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COMPARISON OF EMISSIONS AND ENGINE PERFORMANCE OF CRAMBE BIODIESEL AND BIOGAS

Ivan Werncke¹, Samuel N. M. de Souza¹, Douglas Bassegio^{1*}, Deonir Secco¹

^{1*} Western Parana State University/Cascavel - PR, Brazil.

E-mail: douglas.bassegio@unioeste.br | ORCID ID: <https://orcid.org/0000-0001-6628-8594>

KEYWORDS

Crambe abyssinica, efficiency, fuel consumption, carbon monoxide, nitrogen oxide.

ABSTRACT

The combination of crambe (*Crambe abyssinica* L.) biodiesel and biogas could be a renewable energy alternative for internal combustion engines. Therefore, the emissions and engine performance of crambe biodiesel blends (B0, B10, B30, B50, B75, and B100) were evaluated in both the dual mode (biogas) and normal mode (biodiesel). The tests were performed on a 5-kVA generator engine at loads ranging from 1 to 4 kW. The power generated in the normal mode was 17% lower than that generated in the dual mode. The dual mode showed a lower specific fuel consumption than the normal mode. In the normal mode, loss of power occurred as the proportion of biodiesel increased. Furthermore, nitrogen oxide emissions decreased with the addition of biogas. In the dual mode, the emissions increased as the biodiesel content increased. Carbon monoxide emissions decreased in both the normal and dual modes with an increase in biodiesel. The addition of biogas in the dual fuel mode with crambe biodiesel is an efficient alternative for partial substitution of diesel.

INTRODUCTION

The demand for energy and growing consumption of oil have led to economic growth worldwide (Bozbas, 2008). The growing energy demand is still highly dependent on fossil fuels, which produce gas emissions that influence global climate change, putting life on the planet and the perpetuation of species at risk (Saravanan et al., 2020). Although alternatives to electric mobility and hydrogen technology are increasingly being studied, transformations for vehicles still seem to be long term (Işik, 2021).

Biodiesel is renewable and is a promising fuel for diesel combustion engines. Biodiesel is obtained by transesterification, and triglycerides react with a short-chain alcohol in the presence of a catalyst (Yesilyurt & Cesur, 2020). This fuel is non-toxic and biodegradable, with less exhaust gas emissions and a lower sulfur content. It still has the advantages of a low flash point, low volatility, low content of aromatic compounds, and high lubricity (Noor et al., 2018).

In Brazil approximately 70% of biodiesel in Brazil is generated from soybeans. However, in addition to biodiesel production, soybeans are also necessary for food and animal feed export (César et al., 2019; Souza et al., 2021). In this context, other unconventional oilseeds with sufficient supply for industrial applications, such as crambe (*Crambe abyssinica* L.), may be promising alternatives for increasing the diversity of raw materials used for biodiesel production (Bassegio & Zanotto, 2020; Gongora et al., 2022).

Biogas is another renewable energy source that can be used in internal combustion engines. Biomass is an abundant and renewable source of energy that can be obtained from organic materials produced by human and natural activities, including industrial, urban, forestry, agricultural, and animal solid wastes. As biogas is in a gaseous form, it can be used in compression ignition engines as a dual fuel (Bedoya et al., 2009). The combustion of a mixture of biogas and biodiesel is promising for clean

¹ Western Parana State University/Cascavel - PR, Brazil.

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combustion in engines and substantial emission reductions (Yoon & Lee, 2011).

Although several studies have investigated the dual fuel concept, it is necessary to comprehensively evaluate the emissions and performance of the biogas-biodiesel-crambe bi-fuel engine as an alternative fuel. No results were obtained for the interaction between crambe biodiesel and biogas. The present study evaluated the emissions and performance of an engine operating with blends of crambe biodiesel with and without biogas in the dual fuel mode.

MATERIAL AND METHODS

The experiment was conducted at the Biomass Gasification and Electricity Microgeneration Laboratory of the Western Parana State University (UNIOESTE) and on a farm in Parana, Brazil.

The tests were performed using biodiesel blends with B10 crambe biodiesel (10% crambe biodiesel and 90% diesel), B20 (20% crambe biodiesel and 80% diesel), B50 crambe (50% crambe biodiesel and 50% diesel), B75 crambe (75% crambe biodiesel and 25% diesel), and B100 crambe (100% crambe biodiesel and 0% diesel) in a diesel cycle generator engine set in dual mode (with insertion of biogas in the engine) and normal mode. The normal mode uses normal fuel (diesel and biodiesel), and the dual mode (biogas–diesel and biogas–biodiesel). Dual mode tests were carried out on pig manure at the anaerobic digester of piston flow. The volume of gas consumed is calculated by taking

the difference between the initial and the final gas consumption reading. Biogas consumption in dual mode was 3; 3.3; 4; 4; 3.9 and 4.1 m³ ha⁻¹ in blends B0, B10, B20, B50, B75 and B100, respectively.

The crambe used was grown on a farm in the city of Cascavel, PR. Biodiesel was obtained via a transesterification reaction, with potassium hydroxide (KOH) as a catalyst (1% of oil weight) and methanol as an alcohol (25% of oil volume) (Rosa et al., 2014). The biodiesel blends were homogeneous and stable.

A diesel generator set manufactured by Branco, model BD 6500CF, and normal phase was used with 7.36 kW (10 HP; 3600 rpm). The engine was coupled to a 110/220 V Kohlbach normal phase generator, with a maximum continuous power of 5.5 kVA and a maximum current of 20 A. The generator was connected to a resistance bank with resistance ranging from 0 to 9 kVA. A resistance bank was used to simulate different loads in the motor-generator set, with the variation of the motor capacity ranging from 0 to 100%. The engine was evaluated within a range of 0 to 4 kW, with a variation of 1.0 kW. No changes to the engine were necessary. After each test, the engine was run again with diesel to drain all the blended fuel out of the fuel line, and this procedure was followed for all blends.

A heat pump calorimeter model E2K with values provided in MJ kg⁻¹ enabled the determination of the gross heating value of the fuels (Table 1). The method described by Volpato et al. (2009) allowed calculation of the lower heating value (LHV) using [eq (1)].

TABLE 1. Higher heating value (HHV), lower heating value (LHV) and density of fuels.

Fuel	HHV (kJ kg ⁻¹)	LHV (kJ kg ⁻¹)	Density (g L ⁻¹)
B0	43193	40141	852
B10	42864	39812	854
B20	42536	39484	856
B50	41549	38497	863
B75	40727	37675	869
B100	39905	36853	874

$$\text{LHV} = \text{HHV} - 3052 \quad (1)$$

in which:

LHV - lower heating value, kJ kg⁻¹,

HHV - higher heating value, kJ kg⁻¹.

A pycnometer and four-decimal precision balance (Marte, model Ay220) were used to obtain the density at 20 °C (Table 1). The values were within the limit of 850–900 kg m⁻³, as required by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP, 2008).

The concentration of methane in the biogas was 66%, obtained using a gas analyzer (Landtec GEM™ 5000 Plus). The lower heating value of methane (LHV_m) was 35530 kJ m⁻³. In the literature, the calorific value of 1 m³ of methane gas is specified as 8500 kcal (Buller et al., 2021). Equation (2) was applied to evaluate the amount of biogas energy.

$$\text{LHV}_b = \frac{P_m}{100} * \text{LHV}_m \quad (2)$$

in which:

LHV_b - lower heating value of biogas, kJ m⁻³;

P_m - percentage of methane in biogas, %,

LHV_m - lower heating value of methane, kJ m⁻³.

The Instrutherm AE-200 analyzer allowed the measurement of power (P). A Venturi-type mixer and manually adjustable ball valve for biogas flow were connected to the engine air inlet to insert and mix the biogas into the air.

The Oval MII LSF41 flowmeter enabled the measurement of fuel consumption. The Novus FieldLogger allowed the collection of information from the flowmeter. The Schimberger Gallus 1000 flow meter measured the biogas consumption. Biogas energy consumption was obtained using [eq. (3)].

$$B_{ec} = \frac{V * \text{LHV}_b}{t} \quad (3)$$

in which:

B_{ec} - biogas energy consumption, kJ s⁻¹;

V - volume of biogas consumed, m³,

t - time, s.

The engine was run on a minimum amount of fuel; therefore, detonation occurred at the compression stage of the engine cylinder. Equation (4) shows the consumption calculations.

$$Bc = \frac{Fv - Iv}{t} \quad (4)$$

in which:

- Bc - biogas consumption, m³ h⁻¹;
- Iv - initial value reading of biogas levels, m³;
- Fv - final value reading of biogas levels, m³,
- t - time, h.

The volumetric fuel consumption calculated by [Eq. (5)].

$$Vc = \frac{(Fv - Iv)}{t} \quad (5)$$

in which:

- Vc - volumetric fuel consumption, L s⁻¹;
- Fv - final value recorded by the data logger, L;
- Iv - initial value recorded by the data logger, L,
- t - time, s.

Fuel consumption given by [eq. (6)].

$$Fc = Vc * \rho_c \quad (6)$$

in which:

- Fc - fuel consumption, g s⁻¹,
- ρ_c - density of the mixture, g L⁻¹.

Equation (7) provides the specific fuel consumption.

$$SFC = \frac{Fc * 3600}{P} \quad (7)$$

in which:

- SFC - specific fuel consumption, g kWh⁻¹,
- P - power, kW.

Equation (8) presents the energy consumption given by the relationship between the sum of the fuel consumption of liquid fuel (diesel-biodiesel) and gas (biogas).

$$EC = \left(\frac{1}{3.6} * Fc * LHV + Bc * LHV_b \right) \quad (8)$$

in which:

EC - energy consumption, kJ h⁻¹.

Equation (9) defines the efficiency of the system.

$$E = \frac{P}{EC} * 360000 \quad (9)$$

in which:

E - efficiency, %.

The gases carbon monoxide (CO; ppm), nitrogen oxide (NOx; ppm), as well as exhaust gas temperatures (EGT, °C), were analyzed using a Bacharach PCA3-285 gas analyzer (Klajn et al., 2018). This equipment has adapted sensors that are capable of detecting emissions from a wide range of fuels. It has an accuracy of approximately 5% for the measurement of gases and 3% for the measurement of temperature. During the experiment, the Bacharach gas detector was inserted at the engine outlet.

The uncertainty results for each type of equipment were calculated. It is known that the acceptable range for uncertainty is below ± 5%. In this context, the overall uncertainty of the system was within acceptable limits.

RESULTS AND DISCUSSION

In the dual mode, the power remained stable and increased stably with an increasing load (Figure 1a). In the normal mode (biodiesel), a loss of power occurred as the biodiesel content in the blend increased (Figure 1b). According to Nietiedt et al. (2011), the reduction in power is due to the calorific value of the biodiesel. According to Mofijur et al. (2014), power reduction when using palm (B10) and moringa (B10) biodiesel may be due to the high viscosity of the oil. Although the present study did not evaluate the viscosity of crambe biodiesel, crambe biodiesel shows a high kinematic viscosity (at 40°C) and is one of the few native natural oils with properties close to those of conventional fluids normally used for hydraulic systems (Fanigliulo et al., 2021).

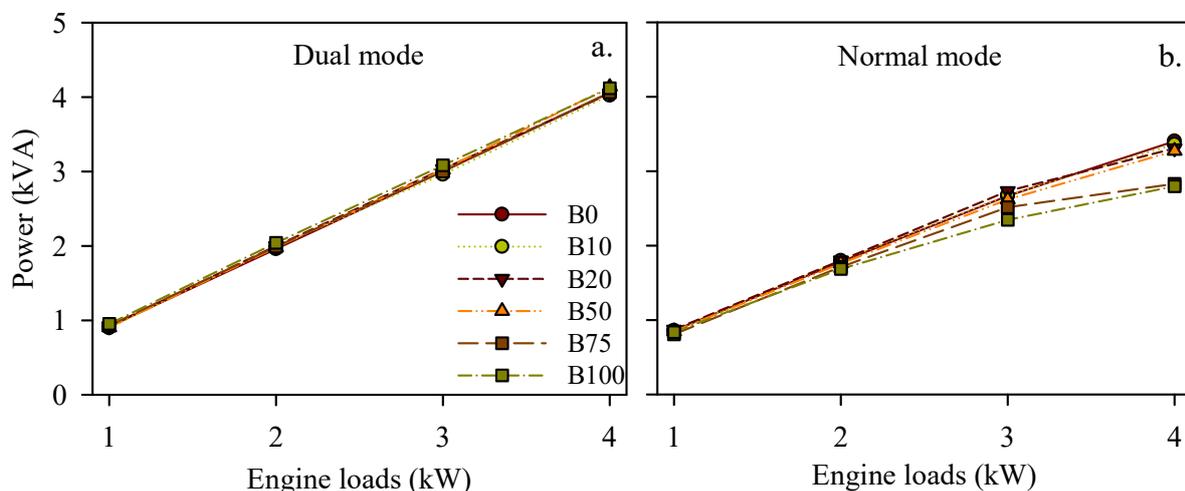


FIGURE 1. Power in dual mode (a) and normal mode (b) at different loads and biodiesel blends.

The specific fuel consumption (SFC) was lower in the dual mode (Figure 2a) than in the normal mode (Figure 2b). There was a substantial difference in the SFC in the dual mode. This factor is due to the manual control mechanism of biogas insertion in the generator-motor group, leading to different proportions of biogas insertion.

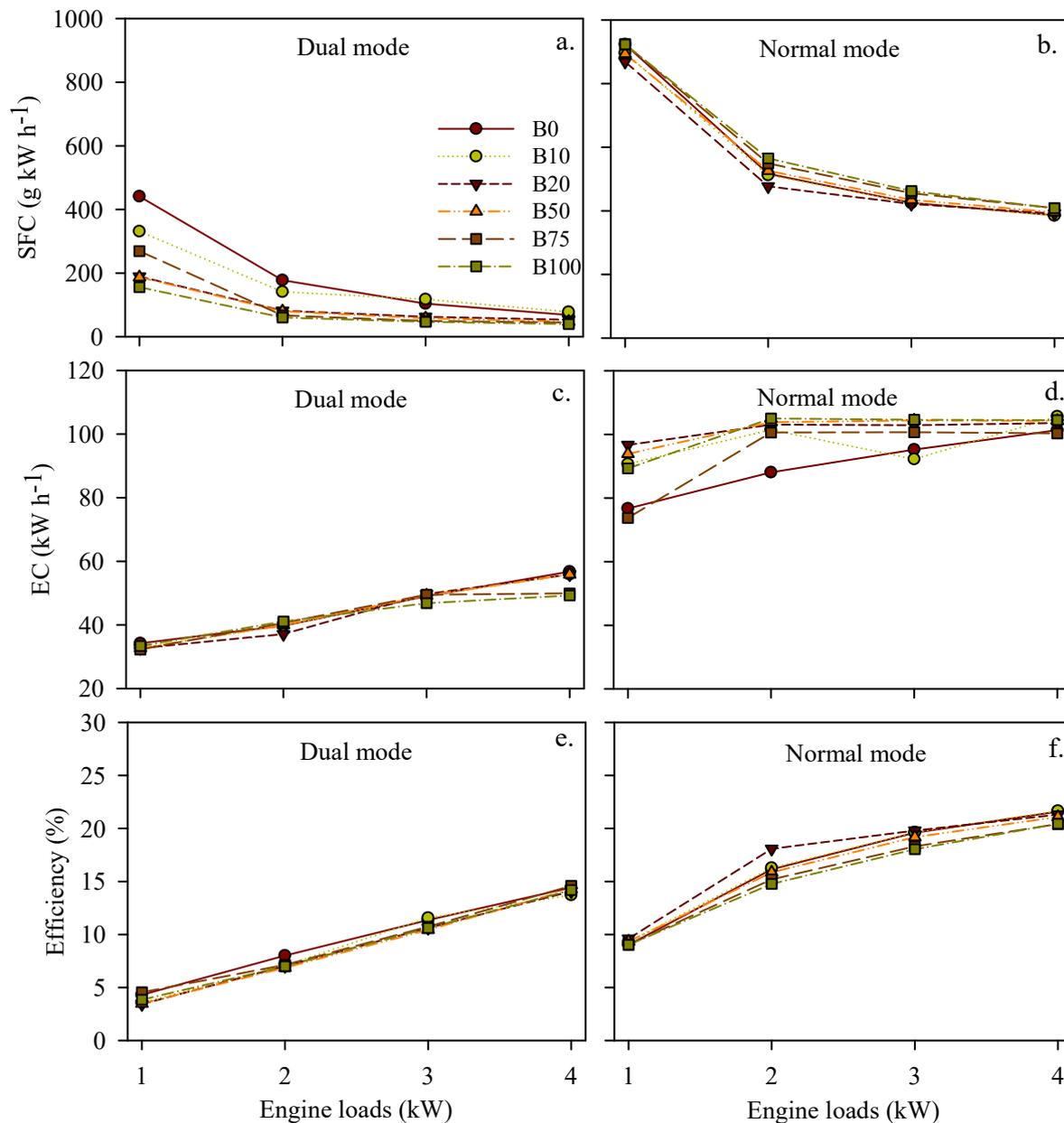


FIGURE 2. Specific fuel consumption (SFC; a and b), energy consumption (EC; c and d), and efficiency (e and f) in dual mode and normal mode at different loads and biodiesel blends.

The insertion of biogas proved to be efficient in reducing SFC (Figure 2a). Energy consumption (EC) was higher in the normal mode (Figure 2c) than in the dual mode (Figure 2d) because in this mode, it is essential that diesel or biodiesel cause detonation of the air-fuel mixture. Even when detonation occurs, there is no complete combustion of hydrocarbons, and the exhaust temperature increases relatively according to the emission data presented and discussed later.

The higher proportions of biodiesel resulted in a greater reduction of SFC in the dual mode (Figure 2a). The reduction in SFC may be related to the higher oxygen concentration and a higher flash point of the biodiesel that contributes to explosion (Wazilewski et al., 2013).

The increased load on the generator-motor group had a positive influence, leading to a reduction in the SFC in the

dual and normal modes (Figure 2a and b). This is due to improved combustion (Deheri et al., 2020). This reduction was more pronounced in the dual mode owing to the tendency to diminish due to more complete combustion of the natural gas (Egúsquiza et al., 2009).

The highest efficiency calculated in the dual mode was 14% at a 4 kW load and with biodiesel B0 (Figure 2e). Under the same settings (4 kW and B0), in the normal mode operation, the efficiency was 22% (Figure 2f). The decrease in efficiency in the dual mode might be due to the introduction of biogas into the engine cylinder, which diminishes the O₂ concentration; therefore, the fuel conversion efficiency decreases, leading to incomplete combustion (Bora & Saha, 2015; Barik et al., 2017). Another reason might be the decrease in the flame

propagation velocity and enhanced work of compression, leading to the induction of large amounts of air-biogas mixtures (Aithal, 2010). The latter reason can be explained by the residual effect of the biogas. Consequently, there is a lower combustion temperature and the highest fuel flow rate during the combustion process (Yoon & Lee, 2011).

The exhaust gas temperature (EGT) variation between the intake air and exhaust gases increased with

increasing load in the dual mode (Figure 3a) as well as in the normal mode (Figure 3b). It is possible to relate the temperature increase of the gas emission to the efficiency reduction of the engine generator set in the dual mode compared to the normal mode. When evaluating the thermal cycle of diesel engines, we can conclude that the heat that affects these gases does not generate mechanical energy but rather generates thermal energy.

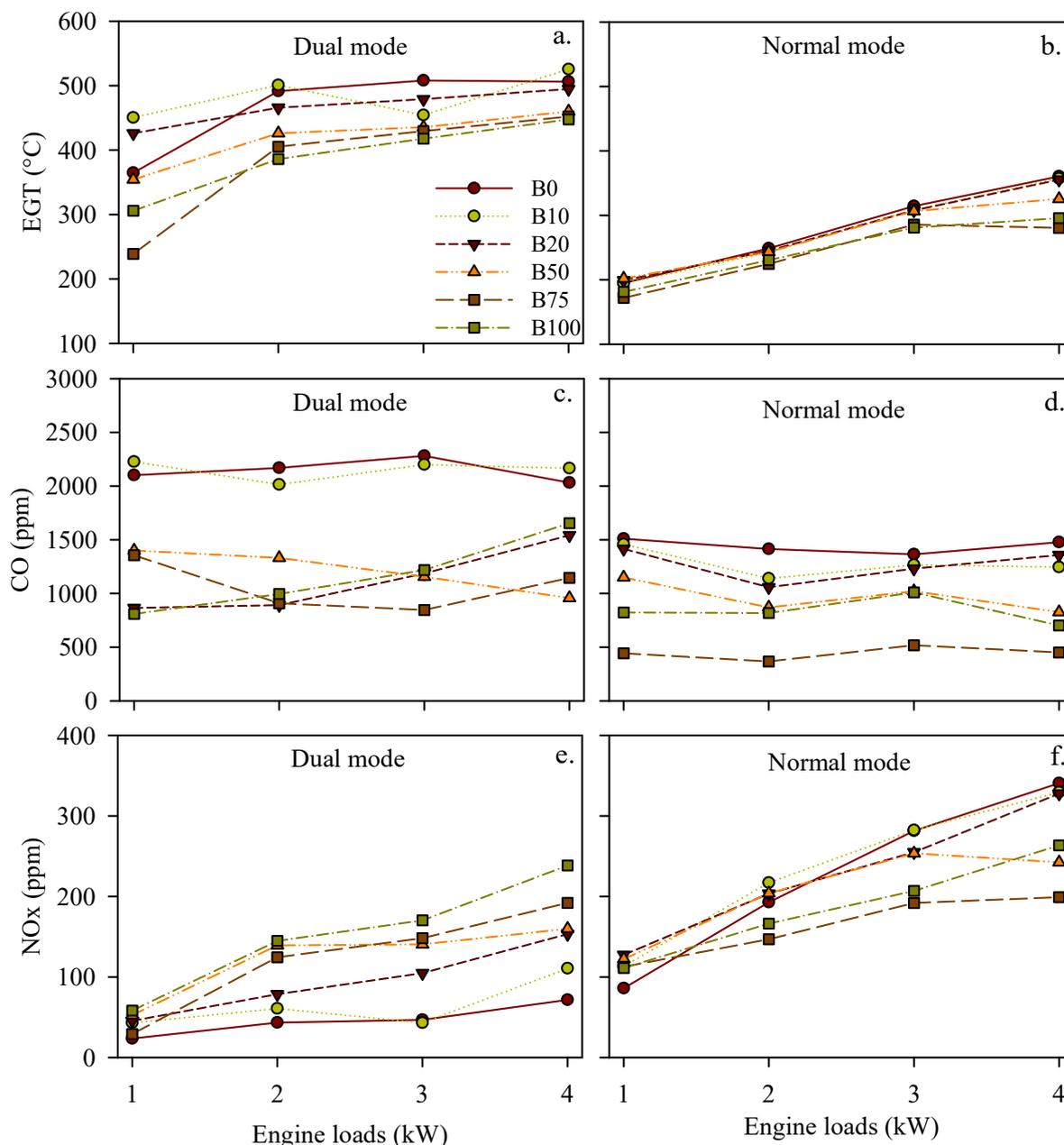


FIGURE 3. Exhaust gas temperature (EGT; a and b), carbon monoxide (CO; c and d), and nitrogen oxide (NOx; e and f) in dual mode and normal mode at different loads and biodiesel blends.

The lower the EGT, the greater the tendency to increase the efficiency of the motor-generator set (Figure 3a and b). According to Castellaneli et al. (2008), an increased load on the generator-engine set requires a higher engine performance, which leads to an increase in fuel consumption and heat loss. Moreover, an increase in temperature leads to an upward trend in the emission of gaseous pollutants. Yoon & Lee (2011) reported that the

temperature increases proportionally to the load increase in the normal and dual modes.

The CO emission was higher in the dual mode (Figure 3c) operation than in the normal mode (Figure 3d), possibly due to the presence of CO₂ in the biogas. This may be due to the replacement of fresh air by the carbon dioxide present in the biogas. With increasing CO₂ content in biogas, the flame speed is reduced, and incomplete

oxidation of charge takes place, resulting in higher CO emissions (Deheri et al., 2020).

In both the modes, CO emissions decreased as the percentage of biodiesel in the liquid fuel increased (Figure 3c and d). CO emissions from crambe biodiesel were reduced with an increase in the blending of crambe biodiesel with diesel (Leite et al., 2019). The higher oxygen content in biodiesel allows more carbon molecules to burn, and thus complete fuel combustion occurs.

With higher engine loads and high combustion temperatures, combustion is more efficient and generates less CO emissions. According to Kivevele et al. (2011), carbon dioxide results from incomplete combustion. Crambe biodiesel produces low emissions at all loads (Rosa et al., 2014). This reduction in CO emissions is attributed to the higher oxygen content and quantity of cetane in the crambe biodiesel, which facilitate total combustion, promote a reduction in ignition time, and lead to a low ease of CO (Rosa et al., 2014). Mofijur et al. (2014) observed that the blends of palm biodiesel (B5 and B10) and moringa biodiesel (B5 and B10) presented 13, 17, 5 and 10% lower CO emissions than biodiesel (B0), respectively.

The presence of biodiesel and biogas considerably affects the nitrogen oxide (NOx) concentration. The NOx emission reduction occurred because of the insertion of biogas. In the dual mode, emissions increased as biodiesel increased during blending (Figure 3e). The excess oxygen in biodiesel and the longer delay before ignition when using biodiesel causes an increase in the peak temperature during combustion, leading to the formation of NOx (Maawa et al., 2020).

High levels of unsaturated fatty acids and longer chain length in vegetable oils have also been correlated with elevated NOx emissions (Ghazali et al., 2015). In the normal mode, unlike the dual mode, the increase in the biodiesel blend percentage reduced NOx emissions (Figure 3f). The main factors that favor the formation of NOx are a higher oxygen concentration, residence time, and peak combustion temperature (Mohsin et al., 2014).

High combustion temperatures and the presence of oxygen cause high NOx emissions (Yoon & Lee, 2011). NOx formation occurs in the high-temperature combustion gases inside the cylinder, primarily through the oxidation of nitrogen present in the induced air (Bora & Saha, 2015). The insertion of biogas into an engine generator reduces NOx emissions (Yoon & Lee, 2011). Lee et al. (2010) verified that with an increase in temperature, NOx emissions are increased. The application of biogas is an effective technique for reducing NOx emissions from biofuel engines under all load conditions. This biogas induction dilutes the inlet charge concentration, increases the specific heat capacity, and reduces the combustion temperature (Mahla et al., 2018).

CONCLUSIONS

1. In the normal mode, a loss of power occurred as the biodiesel content in the blend increased.

2. The insertion of biogas proved to be efficient in reducing SFC.

3. The highest efficiency calculated in the dual mode was 14% at a 4 kW load and with biodiesel B0. Under the same settings (4 kW and B0), in the normal mode operation, the efficiency was 22%.

4. CO emissions was higher in the dual mode operation than in the normal mode.

5. NOx emissions were lower with the addition of biogas, especially up to the B10 blends.

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