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ELECTRICAL ENGINEERING

Energy efficiency in a dual engine using biogas and waste frying oil biodiesel

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ABSTRACT. The generation of electric energy using alternative energy sources has been constantly studied by researchers owing to concerns regarding energy supply alternatives and the desire to reduce environmental impacts in its generation. This study evaluated the performance of an electricity generator operating in dual mode using biogas and biodiesel blends, which were obtained from a swine-waste biodigester and residual frying oil, respectively. The experiment was performed using blends B8, B20, B50, B80, and B100. The electrical power generated was higher in the dual mode corresponding to a load of 5.0 kW, showing differences of 18.7% for B8 and 21.7% for B100. In normal and dual modes, the B8 blend exhibited the lowest specific consumption of liquid fuel with values of 389.2 and 270.2 g kWh^{-1}, respectively. The efficiency was higher in the normal mode, showing results of 22.0 and 24,7% using B8 and B100, respectively, compared to 17 and 20% in the dual mode corresponding to a load of 5.0 kW. These results indicate that biodiesel from residual frying oil can be used in normal mode and in combination with biogas in dual mode.

Keywords: renewable energy; alternative fuel; biodiesel blends; fuel consumption; engine performance.

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Introduction

The demand for electricity, along with its cost, has gradually increased significantly over the years. This raises concerns about its generation, particularly in rural properties isolated from large centers, owing to the high risk of insufficient electricity supply through the distribution network (Vidotto et al., 2024). Therefore, electricity from small power stations has become a good alternative for solving both the demand and cost problems (Lacchini & Rüther, 2015; Almeida et al., 2016).

In this context, the use of biodiesel is a viable alternative to fossil fuels (Paiva et al., 2022; Nguyen et al., 2024). It has the advantages of reducing greenhouse gas emissions, presenting a zero CO_2 balance, and being renewable, biodegradable, and nontoxic (Atapour et al., 2014). However, the developments in biodiesel production, mostly derived from vegetable oils, raise concerns about its sustainability. The use of vegetable oil has a direct impact on food security and the prices of agricultural commodities (Nogueira & Capaz, 2013; Ajanovic & Haas, 2014).

An alternative may be the use of residual frying oil as a raw material for biodiesel production. Recycling waste frying oil (Atapour et al., 2014) is essential in reducing biodiesel production costs although it requires pretreatment before using it as a raw material, as it can contain residual food and other impurities (Lam et al., 2012; Talebian-Kiakalaieh et al., 2013). In addition, the use of residual frying oil can reduce sanitation costs by mitigating irregular disposal of residual frying oil in the environment (César et al., 2017).

Biogas, which is considered one of the main sources of energy today, is another fuel from biomass that can be used in biodiesel production in addition to having several uses because of its direct use in space heating (Souza et al., 2013; Kadam & Panwar, 2017). Biogas can originate from several sources, including pig waste (Souza et al., 2023). Consequently, swine biogas is converted into biogas through biodigesters installed in rural areas (Souza et al., 2016; Werncke et al., 2023). In addition to biogas production, the residual solid matter is used as a fertilizer for agriculture (Mydeen et al., 2016).

To generate energy from biomass, internal combustion engines in dual mode can simultaneously operate on liquid and gaseous fuels (Bora & Saha, 2015; Mohite et al., 2024). A quantity of liquid fuel (diesel, biodiesel, or blends of biodiesel with diesel) must be injected into the chamber as an ignition source along with the biogas. The liquid fuel is called pilot fuel, and the gaseous fuel (biogas) is the primary fuel responsible for producing power in the engine (Bora & Saha, 2015). Different liquid fuels, such as biodiesel from waste frying oil, can affect the efficiencies of biodiesel and biogas blends. Although several studies have investigated the concept of dual fuels (Yoon & Lee, 2011; Bora & Saha, 2015; Werncke et al., 2023), interactions between biogas and waste-frying biodiesel have not been investigated yet—this is necessary to evaluate the viability of this type of bifuel as an alternative fuel comprehensively. Therefore, this study aims to evaluate the energy performance of an electric generator engine operating in dual mode using biodiesel from waste frying oil and biogas.

Material and methods

The study was conducted at the Biomass Gasification and Electricity Microgeneration Laboratory at the State University of Western Paraná (UNIOESTE) (latitude 24°59'20.8"S and longitude 53°26'58.8"W) and in a pig farm in the municipality of Maripá in western Paraná (latitude 24°24'07.2"S and longitude 53°52'19.3"W).

Biodiesel was developed using a transesterification reactor. Methyl alcohol (CH_3OH) and sodium hydroxide (NaOH) were used as catalysts for the biodiesel production, after which the residue was cleaned with water. For the transesterification reaction, sodium hydroxide was dissolved in methyl alcohol and subsequently added to the reactor already containing the ORF heated to 50°C. During the reaction, the temperature was maintained, and the mixer was turned on. After the reaction, the electrical resistance and mixer were turned off to decant the glycerin. Subsequently, the biodiesel was washed with water and dried by activating the mixer and the electrical resistance, maintaining the temperature constant at 60°C for 24h.

After biodiesel production, liquid fuel blends with the following nomenclatures were created: B8 (8% biodiesel and 92% diesel – commercial diesel), B20 (20% biodiesel and 80% diesel), B50 (50% biodiesel and 50% diesel), B80 (80% biodiesel and 20% diesel), and B100 (pure biodiesel).

To conduct the experiments, a single-cylinder, air-cooled diesel generator set (BD-6500 CF, Branco) (Table 1) was used. For each liquid fuel blend, four repetitions were performed with load variations ranging from 0 to 100%.

Table 1. Engine technical specifications.

Engine		Engine generator set	
Description	Specification	Description	Specification
Maximum power	10 cv at 3600 rpm	Maximum power	5.5 kVA
Continuous power	9 cv at 3600 rpm	Continuous power	5.0 kVA
Cylinder capacity	406 cm^3	Output tension	110 V / 220 V
Compression ratio	19:1	Tension control	Capacitor/brushless
Diameter x stroke	86x70 mm	Phases	Single phase
Combustion system	Direct injection	Autonomy	5.20 h
Maximum torque	2.70 kgfm at 2000 rpm	Tank capacity	12.5 L
Consumption	2.15 Lh^{-1}	Mass (set)	95 kg
Lubrication	Forced by oil pump	Noise 7 m	79 dB
Dimensions (LxWxH)	417x470 x494 mm	Dimensions (LxWxH)	735x458x670 mm

A heat pump calorimeter model E2K with values in MJ kg^{-1} enabled the determination of the gross heating value of the fuels (Table 2). The method described by Volpato et al. (2009) allowed the calculation of the lower heating value (LHV) using Equation (1).

$$LHV = HHV - 3052 \quad (1)$$

where HHV is the higher calorific value of methane.

Table 2. Higher heating value (HHV), and lower heating value (LHV) to biodiesel blends.

Biodiesel blend	HHV (kJ kg^{-1})	HHV (kJ kg^{-1})
B8	45090	42038
B20	44557	41505
B50	41703	38651
B80	39867	36815
B100	38964	35912

The concentration of methane in the biogas was 63.5%, which was obtained using a gas analyzer (Landtec GEM™ 5000 Plus). The lower heating value of methane (LHVm) was 22,562 kJ m^{-3}. In the literature, a calorific value of 1 m^3 of methane gas is specified as 8,500 kcal (Buller et al., 2021). Equation (2) was used to evaluate the amount of biogas energy.

$$LHV_b = (P_m/100) * LHV_m \quad (2)$$

where the lower calorific value of methane (LHVm) is equivalent to 8,500 kcal m^{-3}, and Pm is the percentage of methane in the biogas (%).

To simulate the consumption of electric energy, we used a bank of resistive loads composed of eight resistors with a supply voltage of 220 V in alternating current.

The biogas flow was analyzed using a YF-S201 flow sensor coupled to the biogas inlet of the engine generator set, with the data stored using a data collection system. A Magnetrol thermal mass flow meter (model TA2) was also used, directly indicating the biogas flow (m^3 h^{-1}) on its display.

The liquid fuel flow was measured using a YF-S401 flow rate sensor, with a measurement range of 0.3-6.0 L $min.^{-1}$, coupled to the outlet of the liquid fuel tank. The data were collected using the data collection system.

Specific consumption, efficiency, and economy were calculated according to the study of Werncke et al. (2023). The uncertainty results for each type of equipment were also determined, with an acceptable range for uncertainty below ± 5%. In this context, the overall uncertainty of the system was within acceptable limits.

Results and discussion

The electrical power generated in the dual mode (liquid fuel and biogas) was slightly higher than that obtained in the normal mode (liquid fuel only). During the normal mode, the power curve decays proportionally to the load increment, exhibiting a sharp loss from a load of 4 kW. In the dual mode, the power curve exhibits a linear behavior without a sharp drop (Figure 1). These changes in potency are due to the lower calorific value of biodiesel (Nietiedt et al., 2011).

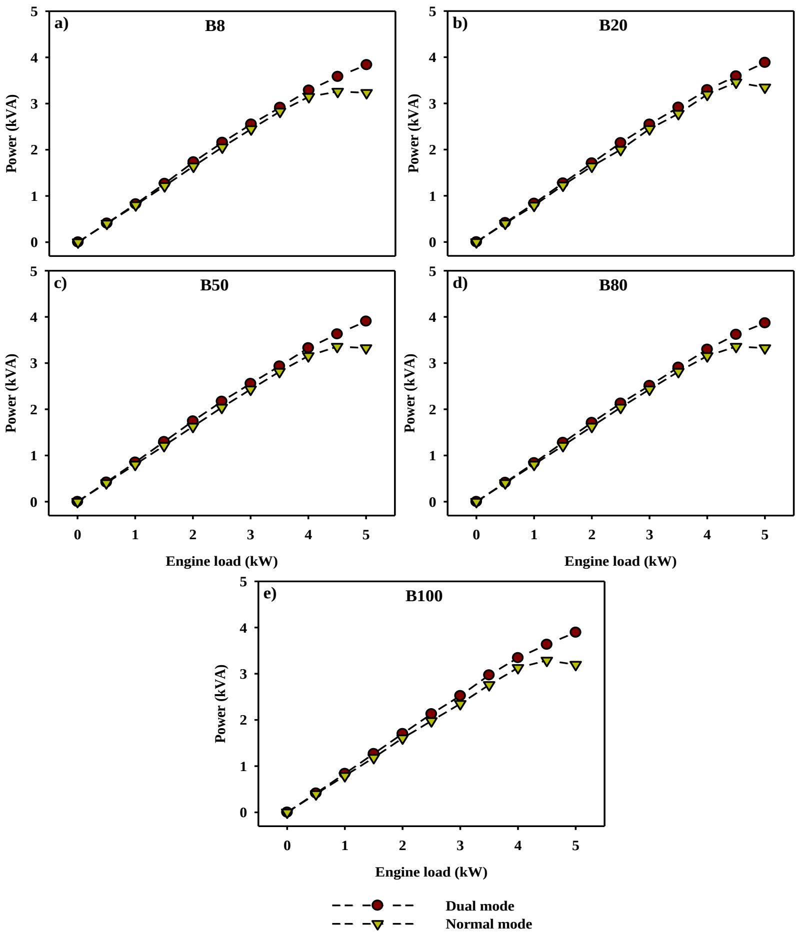

Figure 1. Power at different loads in normal mode and dual mode according to biodiesel blends (a-e).

The difference in electrical power generated during the low-load application showed little difference between the dual and normal modes, being around 5% for all liquid fuels (Figure 1). However, this difference in the generated electrical power increased proportionally with an increase in load, reaching the largest difference at a load of 5.0 kW. The largest differences were 18.7, 16.0, 17.4, 16.3, and 21.7% during the operation with liquid fuels B8, B20, B50, B80, and B100, respectively. These results are similar to those obtained by Ambarita (2017). When studying the behavior of the compression ratio in a dual engine with biogas and biodiesel, Barik et al. (2017) also demonstrated a power increase during dual-mode operation.

The specific consumption of liquid fuel was lower in the dual mode than in the normal mode. It was observed that the increase of biogas as an energy source had a positive influence. This reduction in the specific consumption yielded average results of 33.3, 32.0, 32.7, 31.5, and 34.9% using fuels B8, B20, B50, B80, and B100, respectively (Figure 2). A reduction in the difference between the dual and normal modes was observed with an increase in load. This can be attributed to the insufficient biogas supply required by the engine generator set. This reduction was more pronounced in the dual mode because of the downward trend owing to the more complete combustion of natural gas (Egúsquiza et al., 2009). The lower rate of combustion of gaseous fuel can be attributed to the lower air–fuel ratio in the combustion chamber and the lower combustion temperature. It should be noted that the difference between the specific consumptions of single and dual fuels during combustion is known to diminish with increasing engine load (Ramesha et al., 2015). At lower engine loads with high diesel substitution, most of the combustion chamber is filled with the primary fuel (biogas) and ignited by a small quantity of pilot fuel (diesel) (Verma et al., 2017).

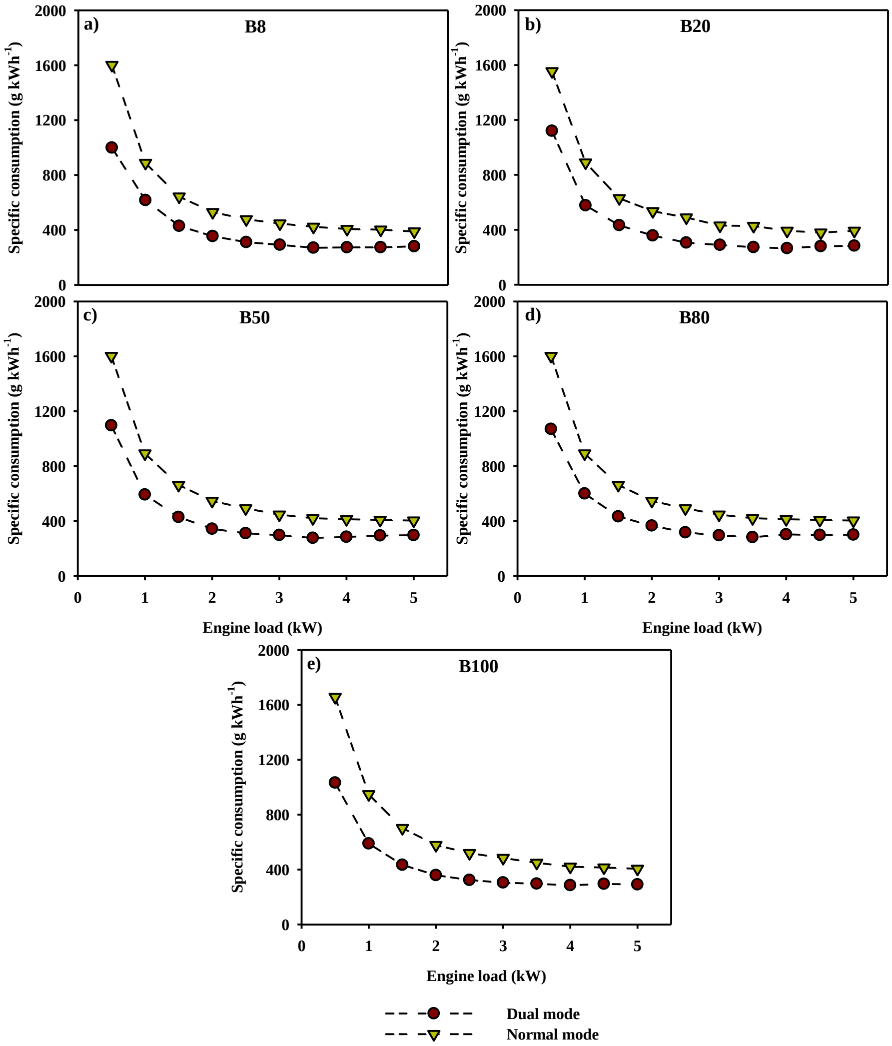

Figure 2. Specific consumption at different loads in normal mode and dual mode according to biodiesel blends (a-e).

The measured efficiency was higher in the normal mode, reaching 22.0, 22.1, 23.1, 24.2, and 24.7% using fuels B8, B20, B50, B80, and B100, respectively, with the highest load application of 5 kW (Figure 3).

The decrease in efficiency in the dual mode might be due to the introduction of biogas into the engine cylinder, which diminishes the O_2 concentration; therefore, the fuel conversion efficiency decreases, resulting in 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, resulting in the induction of large amounts of air-biogas blends (Aithal, 2010). The latter can be explained by the residual effects of the biogas. Consequently, there is a lower combustion temperature and the highest fuel flow rate during the combustion process (Yoon & Lee, 2011). Several researchers have reported decreased efficiency in the biogas-biodiesel dual fuel mode (Karagoz et al., 2016; Mahla et al., 2018; Rahman & Ramesh, 2019).

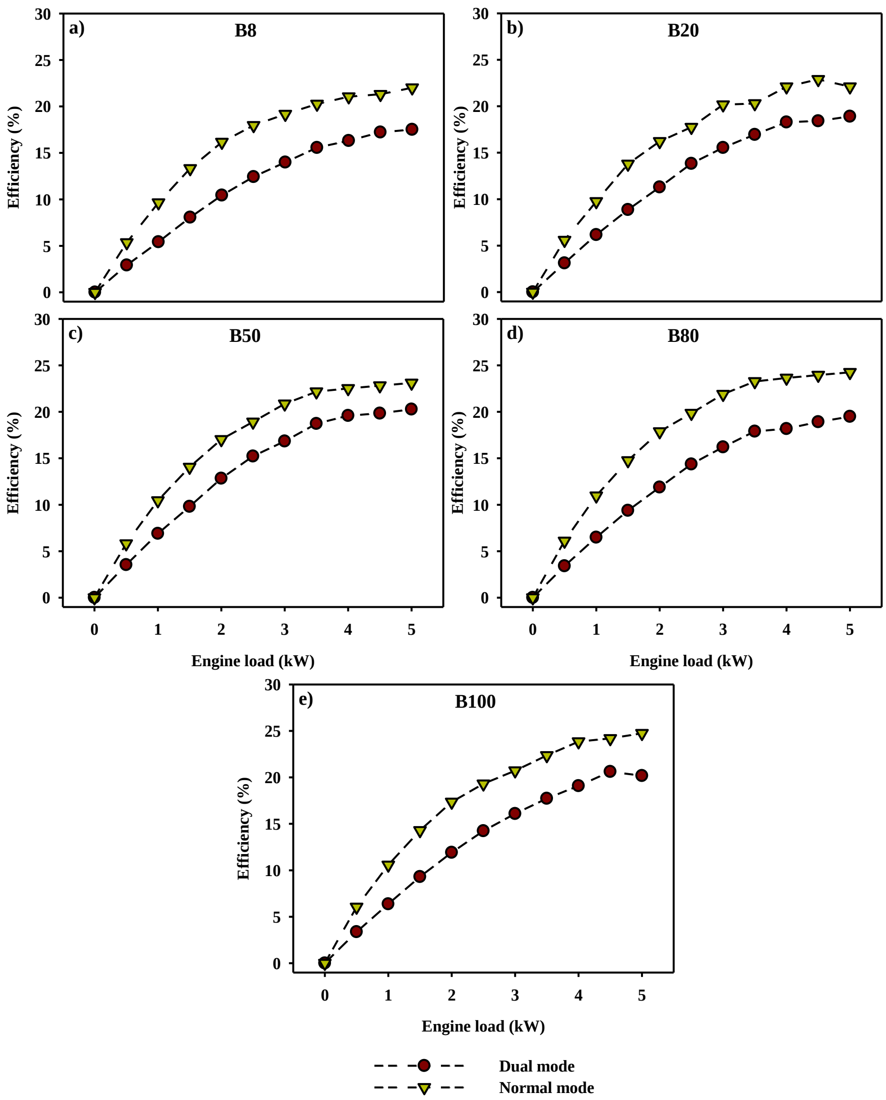

Figure 3. Efficiency at different loads in normal mode and dual mode according to biodiesel blends (a-e).

The economy of liquid fuel shows the replacement behavior curve as a function of the load applied for each fuel blend (Figure 4). In all cases, a reduction in the replacement of liquid fuel was observed with an increase in load, mainly from 4.0 kW onwards. Similarly, it showed a possible insufficiency in the supply of biogas, forcing the generator engine to gradually consume more liquid fuel with an increase in load. The average liquid fuel economies for the B8, B20, B50, B80, and B100 blends were 30.0, 28.3, 27.8, 27.7, and 30.0%, respectively (Figure 4). The liquid fuel economy decreased with an increase in load, increasing from 4.0 kW (80% of the load), which indicates insufficient biogas supply.

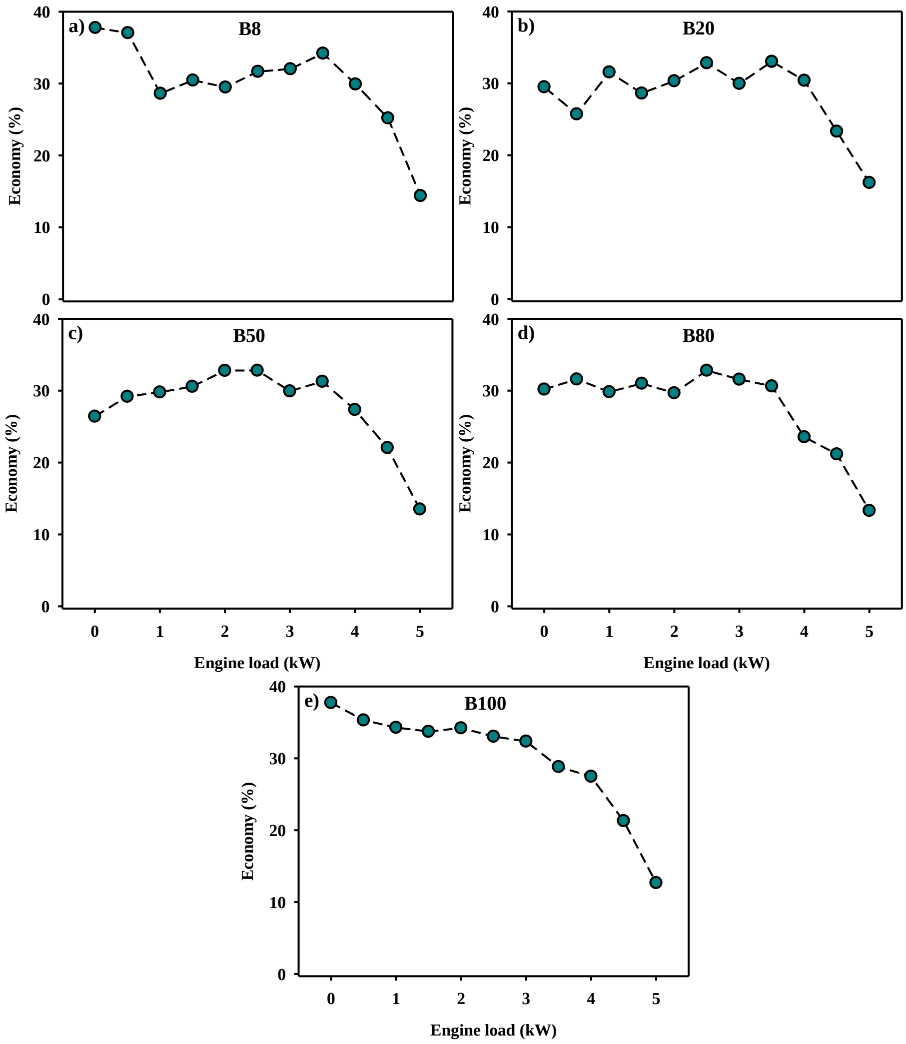

Figure 4. Economy of liquid fuel in dual mode according to biodiesel blends (a-e).

Conclusion

This study demonstrated the use of a diesel cycle generator set to generate technically efficient electricity in the normal mode using diesel/biodiesel blends and dual mode using biogas and diesel/biodiesel blends. Although the dual-mode energy efficiency was slightly lower than that of the normal mode, the generator engine performed well in both cases, with satisfactory electricity generation capacity and reduced liquid fuel consumption in the dual mode. In normal and dual mode, the B8 blend exhibited the lowest specific consumption of liquid fuel with values of 389.2 and 270.2 g kWh^{-1}, respectively. These results indicate that biodiesel generated from residual frying oil can be used in normal mode as well as in combination with biogas in dual mode, especially in the case of B8 blends.

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