sum-squared (RSS) method was used in this study to determine the uncertainty of the independent variables of the errors associated with the measured parameters (Moffat 1988). Equations 1 and 2 are used to compute the mean value and standard deviation of the data (Chen et al. 2012) (Ratel et al. 2015).

$$\bar{X}=\frac{1}{n}\sum_{i=1}^{n}X_i$$

(1)

$$\sigma_i=\left[\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i-\bar{X}\right)^2\right]^{\frac{1}{2}}$$

(2)

mean value of output measured data, n number of the repeatability of the experiment for measured data (dimensionless). X measured output data. is the standard deviation of measured data (Chacko and J 2020).

The uncertainty equation for independent parameters was calculated by equation 3 as follows (Vijayaragavan et al. 2022):

$$W_x=\pm\frac{2\sigma}{\bar{X}}\times 100$$

(3)

The overall uncertainty (WR) of the dependent variable quantity based on its functional relation to the independent parameters, measured by the sensors and instruments was determined using equation 3 below (Moffat 1988). (Pourhoseini et al. 2021)

$$W_R=\left[\left(\frac{\partial R}{\partial x_1}W_{x_1}\right)^2+\left(\frac{\partial R}{\partial x_2}W_{x_2}\right)^2+\dots\dots\dots+\left(\frac{\partial R}{\partial x_n}W_{x_n}\right)^2\right]^{1/2}$$

(4)

Where R is the function uncertainty, WR is the dependent variable total of uncertainty. Wx1, Wx2, and Wxn are the uncertainties of the independent variables of experimental operating parameters measured X1, X2,... ., Xn.

Table 1. specification of measurement equipment.

Specifications of Gasboard-5020 gas analyzer

	Range	Accuracy	Resolution
CO	0-10%	Rel ±3% Abs ±0.06%	0.01%
HC	0-9999 ppm	Rel ±5% Abs ±12 ppm	1 ppm
NOx	0-5000 ppm	Rel ±5% Abs ±25 ppm	1 ppm
Specifications of Opacity Meter Gasboard-6010			
K-value	0-100%	±3%FS	0.01%
Specifications of R-type thermocouple			
R-type thermocouple.	0-1600 C°	0.25%	1.5 C°
Specifications of Rotameter			
Air flow sensors	18-180 m3/hr		±6%

Table 2. Specification of liquid fuel meter type aquametro VZO 8**.**

Type	liquid fuel meter type aquametro VZO 8
Maximum Flow Rate Qmax l/h	200
Nominal Flow Rate Qn l/h	180
Minimal Flow Rate Qmin l/h	4
Approx. Starting Flow Rate l/h	1.6
Maximum Permissible Error	±1% of Actual Value
Repeatability	±0.2%
Smallest Readable Amount: l	0.01
Registration Capacity m^3	1 000

Experimental fuel.

Waste cooking oil biodiesel (WCOB) production and fuel preparation.

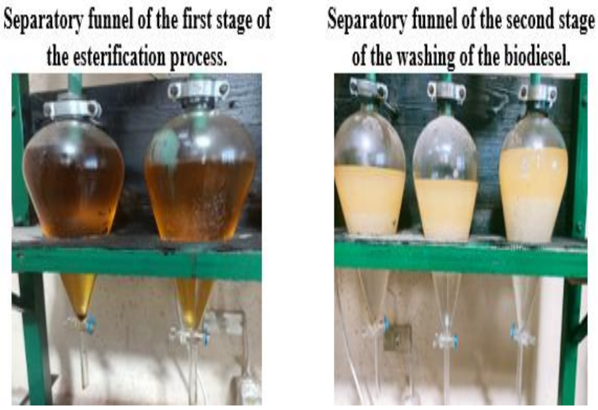
The procedure of WCO biodiesel production is divided into two steps, the first of which involves reaction and the second of which involves washing (Elkelawy et al. 2019) as shown in figure 3. The first stage of the production of waste cooking oil WCO biodiesel from waste oil involved the esterification process using 1% alkaline catalyst (NaOH) on a mass basis of the crude oil was utilized with methanol to the molar ratio of 6:1 (Kumaran et al. 2014) and was pre-mixed with methanol by a mechanical stirrer to create sodium methoxide and water, this mixture was then put to a reacting tank to be mixed with waste cooking oil using a mechanical homogenizer to undergo a transesterification reaction at 600 rpm. The transesterification process's reaction temperature was adjusted to 65:70 °C to prevent methanol vaporization during the biodiesel production process (Subramani and Venu 2019). The transesterification process reaction took 60 minutes to complete. Elkelawy et al. (2020; Topare et al. (2022).

In the second stage, after the esterification process was completed, the reaction oil was poured into a separator funnel for 24 h to separate into two layers, biodiesel, and glycerol, by keeping it motionless due to the difference in density between these two compounds (Venu et al. 2020). The washing of biodiesel that has exited the transesterification reactor with water neutralizes the catalyst and converts any remaining soaps into free fatty acids. The biodiesel is washed with water in a volume ratio of 1 to 1 with stirring for 1 minute and heated to a temperature of 80 to 100, and the washing is repeated about 3 to 4 times. The washed biodiesel product is dried to reduce the water content to an acceptable level for biodiesel standards (Balat 2007; Pinto 2012).

Product yield percentage is defined as the weight of the finished product (biodiesel) relative to the weight of waste cooking oil, as shown in equation 5.

$$\text{Product yield (\%)} = \text{weight of waste cooking oil}/\text{weight of the final product (biodiesel)} \times 100 \qquad \textbf{(5)}$$

Several process variables, including catalyst concentration, the methanol-oil molar ratio (MR), and reaction temperature, were optimized to determine the highest output of biodiesel from waste cooking oil. In lab experiments, The highest yield of 90 wt% was recorded for was achieved at a volumetric methanol-to-oil ratio of 0.25:1 and a weight catalyst concentration of 1% for 65 °C and 600 rpm of a mechanical homogenizer and the time of The transesterification process reaction 60 minutes.



Separatory funnel of the first stage of the esterification process.

Separatory funnel of the second stage of the washing of the biodiesel.

Figure 3. Photo of the first and second stages of biodiesel production

The electric stirring process is used to mix for more than 2 hours to make a mixture of biofuels and diesel. First, biodiesel mix with diesel fuel at a 50:50 volume ratio. Then, two different ratios of bioethanol were added: 15 and 25% by volume in the mixture. They were mixed inside a completely closed tank, and the mixture was stirred by an electric motor for two hours at a constant speed of 500 rpm to ensure good mixing. This process resulted in no separation of the fuel mixture, as shown in Figure 4, and the mixture fuel was burned directly in the industrial burner.

Figure 4. The sample of mixture biofuels D50B50E15

At the National Research Centre (NRC-Dokki), Egypt, the properties of diesel, D50B50, and bioethanol characteristics of the tested fuels were measured by ASTM standards as given in Table 3

Table 3. The properties of diesel D100, biodiesel-diesel blend fuel D50B50, and bioethanol.

Experiment	Method	Standard Limits	Diesel D100	D50B50	Bioethanol E
Density @ 15.56 °C	ASTM D-4052	0.86–0.9	0.8370	0.8604	0.8926
Kinematic viscosity, CST @ 40° C	ASTM D-445	1.9 – 6.0	4.38	3.73	2.24
Total sulfur, wt %	ASTM D-4294	Max 3%	0.231	0.129	0.697
Total acid number, mg KOH/g	ASTM D-664	MAX 0.50	0.056	0.522	1.868
Pour point, °C	ASTM D-97	-15 to -16	0	0	<-42
Ash content, wt.%	ASTM D-482	0.010 - 0.180	Nil	0.060	0.073
Cetane index	ASTM 4737	Min 40	50	44	-
Copper corrosion	ASTM D-130	No.3 Max	1a	1a	1a
Calorific value KJ / Kg	ASTM D-240	Report	44547	43302	42500

Results and Discussion

A laboratory experiment for the prepared fuel samples of diesel and waste cooking oil biodiesel is carried out with and without bioethanol, and the corresponding results such as combustion and emission parameters are assigned. Table 4 shows the different types of fuels used in the experiments and their volume ratios. The variable equivalence ratio of an industrial burner was investigated, and the results are reported in the sections below.

Table 4. Types of fuels tested in the experiments.

Test fuel	Diesel (volume %)	Biodiesel (volume %)	Bioethanol (volume %)
D100	100%	NIL	NIL
D50B50	50%	50%	NIL
D50B50E15	50%	50%	15%
D50B50E25	50%	50%	25%

Effect of Equivalence Ratio on Emission Carbone monoxide (CO)

Carbon monoxide (CO) is formed when carbon fuels are burned incompletely, which occurs when there is insufficient oxygen available during the combustion process. The trend lines of CO variation with equivalence ratios are depicted in figure 5.

Diesel fuel emits a lot of carbon monoxide when compared to other types of fuels (Venu et al. 2019). The emissions of CO from diesel fuel increase in the lean mixture region and fall at the equivalence ratio of 1.0 ($\Phi = 1$) under stoichiometric conditions, then increase in the region of the rich fuel due to excessive fuel consumption and insufficient air supply which promotes increased CO production during combustion Muthiya et al. (2022), as well as all the fuel types, follow the same trend.

The findings imply that biodiesel has reduced CO emissions due to the higher oxygen content of biodiesel fuel in blends, which aids in more complete combustion (Alagu et al. 2019). CO concentrations level decreased by 19% for fuel blends D50B50 compared to conventional diesel. The effect of adding bioethanol in blends on lowering carbon monoxide for all fuels may be clearly shown in Figure 5. As the percentage of bioethanol in the blend increases, CO concentration decreases due to the high oxygen content of biodiesel and bioethanol, which increases the oxygen-to-fuel ratio in the fuel-rich zone and promotes more complete combustion, converges to perfect combustion, and thus reduces Co emission Shahir et al. (2015).

Despite this, the high percentage of bioethanol (more than 15%) affects the reactions of converting carbon monoxide to carbon dioxide due to the low temperature and the occurrence of inhibition in the combustion reactions as a result of the high latent heat of evaporation of the ethanol and the absorption of heat during the reaction. The addition of bioethanol to fuel blends for D50B50E15 and D50B50E25 reduces CO emissions by nearly 69 and 65%, respectively, compared to diesel fuel. Carbon monoxide emissions increase by about 4% when the ethanol percentage in the mixture is increased from 15 to 25%.

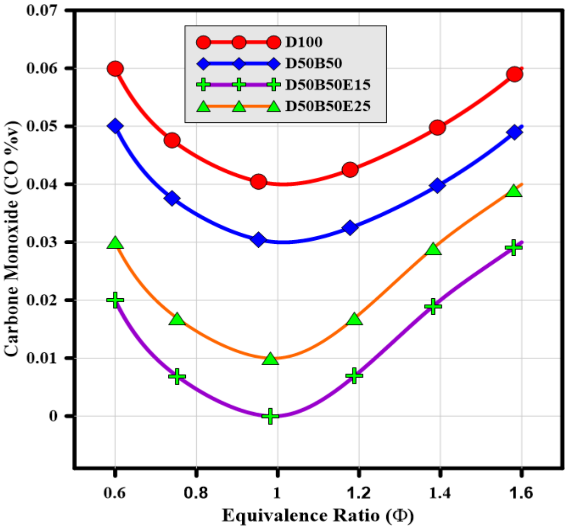


Figure 5. The trend lines of CO variation with an equivalence ratio.

Unburned Hydrocarbon

The UHC comprises fuel droplets or vapors that did not completely burn during combustion. It is formed mainly due to larger fuel droplet sizes, poor atomization, insufficient burning rate, and quenching process. Figure 6 depicts HC emissions as a function of the equivalence ratio and the types of fuels used.

In the lean mixture region, the higher the equivalent ratio, the lower the HC emissions until they reach their lowest value when the equivalent ratio is equal to 1.0 (Φ=1), then in the rich-fuel region, the HC emissions increase with an increase in the equivalence ratio. HC emissions are lowest for all fuels when the equivalent ratio equals 1.0 due to complete combustion. In the lean fuel mixture and rich fuel mixture the HC emission increase due to incomplete combustion. All tested fuels follow the same trend.

Biofuels have a significant impact on HC emissions because of the excess oxygen concentration presence in biodiesel and bioethanol. As a result, the increase in oxygen content causes complete combustion, which decreased emissions of unburned hydrocarbons. HC emission levels decreased for fuel blend D50B50 by about 18% compared to diesel.

HC emissions from biodiesel-ethanol-diesel were lower than those from diesel fuel. it can be observed that the HC emission decreased as the amount of ethanol in the fuel mixture increased by 37 and 28% for D50B50E15 and D50B50E25 compared to diesel fuel, respectively. Indicating that increasing ethanol in blends will promote combustion by adding additional oxygen inside the combustion chamber. By increasing the percentage of alcohol in the mixture to more than 15%, the hydrocarbon emissions decrease to 9% for the fuel D50B50E25.

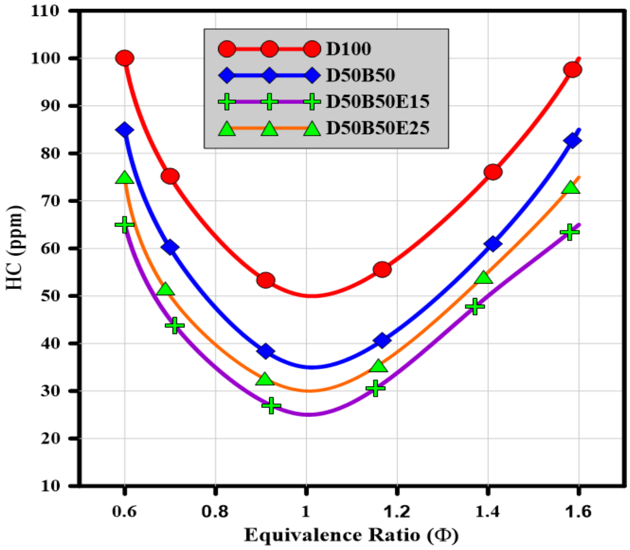


Figure 6. The trend lines of HC variation with an equivalent ratio

Nitrogen Oxide NOx

Figure 7 shows a comparison of NOx emissions for D100, D50B50, D50B50E15, and D50B50E25 at various equivalence ratios. It can be seen that diesel produces significantly less NOx than all other fuel blends. due to the reduced flame temperature, which suppresses the creation of thermal NOx. The maximum level of NOx emissions from D100 was measured at an equivalent ratio of 1 (Φ=1) due to complete combustion and at low and high equivalent ratios, NOx decreases slightly, due to the effect of the amount of air on combustion. Bazooyar et al. (2015).

For diesel-biodiesel blends D50B50, the emission of NOx increases by about 6% compared with diesel Because biodiesel is oxygenated and contains more unsaturated molecules (having carbon double bonds), it produces more hydrocarbon radicals during combustion, which leads to more prompt NOx. For blends D50B50 in the stoichiometric zone, it reaches the highest value in nitrogen oxides emissions 55 ppm, and then, in the rich and lean mixture region, the emissions of nitrogen oxides decline as the amount of air is changed. According to Ng and Gan (2010), the use of biodiesel and its blending with diesel in the boiler causes an increase in NOx emissions. Additionally, Macor and Pavanello (2009) demonstrated that biodiesel emits more NOx than home heating oil. The curves in Figure 6 also show how the content of bioethanol and biodiesel in the blend affects the NOx emission level. In general, NOx emissions recorded a significant increase in the blends of diesel-biodiesel-bioethanol compared to diesel.

Because Biodiesel has a larger isentropic bulk modulus. Tat et al. (2000) and iodine value than conventional diesel fuel, resulting in an earlier injection time in a fuel injector, increasing NOx emissions Hess et al. (2005). Also, biodiesel has more double-bonded molecules than diesel, it raises the flame temperature and, as a result, produces more

NOx according to the Zeldovich mechanism. Ban-Weiss et al. (2007). Furthermore, ethanol has a high oxygen level and increases fuel volatility. As a result, combustion gets closer to being stoichiometric (Asfar and Hamed 1998). On the other hand, as the percentage of bioethanol in the blend increases from 15 to 25% by volume, the level of NOx emissions decreases by about 15% due to the cooling impact of ethanol, which has a high latent heat of vaporization and drops the temperature of the furnace, hence decreasing the NOx emission.

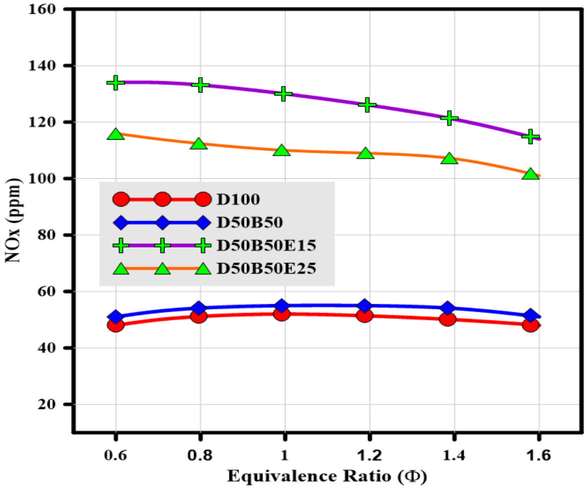


Figure 7. The trend lines of NOx variation with equivalence ratio.

Smoke opacity

The variations of soot emissions concerning fuels and different equivalence ratios are shown in Figure 8. For all fuels the level of soot emission increases as the equivalence ratio increases in the lean mixture region until it reaches its peak value when the equivalence ratio is equal to 1.0 (Φ=1) at stoichiometric conditions, then in the rich-fuel region, the soot emissions decrease gradually with an increase in the equivalence ratio. Ahmad et al. (2020). Figure 8 shows that conventional diesel fuel emits more soot than the other test fuel blends due to the fuel composition, which contains a complex mixture of elemental carbon, a variety of HCs, and sulfur compounds. For biodiesel and diesel blends fuels D50B50, soot emissions levels decreased by about 8% compared to diesel Because biodiesel is oxygenated and contains more oxygen than diesel, the pyrolysis zone of combustion improved, resulting in lower soot emissions(Janakiraman et al. 2020). On the other hand, bioethanol has a low propensity to produce soot due to its high H/C ratio. The concentration of soot emission decreases with the increase in the amount of bioethanol in the mixture up to 15% concentration, then the soot emission increases due to the cooling effect of ethanol. The soot emission of D50B50, D50B50E15, and D50B50E25 was reduced by about 8%, 50%, and 30% compared to diesel, respectively. This trend may be attributed to the high oxygen content of biodiesel and bioethanol fuels, which reduces soot emissions (Swamy et al. 2019).

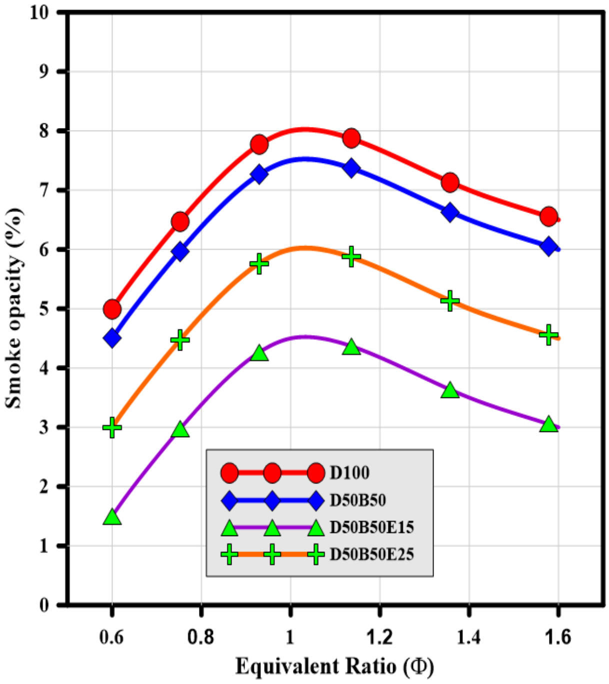


Figure 8. The trend lines of soot emission variation with an equivalent ratio.

Combustion performance

The effect of different equivalence ratios on the exhaust gas temperature

The R-thermocouple measures the exhaust temperature at the end of the furnace, at a distance of 140 cm from the burner nozzle, and it is clear from figure 9 that all types of fuel raise the exhaust temperature with an increase in the equivalence ratio, as a result of the increased fuel-air mixture, and thus the total combustion temperature. This is due to the additional fuel in the mixture releasing a lot of heat. The exhaust temperature increases with the increased proportion of biodiesel in the mixture. For fuel blends D50B50, the exhaust temperature increases by 2% compared with diesel. This is because biodiesel contains a higher content of oxygen compared to diesel (Subramani and Venu 2019). Bioethanol affects blends as demonstrated in Figure 9. For fuel mixtures D50B50E15 and D50B50E25, the exhaust temperature increases by about 3 and 1% compared to diesel, respectively. The relatively small amount of ethanol in blends D50B50E15 causes a significant increase in exhaust temperature when comparing all types of fuels tested, which may be caused by the oxygenated component in biodiesel and bioethanol. However, as the amount of bioethanol in the fuel blend increases from 15 to 25%, the temperature of the exhaust gas drops by about 2%. Since ethanol has a high latent heat of vaporization, a high percentage of bioethanol fuel absorbs a large amount of heat from the combustion furnace during vaporization. Paul et al. (2017).

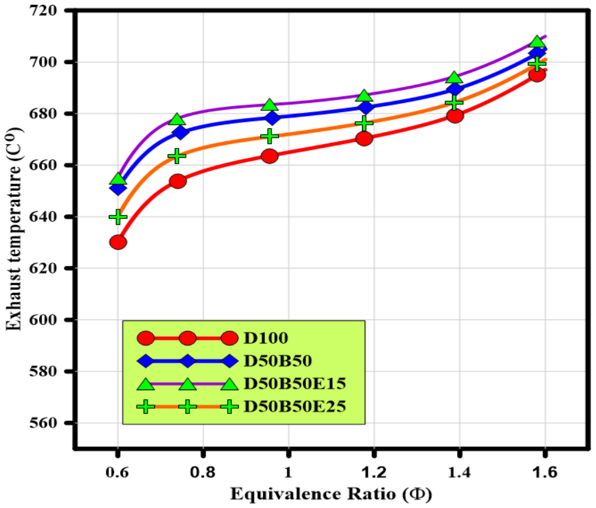


Figure 9. The effect of the equivalence ratio on exhaust gas temperature.

The effect of different equivalence ratios on the maximum flame temperature of the combustion chamber

Figure 10 shows the maximum flame temperature for different types of fuels and the equivalence ratio. According to the results, the flame maximum temperature increases by increasing the equivalence ratio because at a higher fuel-air ratio more fuel will be injected into the furnace. biodiesel has a higher oxygen content, which enhances the combustion rate, contributing to the increased peak temperature in comparison with the diesel fuel D100 and blends with diesel and biodiesel D50B50. As the figure demonstrates, using a biodiesel and diesel blend (D50B50) causes the maximum gas temperature inside the furnace to increase by roughly 5% compared to diesel. Figure 10 also shows the effect of bioethanol with diesel and biodiesel on the maximum flame temperature. For fuel mixtures D50B50E15 and D50B50E25, the maximum flame temperature increases by about 9% and 4% compared to diesel, respectively. As the equivalence ratio increases, the maximum flame temperature increases for D50B50E15. On the other hand, the maximum flame temperature decreases as the percentage of ethanol in the fuel blends rise over 15%. For D50B50E25, the maximum flame temperature decreases by about 5% compared with D50B50E15 due to ethanol having a high latent heat of combustion and a low cetane number, which impacts the fuel mixture and lowers the maximum flame temperature produced by combustion. Furthermore, particularly in the lean mixture region, the reduction in maximum flame temperature in the alcohol blends D50B50E25 appears more clearly in the lean zone at an equivalence ratio lower than 1. This reduction can be attributed to the excess oxygen in the biodiesel and ethanol and the high latent heat of the vaporization of ethanol, which affects the rate of combustion and decreases the maximum flame temperature. Because of the high content of ethanol in blends D50B50E25, the maximum flame temperature drops at the high equivalence ratio of 1.6 due to the fuel-rich condition that forms inside the combustion furnace, which causes the cumulative cetane number of the blends to decrease because of the low cetane number of bioethanol and results in incomplete combustion.

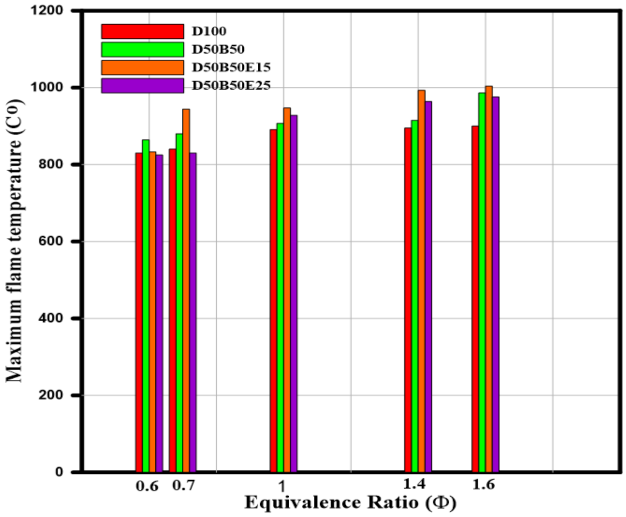


Figure 10. The effect of the equivalence ratio on maximum flame temperature.

The contour plot of the flame temperature for a bioethanol content in blends D50B50E15, D50B50E25

Flame temperature is the most important factor influencing flame characteristics, particularly pollutant emission and heat flow. The flame temperature was monitored during the passage of the flame at various locations to comprehend and compare the flame behavior of various fuels. Figures 11a and 12b depict a Three-dimensional contour plot for the distribution of flame temperature at various points in the furnace at a constant mass fuel rate input of 0.14 l/min and variable air flow rate for an ethanol content of 15% (a) and 25% (b) in blends. Figures 11a and 11b demonstrate the differences in flame temperature of the furnace from the center line of the burner to the wall of the furnace for different fuel mixtures and different equivalence ratios. The results show that the maximum flame temperatures of fuels D50B50E15 and D50B50E25 were nearly 1004 ˚C and 976 ˚C at an equivalence ratio equal to 1.6, respectively. The gas temperature decreases with a constant trend when the distance from the burner to the end of the furnace increases. According to the results, the maximum flame temperature occurs at a distance of about 30 cm from the burner, this is because complete combustion occurs in this place and leads to an increase in the average temperature of the flue gas. The flame temperature inside the furnace is positively affected by the presence of bio-ethanol up to a 15% concentration in the fuel mixture. On the other hand, higher proportions of bioethanol in mixtures from 15 to 25% cause a decrease in flame temperature of about 4% due to the high latent heat of bioethanol. As a result, during vaporization, Ethanol absorbs a large amount of heat from the combustion process inside the furnace, lowering its temperature in all different equivalent ratios (Motamedifar and Shirneshan 2018). the furnace, lowering its temperature in all different equivalent ratios (Motamedifar and Shirneshan 2018). Also, it is noticeable from figures 11a and 11b that the flame temperature along its center line as measured from the burner to the end of the furnace increases by increasing the equivalence ratio, as a result of the increased fuel-air mixture, and thus the total combustion temperature increase. This is due to the additional fuel in the mixture releasing a lot of heat. The figure shows that the temperature of the flame inside the furnace falls from the furnace center line of the burner to the wall. As a result of heat loss by radiative transfer from the combustion gases to the furnace walls.

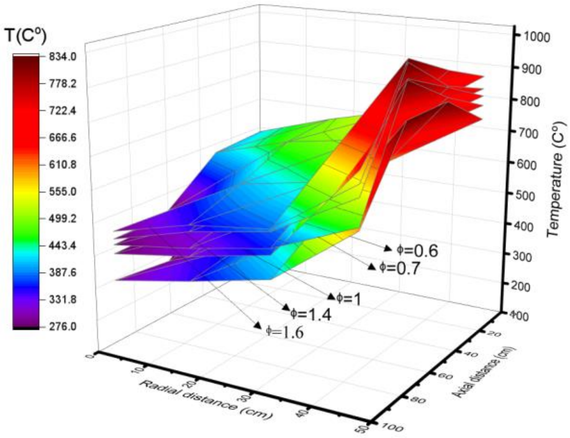


Figure 11a. Three-dimensional contour plot of the effect of D50B50E15 on the temperature flame inside the furnace at a different equivalence ratio.

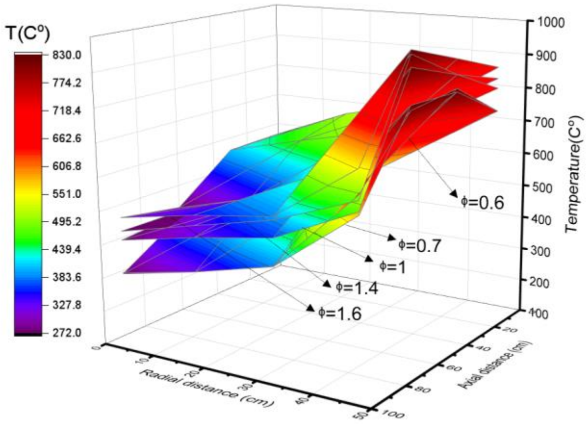


Figure 11b. Three-dimensional contour plot of the effect of D50B50E25 on the temperature flame inside the furnace at a different equivalence ratio.

The effect of different equivalence ratios on the flame length and contour Temperature

Figure 12 illustrates the flame length for three different fuels, D100, D50B50E15, and D50B50E25, in various equivalence ratios. For all types of fuel, flame length and area showed a consistent tendency. As the equivalence ratio increase, the flame length for all fuels increase. A higher equivalence ratio indicates that less air is used during combustion. In this case, combustion results in a larger flame as the equivalence ratio values rise and flame length increase. flame length of diesel fuel was lower than D50B50E15 and D50B50E25 from an equivalence ratio of 0.6 to 1.6.

D50B50E15 and D50B50E25 have average flame lengths that are 57% and 19% longer than diesel, respectively. Additionally, the flame length of diesel fuel is close to the values of the D50B50E25 flame lengths at an equivalence ratio of 0.6. When the proportion of ethanol in the mixture is higher than 15%, the flame characteristics deteriorate and its length decreases. A result of the properties of ethanol fuel, which cause a decrease in the burning rate due to its higher latent heat of vaporization and lower cetane number compared to other types of fuel mixed with it.

Figure 13 displays the Contour map and flame pictures for biofuel mixture D50B50E15 and D50B50E25 at various equivalence ratios at a constant mass fuel rate input of 0.14 l/min and variable air flow rate. A digital camera was used to capture these images. It is noticeable that the equivalence ratio has an important effect on the flame that can be controlled by the air supply. The Contour map is drawn to characterize each fuel and identify the length, area, and location of the maximum flame inside the furnace at different equivalence ratios. From the figure, we can deduce that the stability of the flame and combustion characteristics were impacted by an increase in the fuel-air ratio. With a rising equivalence ratio, the flame area expanded, and the flame length increased. Additionally, flame brightness increases dramatically due to the homogeneity of the fuel mixture. D50B50E15 flame has brilliantly yellow indicating complete combustion. Visually, with a bioethanol percentage above 15% in the mixture, for D50B50E25, the length and area of the flame decreased, in addition to the decrease in the yellow luminosity of the flame due to the higher latent heat of vaporization of the bioethanol, which causes energy absorption during the evaporation process of the bioethanol fuel and reduces the combustion temperature and affects the shape of the flame. Furthermore, higher soot formation and lower flame temperatures were observed when compared to D50B50E15

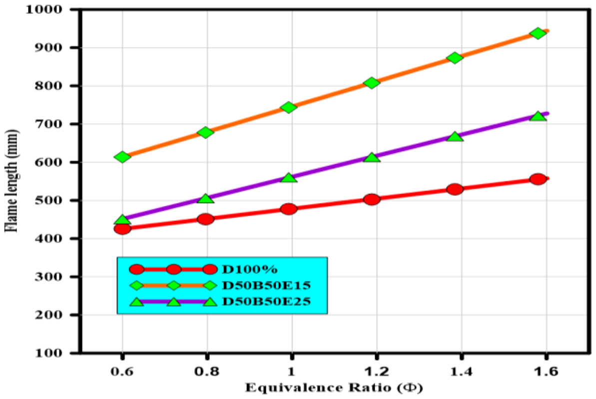


Figure 12. The trend of the flame length of different types of fuels as a function of equivalence ratio.

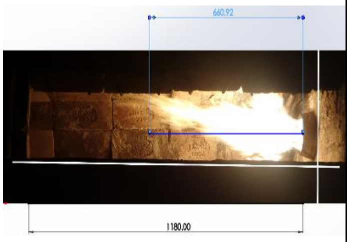
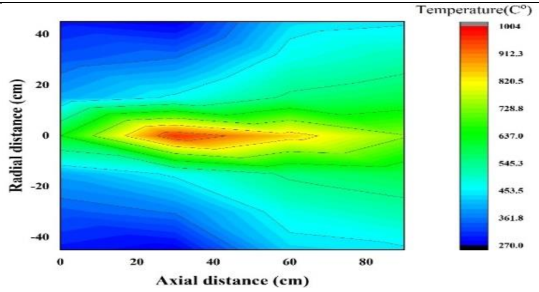
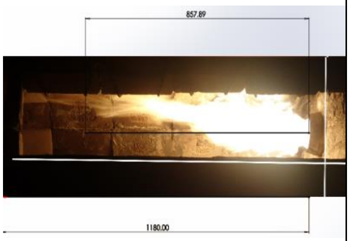
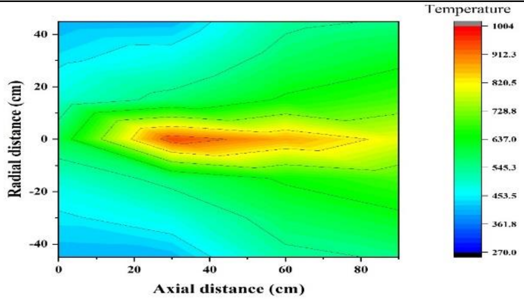
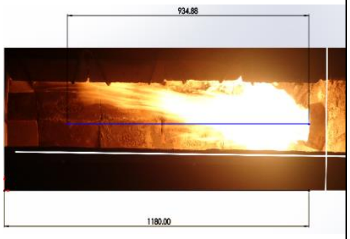
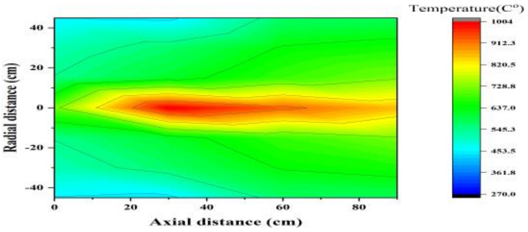
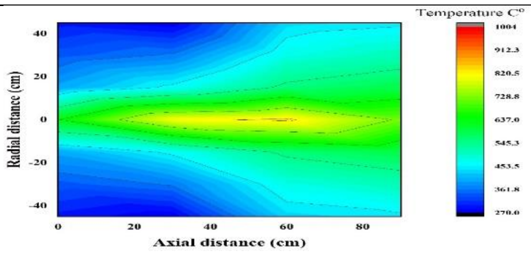
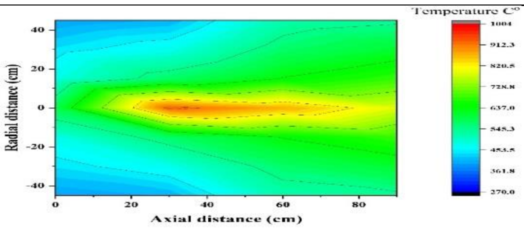
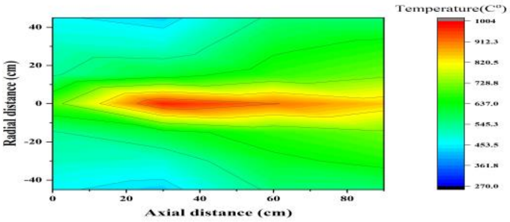
	Flame	D50B50E15
Equivalence ratio = 0.6		
Equivalence ratio = 1		
Equivalence ratio = 1.6		
	Flame	D50E50E25
Equivalence ratio = 0.6		
Equivalent ratio = 1		
Equivalentce ratio = 1.6		

Figure13. Temperature contour and images of flames of biofuel mixtures D50B50E15 and D50B50E25 at various equivalence ratios.

Conclusions

The experiments are performed to investigate the combustion performance and emission characteristics of biofuel blends with diesel. All the fuels were tested using different equivalence ratios.

Measurements of CO, UH and soot emission levels revealed that biofuel blends with diesel oil produced significantly lower emissions than diesel oil. The biofuel blends to diesel D100 result in a significant reduction in CO emission by 19%, 69%, and 65% of the D50B50, D50B50E15, and D50B50E25 fuels, respectively.

Compared with diesel fuel. the dramatic decrease in CO of ethanol blends in fuel is due to the high oxygen content of ethanol and biodiesel. The highest reduction percentages in HC emissions were obtained by 18%, 37%, and 28% of the D50B50, D50B50E15, and D50B50E25 fuels, respectively. Compared with the D100 reference fuel. Opacity smoke decreased by 10%, 70%, and 40% of the D50B50, D50B50E15, and D50B50E25 fuels, respectively.

Compared with diesel fuel. The concentration of NOx emission measurement is observed to increase as the biofuel in the blend is increased significantly more NOx emissions were produced when ethanol was present in blends. For D50B50, D50B50E15and D50B50E25 increased the exhaust flame temperature by about 2%,3%and 1% and maximum flame temperature by 5%,9%and 4%, respectively. compared with diesel fuel.

The highest exhaust flame temperature and the maximum flame temperature were recorded at 15% of the ethanol content in the blends and reduced when the ethanol percentage was increased to 25%. Because ethanol has a high latent heat of vaporization and a low cetane number. Compared to diesel, The area and length of the flame increased at the diesel-biodiesel D50B50 and diesel-biodiesel-bioethanol D50B50E15 blends. as well as the intensity and brightness of the flame.

Nonetheless, the flame and area were reduced when the ethanol content was increased to 25% in blends. In the case of D50B50E25, flame combustion shows relatively low luminosity and the flame length is short. Furthermore, higher soot formation and lower flame temperatures were observed when compared to D50B50E15.

In industrial burners, biofuel can be used without any modifications. It can also be combined with petroleum diesel in any ratio to create biofuel blends. In the biofuel blend, it is not recommended to raise the percentage of ethanol to more than 25%, despite the improvement of some emissions pollutants, but the combustion efficiency declined. The optimum percentage of bioethanol was 15% in the blend, which produced acceptable readings for temperature and emissions.

Reference

Ahmad AA, Jaafar MNM, Othman NB, Azli AAM, Said M, Rahim MR, Malik MSA, Omar WZW (2020) Combustion and Emission Characteristics of Palm Oil-Based Biodiesel in a Liquid Fuel Burner. IOP Conference Series: Materials Science and Engineering 884:012026

Alagu K, Venu H, Jayaraman J, Raju VD, Subramani L, Appavu P, S D (2019) Novel water hyacinth biodiesel as a potential alternative fuel for existing unmodified diesel engine: Performance, combustion and emission characteristics. Energy 179:295-305

Asfar KR, Hamed H (1998) Combustion of fuel blends. Energy Conversion and Management 39:1081-1093

Balat M (2007) Production of Biodiesel from Vegetable Oils: A Survey. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 29:895-913

Ban-Weiss GA, Chen JY, Buchholz BA, Dibble RW (2007) A numerical investigation into the anomalous slight NOx increase when burning biodiesel; A new (old) theory. Fuel Processing Technology 88:659-667

Barroso J, Ballester J, Pina A (2010) Some considerations about bioethanol combustion in oil-fired boilers. Fuel Processing Technology 91:1537-1550

Bazooyar B, Shariati A, Hashemabadi SH (2015) Characterization and Reduction of NO during the Combustion of Biodiesel in a Semi-industrial Boiler. Energy & Fuels 29:6804-6814

Bušić A, Marđetko N, Kundas S, Morzak G, Belskaya H, Ivančić Šantek M, Komes D, Novak S, Šantek BJFt, biotechnology (2018) Bioethanol production from renewable raw materials and its separation and purification: a review 56:289-311

Chacko N, J T (2020) Effect of pilot and post fueling on the combustion and emission characteristics of a light-duty diesel engine powered with diesel and waste cooking biodiesel blend. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects:1-24

Chen W-H, Liao C-Y, Hung C-I, Huang W-L (2012) Experimental study on thermoelectric modules for power generation at various operating conditions. Energy 45:874-881

Choi SK, Choi YS, Kim SJ, Jeong YW (2016) Characteristics of flame stability and gaseous emission of biocrude-oil/ethanol blends in a pilot-scale spray burner. Renewable Energy 91:516-523

Duraisamy R, Salelgn K, Berekute ak (2017) Production of Beet Sugar and Bio-ethanol from Sugar beet and it Bagasse: A Review. International Journal of Engineering Trends and Technology 43:222-233

El-Sheekh MM, Bedaiwy MY, El-Nagar AA, ElKelawy M, Alm-Eldin Bastawissi H (2022) Ethanol biofuel production and characteristics optimization from wheat straw hydrolysate: Performance and emission study of DI-diesel engine fueled with diesel/biodiesel/ethanol blends. Renewable Energy 191:591-607

Elkelawy M, Alm-Eldin Bastawissi H, Esmaeil KK, Radwan AM, Panchal H, Sadasivuni KK, Ponnamma D, Walvekar R (2019) Experimental studies on the biodiesel production parameters optimization of sunflower and soybean oil mixture and DI engine combustion, performance, and emission analysis fueled with diesel/biodiesel blends. Fuel 255:115791

Elkelawy M, Alm ElDin Mohamad H, Abdel-Rahman AK, Abou Elyazied A, Mostafa El malla S (2022) Biodiesel as an Alternative Fuel in Terms of Production, Emission, Combustion Characteristics for Industrial Burners: a Review %J Journal of Engineering Research 6:45-52

Elkelawy M, Bastawissi HA-E, Esmaeil KK, Radwan AM, Panchal H, Sadasivuni KK, Suresh M, Israr M (2020) Maximization of biodiesel production from sunflower and soybean oils and prediction of diesel engine performance and emission characteristics through response surface methodology. Fuel 266:117072

Ergun M, Ferda Mutlu S (2000) Application of a statistical technique to the production of ethanol from sugar beet molasses by Saccharomyces cerevisiae. Bioresource Technology 73:251-255

Garcia Gonzalez MN, Björnsson L (2022) Life cycle assessment of the production of beet sugar and its by-products. Journal of Cleaner Production 346:131211

Gerpen JV (2005) Biodiesel processing and production. Fuel Processing Technology 86:1097-1107

Ghorbani A, Bazooyar B (2012) Optimization of the combustion of SOME (soybean oil methyl ester), B5, B10, B20 and petrodiesel in a semi industrial boiler. Energy 44:217-227

Hess MA, Haas MJ, Foglia TA, Marmer WN (2005) Effect of Antioxidant Addition on NOx Emissions from Biodiesel. Energy & Fuels 19:1749-1754

Issariyakul T, Kulkarni MG, Dalai AK, Bakhshi NN (2007) Production of biodiesel from waste fryer grease using mixed methanol/ethanol system. Fuel Processing Technology 88:429-436

Janakiraman S, Lakshmanan T, Chandran V, Subramani L (2020) Comparative behavior of various nano additives in a DIESEL engine powered by novel Garcinia gummi-gutta biodiesel. Journal of Cleaner Production 245:118940

Krishnan RY, Manikandan S, Subbaiya R, Kim W, Karmegam N, Govarthanan M (2022) Advanced thermochemical conversion of algal biomass to liquid and gaseous biofuels: A comprehensive review of recent advances. Sustainable Energy Technologies and Assessments 52:102211

Kumaran P, Gopinathan M, Kantharrajan S (2014) COMBUSTION CHARACTERISTICS OF IMPROVED BIODIESEL IN DIFFUSION BURNER. International Journal of Automotive and Mechanical Engineering 10:2112-2121

Leung DYC, Guo Y (2006) Transesterification of neat and used frying oil: Optimization for biodiesel production. Fuel Processing Technology 87:883-890

Macor A, Pavanello P (2009) Performance and emissions of biodiesel in a boiler for residential heating. Energy 34:2025-2032

Mandolesi de Araújo CD, de Andrade CC, de Souza e Silva E, Dupas FA (2013) Biodiesel production from used cooking oil: A review. Renewable and Sustainable Energy Reviews 27:445-452

Moffat RJ (1988) Describing the uncertainties in experimental results. Experimental Thermal and Fluid Science 1:3-17

Motamedifar N, Shirneshan A (2018) An experimental study of emission characteristics from cylindrical furnace: Effects of using diesel-ethanol-biodiesel blends and air swirl. Fuel 221:233-239

Muthiya SJ, Natrayan L, Kaliappan S, Patil PP, Naveena BE, Dhanraj JA, Subramaniam M, Paramasivam P (2022) Experimental Investigation to Utilize Adsorption and Absorption Technique to Reduce CO₂ Emissions in Diesel Engine Exhaust Using Amine Solutions. Adsorption Science & Technology 2022:9621423

Ng HK, Gan S (2010) Combustion performance and exhaust emissions from the non-pressurised combustion of palm oil biodiesel blends. Applied Thermal Engineering 30:2476-2484

Norwazan AR, Jaafar MNM, Sapee S, Farouk H (2018) Emissions of Jatropha oil-derived biodiesel blend fuels during combustion in a swirl burner. IOP Conference Series: Earth and Environmental Science 136:012001

Paul A, Panua R, Debroy D (2017) An experimental study of combustion, performance, exergy and emission characteristics of a CI engine fueled by Diesel-ethanol-biodiesel blends. Energy 141:839-852

Phan AN, Phan TM (2008) Biodiesel production from waste cooking oils. Fuel 87:3490-3496

Pinto MJPdM (2012) Biodiesel fuel formulation. Universidade de Aveiro (Portugal), Ann Arbor, p 322

Pourhoseini SH, Namvar-Mahboub M, Hosseini E, Alimoradi A (2021) A comparative exploration of thermal, radiative and pollutant emission characteristics of oil burner flame using palm oil biodiesel-diesel blend fuel and diesel fuel. Energy 217:119338

Prieto-Fernandez I, Luengo-Garcia J-C, Ponte-Gutierrez D (1999) Improvements in light oil combustion by adding small quantities of alcohol. Possible application in cold starts up, in thermal power stations. Fuel Processing Technology 60:15-27

Rashid U, Anwar F, Moser BR, Ashraf S (2008) Production of sunflower oil methyl esters by optimized alkali-catalyzed methanolysis. Biomass and Bioenergy 32:1202-1205

Ratel G, Michotte C, Bochud FO (2015) Uncertainty of combined activity estimations. Metrologia 52:S30-S41

Shahir SA, Masjuki HH, Kalam MA, Imran A, Ashraful AM (2015) Performance and emission assessment of diesel–biodiesel–ethanol/bioethanol blend as a fuel in diesel engines: A review. Renewable and Sustainable Energy Reviews 48:62-78

Sharma B, Larroche C, Dussap C-G (2020) Comprehensive assessment of 2G bioethanol production. Bioresource Technology 313:123630

Singh D, Sharma D, Soni SL, Inda CS, Sharma S, Sharma PK, Jhalani A (2021) A comprehensive review of biodiesel production from waste cooking oil and its use as fuel in compression ignition engines: 3rd generation cleaner feedstock. Journal of Cleaner Production 307:127299

Slathia PS, Raina N, Kiran A, Kour R, Bhagat D, Sharma P (2020) Dilute acid pretreatment of pine needles of Pinus roxburghii by response surface methodology for bioethanol production by separate hydrolysis and fermentation. Biomass Conversion and Biorefinery 10:95-106

Subramani L, Venu H (2019) Evaluation of methyl ester derived from novel Chlorella emersonii as an alternative feedstock for DI diesel engine & its combustion, performance and tailpipe emissions. Heat and Mass Transfer 55:1513-1534

Swamy DLSVN, Kowsik Y, Dhana Raju V, Appa Rao K, Venu H, Subramani L, Bala Prasad K (2019) Effect of 1-butanol on the characteristics of diesel engine powered with novel tamarind biodiesel for the future sustainable energy source. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects:1-19

Szulczyk KR, Tan Y-M (2022) Economic feasibility and sustainability of commercial bioethanol from microalgal biomass: The case of Malaysia. Energy 253:124151

Tabatabaei M, Aghbashlo M (2018) Biodiesel: From Production to Combustion. Springer

Talebian-Kiakalaieh A, Amin NAS, Mazaheri H (2013) A review on novel processes of biodiesel production from waste cooking oil. Applied Energy 104:683-710

Tashtoush G, Al-Widyan MI, Al-Shyoukh AO (2003) Combustion performance and emissions of ethyl ester of a waste vegetable oil in a water-cooled furnace. Applied Thermal Engineering 23:285-293

Tat ME, Van Gerpen JH, Soylu S, Canakci M, Monyem A, Wormley S (2000) The speed of sound and isentropic bulk modulus of biodiesel at 21°C from atmospheric pressure to 35 MPa. Journal of the American Oil Chemists' Society 77:285-289

Topare NS, Jogdand RI, Shinde HP, More RS, Khan A, Asiri AM (2022) A short review on approach for biodiesel production: Feedstock's, properties, process parameters and environmental sustainability. Materials Today: Proceedings 57:1605-1612

Venu H, Raju VD, Subramani L (2019) Influence of injection timing on torroidal re-entrant chamber design in a single cylinder DI engine fuelled with ternary blends. Heat and Mass Transfer 55:2931-2948

Venu H, Raju VD, Subramani L, Appavu P (2020) Experimental assessment on the regulated and unregulated emissions of DI diesel engine fuelled with Chlorella emersonii methyl ester (CEME). Renewable Energy 151:88-102

Vijayaragavan M, Subramanian B, Sudhakar S, Natrayan L (2022) Effect of induction on exhaust gas recirculation and hydrogen gas in compression ignition engine with simarouba oil in dual fuel mode. International Journal of Hydrogen Energy 47:37635-37647