



Article

Performance and Emissions of a CI-ICE Fuelled with *Jatropha* Biodiesel Blends and Economic and Environment Assessment for Power Generation in Non-Interconnected Areas

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Abstract: An experimental investigation into the effects of *Jatropha* biodiesel (JB) blends on the performance and emissions of a diesel engine was performed, and an economic and environmental assessment of the *Jatropha curcas* L. (JCL) crop for JB production and its use was also presented. The results revealed that when the engine operates with JB blends in proportions of up to 10%, the brake-specific fuel consumption (BSFC) increases to 37.5% at full engine load, and the engine's thermal efficiency is reduced by 10% regarding diesel operation. A reduction in the specific emissions of carbon monoxide, unburned hydrocarbons, and particulate matter with JB blends of up to 75% of the engine load was found. On the other hand, specific carbon dioxide and nitrogen oxide emissions, with regard to diesel, increased by 21.8 and more than 100%, respectively. The lower heating value (LHV) was the property that most influenced the engine's performance and emissions fuelled with JB blends, because JB has a lower value of LHV than diesel. Finally, the economic and environmental assessment showed that Colombian soil is well-suited to JCL crops. The use of JB instead of palm biodiesel could mean a decrease of 27,730 USD/day and 1588 kg/day of CO₂ emissions.

Keywords: *Jatropha curcas* L.; internal combustion engine; biodiesel; emissions



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1. Introduction

Due to difficult geographical conditions, Colombia has nearly 1785 locations without connections to the electric grid [1]. Therefore, more than 250,000 people lack adequate electric services, preventing them from developing economic and social activities that allow them to improve their quality of life. The installed power of those zones is 312,911 kW, mainly supplied by internal combustion engines (ICE) fuelled with diesel.

On the other hand, in Colombia, passenger and road freight transport are also propelled mainly by ICEs fuelled with diesel. The diesel these vehicles use contains 10% palm biodiesel (PB) to reduce greenhouse emissions, thus reducing the global CO₂ footprint and minimising the dependence on fossil fuels. However, the blend between palm biodiesel and diesel fossil has another series of problems associated with the physical PB properties and its production.

The massive production of palm biodiesel involves a loss in biodiversity in tropical areas [2]. Indonesia provides an example of this loss, since palm crops have replaced nearly 56% of tropical forests [3]. Moreover, in Colombia, the displacement of people from their place of origin by illegal groups to cultivate palm has been documented [2]. Additionally, biodiesel production using raw food materials, such as palm, is not sustainable because they compete with crop areas intended for food [4–6]. On the other hand, Colombia has several cities and routes above 2000 masl, where morning temperatures are less than 10 °C. In these conditions, PB fluidity is compromised, forming lumps in the fuel tank that

clog fuel filters and injectors, thus increasing vehicle maintenance costs. For these reasons, and to keep the political government that promotes the use of biofuels, it is imperative to migrate to another crop to produce biodiesel. According to the literature, the *Jatropha curcas* L. (JCL) tree seems to be the crop most suitable to replace palm crops for biodiesel production [7].

The JCL is a tree whose seeds contain a large amount of non-edible oil that could be used for second-generation biofuel production. The JCL crop consumes less water than the palm crop. Also, the JCL can be cropped in semi-arid and tropical zones (where Colombia is located) [8]. According to the literature, it only requires a few agricultural inputs, which could be profitable for farmers [9]. Hence, JCL biodiesel (JB) could become an excellent option to replace the PB used in Colombia.

Like PB, JB can be used directly or blended with fossil fuel diesel in compression ignition (CI) ICE without modifications in the supply fuel system [10]. In addition, JB can withstand lower temperatures without affecting biodiesel fluidity, making it an excellent option for use on all Colombian thermal floors [10,11]. Based on this, the change of PB for JB in blends with diesel fossil should not affect the fuel supply chain, or the emissions and performance of engines. On the contrary, due to the better fluidity and low tendency to saponification, the use of JB would provide a reduction in the operation costs of the ICE.

Several studies have evaluated CI-ICE fuelled with blends of JB with fossil fuel diesel. They have shown that the engine's performance and emissions are similar to those obtained with a CI-ICE fuelled with PB, and the performances parameters, such as torque, brake-specific fuel consumption (BSFC) and thermal efficiency are lower than those obtained using diesel; this is mainly due to the lower heating value (LHV) of JB. However, JB increases the volumetric efficiency produced by the oxygen content in biodiesel. Regarding the emissions with blends of JB, there is a rise in NO_x due to the higher temperature of the exhaust gases that promote NO_x formation. Also, due to a better combustion process, there is a rise in carbon dioxide (CO₂) emissions and a reduction in unburned hydrocarbon emissions (HC) and carbon monoxide (CO) [12–29].

Despite a large number of studies on the topic, there have yet to be any particulate matter emissions studies with blends of JB, and fewer studies on the performance and emissions of CI-ICE fuelled with blends of JB operating at high altitudes above sea-level. On the other hand, there needs to be more information on how the JCL crop and JB production in areas not connected to the national electricity grid could improve their power autonomy. This research could contribute to improving the quality of life of the inhabitants of these locations because they could be self-sufficient and thus not depend on third parties for fuel supply.

Based on the above, this research aims to evaluate the performance parameters and emissions of a CI-ICE fuelled with blends of JB with diesel fossil operating at 2600 masl. An analysis of the main aspects of the substitution of palm with JCL as a raw material to produce biodiesel was presented and a key aspect analysis used in power generation in Colombian rural areas that lack a connection to the national electricity grid was provided. Furthermore, the study evaluated the economic and environmental impacts of the production system and the suitability of JCL production in areas requiring electrification. The economic and environmental statements are critical to the scope of this research, which aims to mitigate the negative impacts associated with palm oil crops, including the expansion of palm crops, land degradation, and security issues, among others.

This research work developed experimental performance and emissions tests on a CI-ICE fuelled with several blends of JB and diesel. The engine operation tests were conducted in the atmospheric conditions of Bogota city (2600 masl) at four engine loads in three rotational speeds to understand the behaviour of the CI-ICE in non-ideal operation conditions. The economic and environmental assessment was based on the BSFC obtained to carry out the analyses and determine the feasibility of using the JB as a fuel for power generation in non-interconnected areas.

2. Materials and Methods

This section shows the main characteristics of the testing bench, CI-ICE, the exhausted gas and particulate matter meters, and the different measurement devices used in the experimental tests. It also explains how the biofuel blends are prepared, and a detailed explanation of the developed experimental procedure is presented. Finally, the methodology used in the economic and environmental assessment of implementing the JB for power generation in non-interconnected areas in Colombia is described.

2.1. Testing Bench

The CI-ICE used for experimental tests is a Lister Petter (Gloucestershire, England) reference LPW3, naturally aspirated, water-cooled and direct-injected. This was designed as an electric generator, which means it was designed to operate at a constant rotational speed (1800 rpm). Nevertheless, the engine was modified to operate under different rotational speeds in the experimental tests. Table 1 shows the characteristics of the CI-ICE used in the experimental tests.

Table 1. Main characteristics of the CI-ICE used in the experimental tests.

Engine Parameters	Specifications
Manufacturer	Lister Petter
Engine Type	4 stroke, variable speed
Number of cylinders	3
Type Fuel Injection	Direct
Injection pressure	200 kPa
Displacement volume	1.395 L
Compression ratio	18.5:1
Cooling type	Water

The testing bench used has a hydraulic brake, reference 516-C, made by Go Power Systems (Novi, MI, USA). The inlet water mass flow in the hydraulic brake is regulated by a needle valve, which fixes the water mass flow according to the engine load. A torque sensor reference 4520A1000 made by Kistler (Winterthur, Switzerland) was installed on the testing bench to provide the torque and rotational speed signals. These signals are acquired through a data acquisition card reference 6212 manufactured by National Instruments (Austin, TX, USA).

The airflow mass in the testing bench is measured using Meriam's (Westlake, OH, USA) airflow meter reference 50MW20, coupled with a differential pressure manometer reference DT-8890 made by CEM (Kolkata, India). The exhaust gas emissions were measured with two different gas analysers; the first is a Brain-Bee (Parma, Italy) analyser reference AGS-688, in which CO, CO₂, and HC were measured, and the second is a Testo (Lenzkirch, Germany) analyser reference 350, in which NO_x was measured. Finally, the measurement for the particulate matter was carried out on a Dekati (Kangasala, Finland) device, reference ELPI+. Table 2 shows the main characteristics and accuracies of all measurement devices. A module in the National Instruments software Labview was used for visualising, collecting, and storing the experimental data. Figure 1 shows the layout of the experimental setup.

2.2. Fuels Characterisation

The preparation of the blends of JB and diesel with low sulphur (5 ppm) was carried out with calibrated glass test tubes of 200 mL and with an accuracy of ± 4 mL. Mixtures in proportions of 3, 5, 7, 10, and 20% in volume for JB blends and fossil diesel were made. The density, kinematic viscosity, and the LHV of both fuels were measured following the procedure described in the standards: EN ISO 3675:1998, EN ISO 3104:1996 and DIN 51,900. According to these standards, the test temperature to measure density and kinematic viscosity are 15 °C and 20 °C, respectively. These properties were measured in the material science

Laboratory of Fundación Universitaria Los Libertadores, Bogotá DC Table 3 summarises the results obtained.

Table 2. Measurement equipment used in the experimental tests.

Device	Reference	Brand	Accuracy
Torque	4520A1000	Kistler	1 Nm
Thermocouple	Type K	-	1.5 K
Digital Scale	HN	BBG	1 gr
Data acquisition card	6212	N-I	2.71 mV
Air Flow meter	50MW20	Meriam	-
Differential pressure	DT-8890	CEM	7 Pa
Gas Analyser	AGS-688	Brain-Bee	0.01% CO, 0.1% CO ₂ , 1 ppm HC
Gas Analyser	350	Testo	1 ppm NOx
Particle counter	Elpi +	Dekati	-

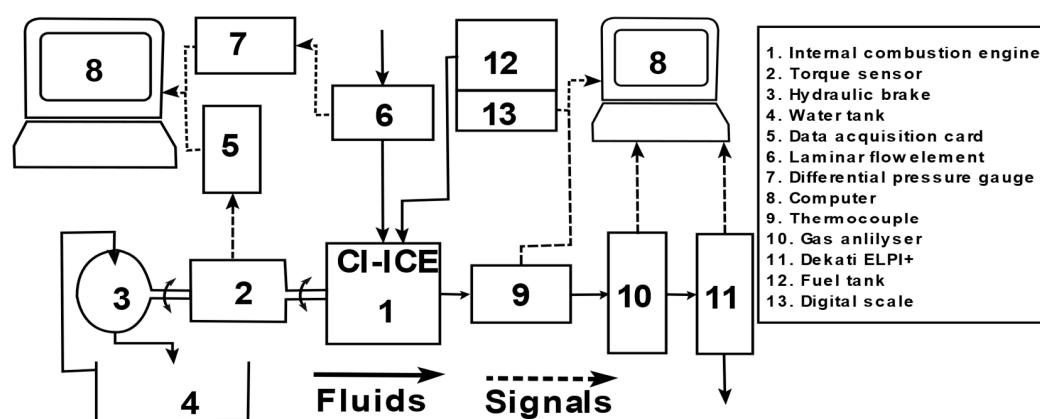


Figure 1. Layout of the experimental setup.

Table 3. Properties of the diesel and JCL biodiesel.

Property	Unit	Diesel	JB
Density at 15 °C	kg/m ³	830	880
LHV	MJ/kg	45.34	39.03
Viscosity at 20 °C	cSt	1.85	4.97

2.3. Experimental Tests Description

Three rotational speeds (1900, 2200, and 2500 rpm) were selected for the experimental tests. This selection aimed to determine the behaviour of the CI-ICE outside of the ideal operating rpm range (1900 rpm). The tests started with the blend of lower LHV, i.e., for the cases of 1900 and 2500 rpm, the blend was JB10, and for 2200 rpm, the blend was JB20. Once the CI-ICE reached the maximum engine load at the rpm established, measurements of the emissions and the engine performance parameters following the procedure of the standard ISO 15550 were conducted. Then, the same procedure was followed at 75, 50 and 25% of the engine load. When the first blend was measured completely, the second blend started and the procedure was repeated, and so on, until the mixtures proposed for the present work were measured.

The engine load was calculated in BMEP terms with the aim of comparing the behaviour under the same conditions. The performance parameters (fuel consumption and temperatures) and emissions (CO₂, CO, HC and NO_x) were measured three times for each condition. However, the particulate matter was only measured at up to 50% of the engine load due to the high level of opacity in the exhaust gases, which may compromise the

accuracy of the measurement. The BSFC and specific emissions calculations were made following the procedure shown in García and Murillo [30].

2.4. Economic and Environmental Assessment

The economic evaluation examined the reduction achieved using a blend of JB10 compared with commercial fuel in Colombia (PB10). For the analysis, the BSFC reported by Abedin et al. [31] was considered, along with the average cost of diesel obtained from an international reference website [32]. To quantify the potential fuel savings in non-interconnected areas in Colombia, daily power consumption data reported by the national government of Colombia were considered [1]. The analysis included an evaluation of the environmental impacts of the replacement of palm crops by JCL crops, considering the impact on the JB production life cycle [33]. The analysis focused on soil degradation from boot palm oil (PO) and JCL cultivation, as discussed by [33,34]. Additionally, the suitability of JB production in the non-interconnected areas was examined based on the agroclimatic compatibility of oleaginous species for different regions in Colombia as developed by [35]. Finally, to verify the benefits of JB as a fuel, the outcomes of the present work were compared with those obtained in previous research.

3. Results

3.1. Engine Performance

3.1.1. Break Specific Fuel Consumption

Figure 2 shows that the BSFC for all JB blends rises in relation to diesel. With the engine operating at 2500 rpm, on average, this rise was 4% for JB3, 14.5% for JB5, 18.5% for JB7 and 27.2% for JB10. At 2200 rpm, the rise was 10.8% for JB3, 20% for JB5, 28.9% for JB7, 38.8% for JB10 and 49% for JB20. At 1900 rpm, the results were 6.2% for JB3, 16.6% for JB5, 30.3% for JB7 and 37.2% for JB10; all of these were compared to the results found for the ICE working with diesel.

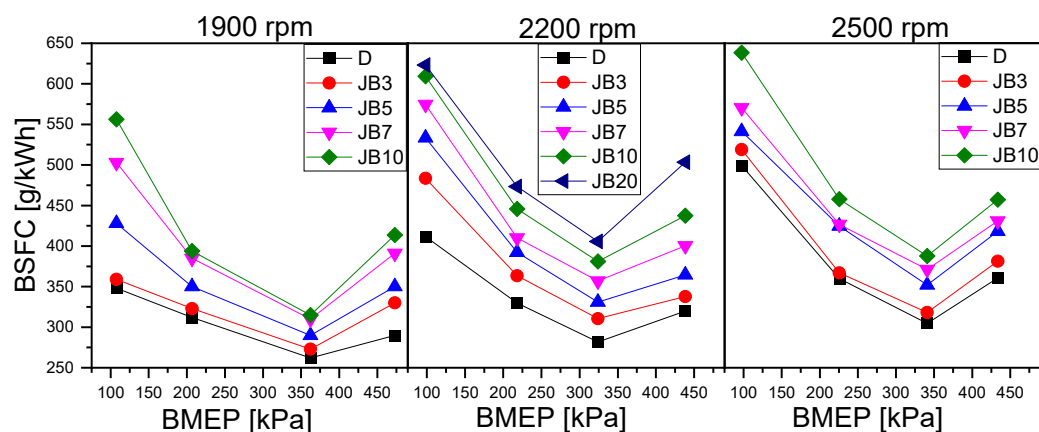


Figure 2. Results obtained for BSFC with BMEP at 1900, 2200 and 2500 rpm for JB blends.

The BSFC results show that no matter the load condition and rotational speed, the BSFC value is higher with blends of JB than with diesel. This behaviour for BSFC in tests occurred because the LHV value for JB is lower than the value for diesel, which results in a higher amount of fuel mass inside the engine to develop the same output power. Figure 2 shows that the value for BSFC rises when the JB percentage increases; this same behaviour was also found in other research [11,16,36].

3.1.2. Break Thermal Efficiency

Figure 3 presents the brake thermal efficiency (η_{th}) obtained from the CI-ICE working with JB and fossil fuel diesel blends. In this figure, it can be seen that the η_{th} on average is lower for JB mixtures of 3.2% for JB3, 10.2% for JB5, 14.2% for JB7 and 19.3% for JB10 in

comparison with the η_{th} reached by the ICE working with diesel at 2500 rpm. In this figure, it also can be seen that the results for η_{th} obtained with the engine working at 2200 rpm and 1900 rpm with the blends of JB, which have a closer behaviour than that reported for 2500 rpm. On average, the differences of η_{th} of the JB mixtures concerning those obtained for diesel were between 4.5 and 24.2% at 1900 rpm and 2200 rpm. Finally, the minimum and maximum η_{th} values varied from 14 to 30.5% at 1900 rpm, 12.5 to 28.3% at 2200 rpm, and 12.1 to 25.9% at 2500 rpm.

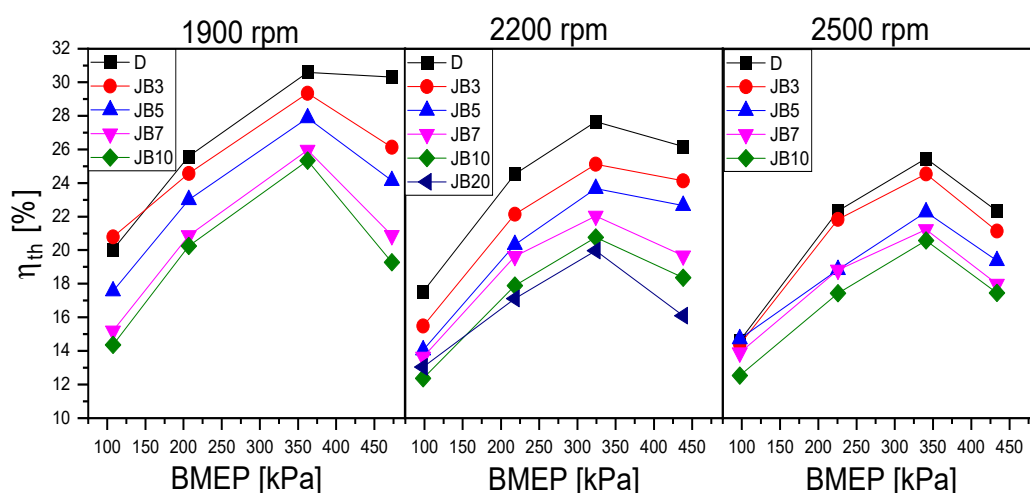


Figure 3. Results obtained for η_{th} with BMEP at 1900, 2200 and 2500 rpm for JB blends.

The results obtained for brake thermal efficiency were expected and agreed with those reported in the literature [12,18,27]. This behaviour of the brake thermal efficiency with JB is because the output power is lower (break power) in every regime and load condition of the ICE with a specific fuel consumption much higher than that of diesel. On the other hand, it was also observed that no matter what kind of blend and rotational speed was set, higher thermal efficiency was found at 75% of the engine load, an operational point where the engine gives the maximum output power with minimum fuel consumption.

3.1.3. Volumetric Efficiency

Figure 4 shows the results obtained for volumetric efficiency (η_{vol}). The results show that the engine's η_{vol} increases when it operates with JB blends compared to the results obtained for diesel operation. On average, this increase with the JB blends at 1900, 2200 and 2500 rpm regarding the diesel operation was 3.1, 2.4, and 4.1%, respectively. This increase in the η_{vol} found in the experimental tests using JB is mainly due to the oxygen content in the molecule of JCL, which supplies the lack of oxygen in the air when it develops a combustion process at a high altitude on CI-ICEs

3.2. Emissions

3.2.1. Exhaust Gas Temperature

It can be seen in Figure 5 that for the whole conditions of load and speed, the exhaust gas temperature was increased for the blends of JB tested. On average, the temperature increased with the blends of JB between 12 and 41 °C at 2500 rpm, 7 and 55 °C at 2200 rpm and between 18 and 51 °C at 1900 rpm regarding diesel. This behaviour is due to a longer combustion process when the CI-ICE is fuelled with JB blends, which is caused by the extra oxygen in the combustion process [12,14,20,25]

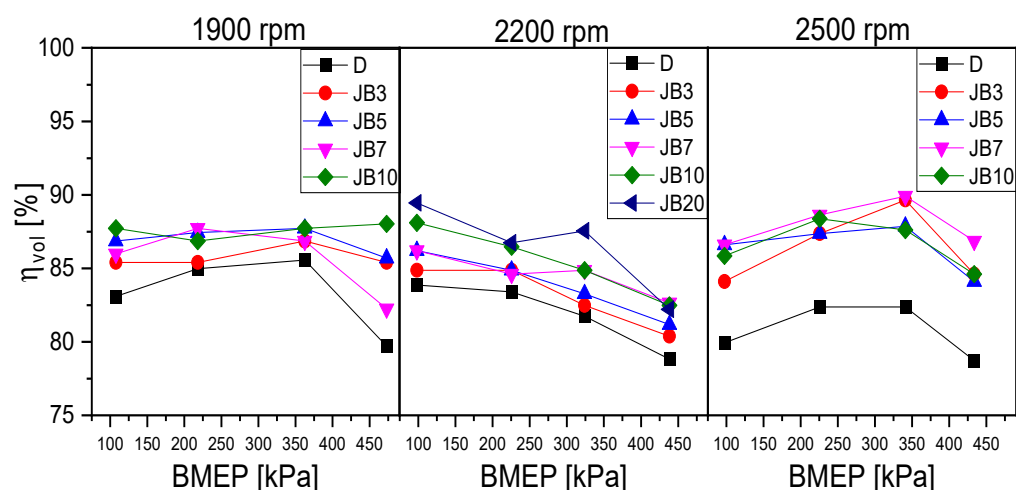


Figure 4. Results obtained of η_{vol} with the BMEP at 1900, 2200 and 2500 rpm for the JB blends.

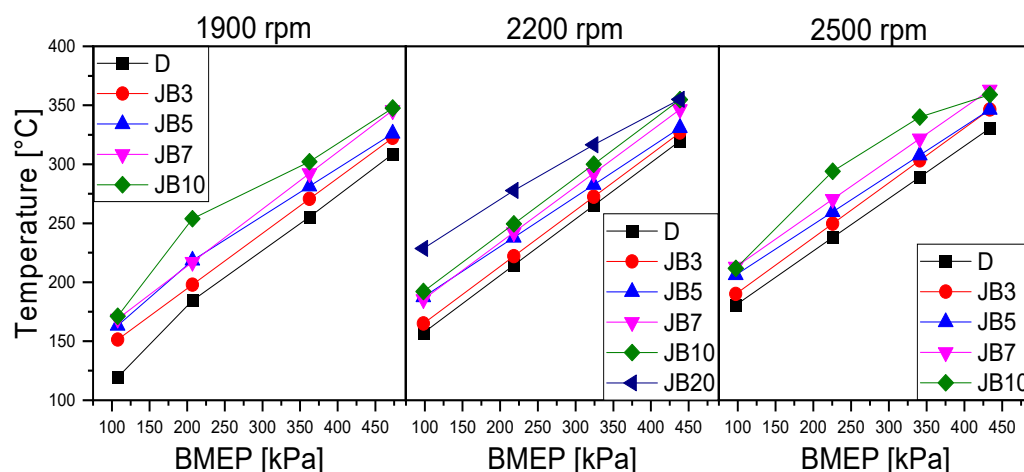


Figure 5. Results obtained for exhaust gas temperature with BMEP at 1900, 2200 and 2500 rpm for JB blends.

3.2.2. Specific Emission of Carbon Dioxide (BSCO₂)

Figure 6 shows that the BSCO₂ obtained for all JB blends and all rpm conditions was higher than diesel operation only. The average increase in the values obtained for all engine load ranges with the JB blends were 18.2, 21.8 and 14.7% at 2500, 2200 and 1900 rpm, respectively. This tendency in the BSCO₂ behaviour with blends of JB was also found by different authors who indicate that this increase in emissions is mainly due to the additional oxygen content in the JCL, which leads to the carbon in the fuel reacting more easily in the combustion process due to the higher amount of oxygen available, and thus to the formation of CO₂ [13,19].

3.2.3. Specific Emission of Carbon Monoxide (BSCO)

Figure 7 presents the results for the BSCO obtained with the JB blends and fossil diesel. This figure shows that blends of JB present a decrease of 30.7, 31.3 and 27.2% at 2500, 2200 and 1900 rpm, respectively, at up to 75% of the engine load. However, the behaviour was the opposite at a full engine load since the lower BSCO was obtained with diesel operation. This behaviour is because the maximum BMEP obtained for each rpm is not the maximum load for the IC-ICE fuelled with diesel, so the engine does not operate with the throttle valve fully open and thus produces a decrease in CO in the exhaust pipe [15,25].

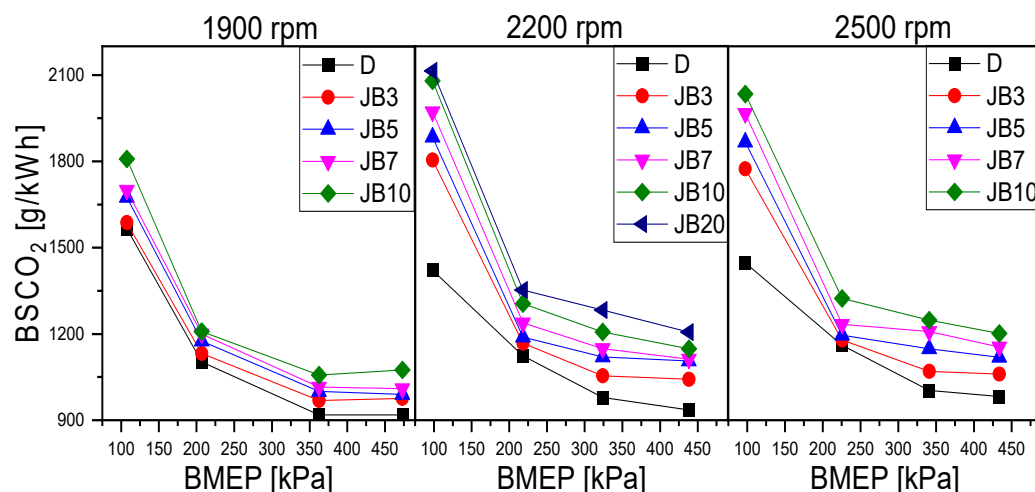


Figure 6. Results obtained of BSCO₂ with the BMEP at 1900, 2200 and 2500 rpm for the JB blends.

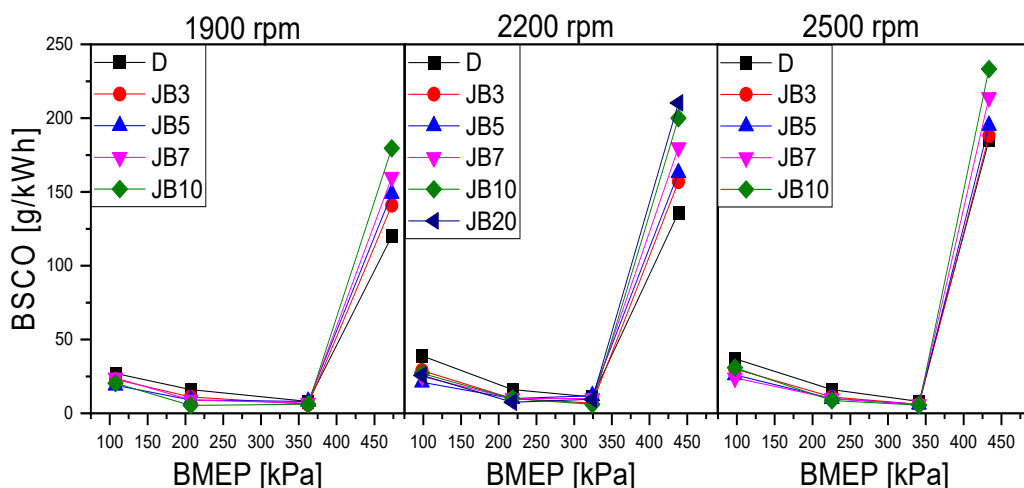


Figure 7. Results obtained for BSCO with BMEP at 1900, 2200 and 2500 rpm for JB blends.

3.2.4. Specific Emissions of Carbon Monoxide (BSNO_x)

Figure 8 shows that BSNO_x values are increased for all engine load conditions and rotational speed when blends of JB are used concerning the values of BSNO_x when the CI-ICE operates with diesel. The percentage increases are 28.5, 55.3 and 70.3% for JB3, 30, 62.8 and 106.6% for JB5, 45.5, 87.7 and 122.5% for JB7 and 96.2, 137.3 and 138.5% for JB10 a 2500, 2200 and 1900 rpm respectively. As can be seen, the rise of the values of BSNO_x is given by the increase of the content of JB in the mixture and the engine's rotational speed. The literature indicates that the decrease in BSNO_x when the engine load rises is due to an increase in the turbulence inside the combustion chamber, which contributes to a faster combustion process, carrying with its a less residence time of the species in the high-temperature zone, avoiding that NO_x can be formed.

In general, the increase in BSNO_x obtained in the experimental tests is caused by the increased exhaust gas temperature when the engine works with JB blends. According to the Zeldovich mechanism of NO formation, a higher exhaust-gas temperature generates a significant reactivity of the nitrogen with the oxygen, leading to the higher production of NO_x in the combustion processes, which concurs with the values obtained for BSNO_x for the different JB blends.

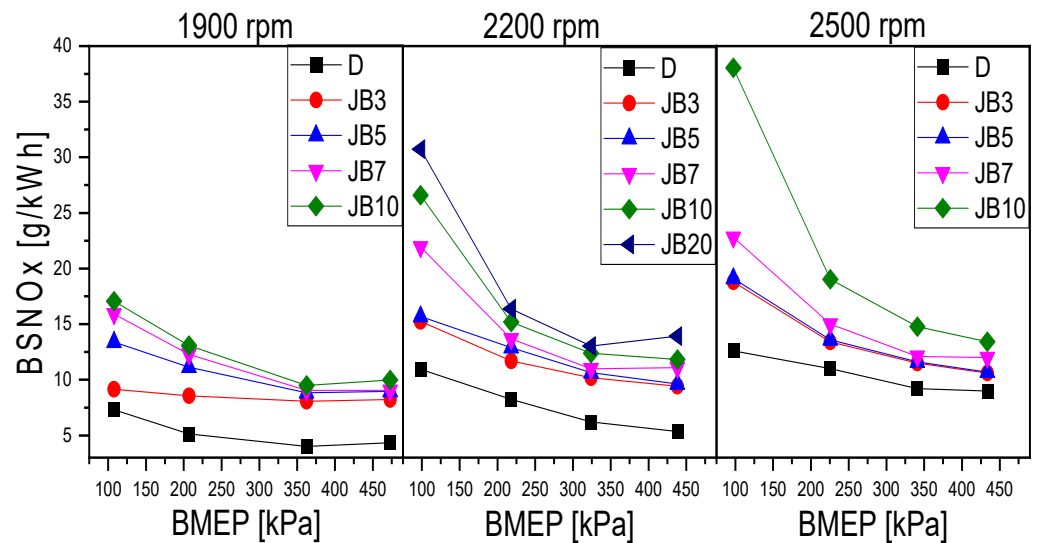


Figure 8. Results obtained of BSNO_x with the BMEP at 1900, 2200 and 2500 rpm for the JB blends.

3.2.5. Specific Emission of Total Unburned Hydrocarbons (BSHC)

Figure 9 shows that the BSHC obtained in the experimental test present a reduction with the JB blends to 75% of the engine load (optimal point of operation). Nevertheless, above 75% of the engine load, the BSHC present an increase with JB blends concerning the diesel operation. The explanation of this behaviour is the same given that for the BSCO. The BSHC behaviour, up to 75% of the engine load, is because the engine works with air excess in the combustion process, allowing JB blends to have a suitable combustion process. Above 75% on the engine load, the explanation of this behaviour is the same given that for the BSCO. The values on average up to 75% of the engine load obtained for the blends of JB are 21.9, 20.2 and 26.7% at 2500, 2200 and 1900 rpm, respectively.

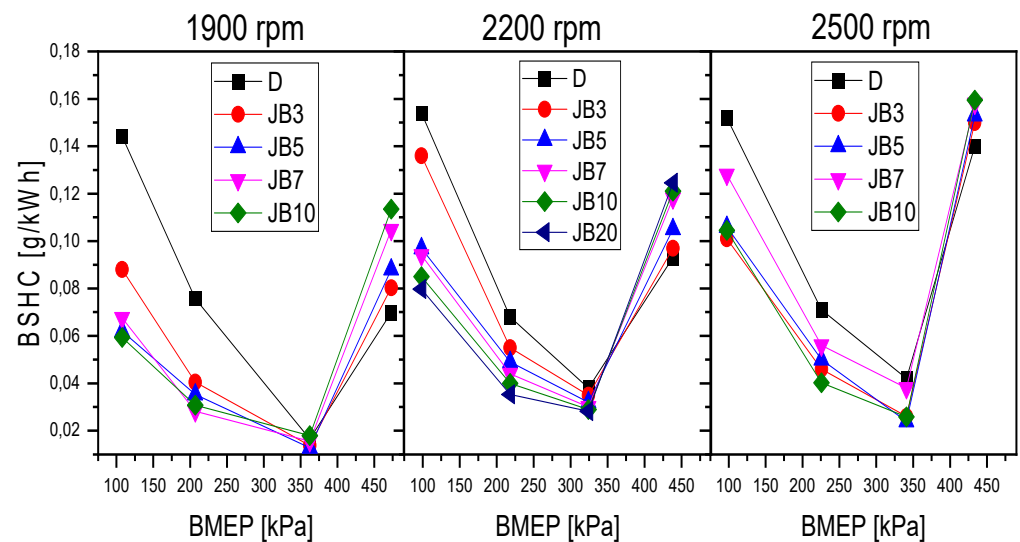


Figure 9. Results obtained for BSHC with BMEP at 1900, 2200 and 2500 rpm for JB blends.

3.2.6. Specific Emission of Particulate Matter (BSPM)

Figure 10 presents the behaviour of the BSPM obtained with the JB blends. As observed, the particulate matter decreases with the JB proportion in the blend at any rotational speed and engine load. The reduction values of BSPM obtained with JB blends are between 1 and 2.2% for JB3, 2.9 and 4.4% for JB5, 5.9 and 6.4% for JB7, 7.4 and 8.2% for JB10 and 7.3 and 9.2% for JB20 for all rotational speeds and engine load. This behaviour with the JB

blends is due to a better combustion process inside the CI-ICE than with diesel. In addition, this behaviour also obeys that the JB does not contain as many metals (particulate matter promoters) as diesel.

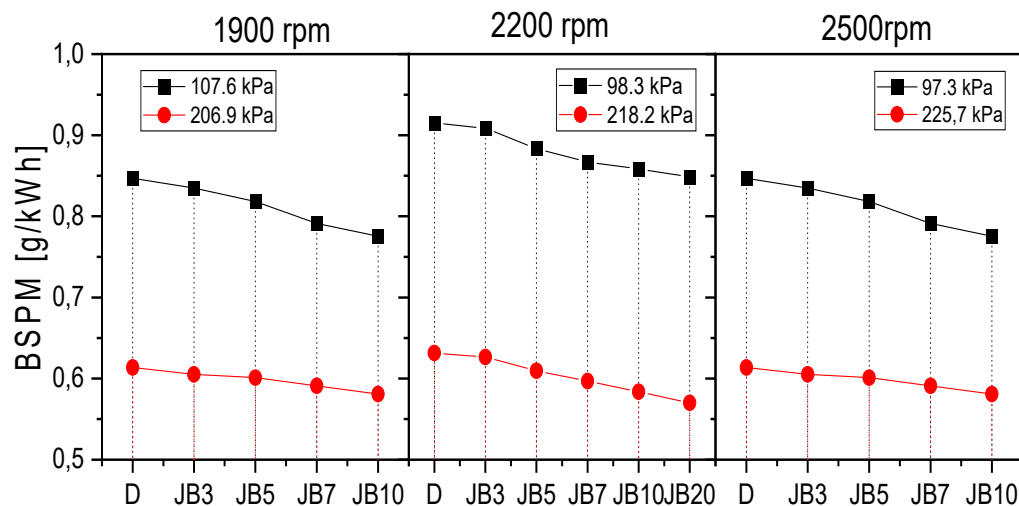


Figure 10. Results obtained for BSPPM with BMEP at 1900, 2200 and 2500 rpm for JB blends.

3.3. Economic and Environment Assessment

Biodiesel blends are essential for power generation with internal combustion engines due to their ability to reduce greenhouse emissions. However, their use does not significantly improve all the measured parameters. The results showed an increase in fuel consumption and emissions of nitrogen oxides and carbon dioxide. On the other hand, a reduction in unburned hydrocarbons and carbon monoxide of up to 75% of the engine load was found. This last reduction is important since the presence of CI-ICE near residential buildings could significantly impact human health. One point to consider is that CO tends to be overlooked due to the symptoms not being specific, and it is tasteless and odourless [37]. For instance, in the USA in 2016, more than 50,000 were affected by CO poisoning with a clinical spectrum ranging from headaches to coma and death [38,39].

Nowadays, in Colombia, diesel includes 10% palm oil biodiesel. The research work done by Abedin et al. [31] found that the BSFC is 369.7 g/kWh for 2500 rpm. For the same blended amount and speed for the JB blend data obtained in the present research, BSFC is 390.8 g/kWh, which means an increase in consumption of approximately 5%. However, for 1900 rpm (the rotational speed close to that used in Colombia for power generation), the value of BSFC with PB is 363 g/kWh; whereas, for the same conditions using JB, the value of BSFC is 320 g/kWh, which means a reduction of approximately 11%. This behaviour means that a fuel change for fixed power generation could reduce energy consumption.

On the other hand, in Colombia, there are more than 1750 locations without direct connection to interconnected electrical systems. These locations have an installed capacity of 312,911 kW. Almost all that installed capacity corresponds to diesel generators, with nearly 85% of the total capacity [1]. Additionally, according to the IPSE reports for 2022, there is an average daily consumption of 1097 MWh/day [40]. Based on previous data, the migration from PB10 to JB10 represents a reduction of 48,307 L, representing a cost decrease of 27,730 USD/day, assuming 85% of power generation is achieved using CI-ICE.

Previous research shows that palm biodiesel has a greater global warming potential (GWP) and higher productivity than JCL [33]. This study also found that palm oil requires more materials and energy to produce biodiesel than JCL oil. Additionally, they found that in the first five years, the palm crop emitted 1695,36 kgCO_{2eq} for each ton of biodiesel produced, while the JCL crop emitted only 740,90 kgCO_{2eq} for the same quantity of biodiesel.

Another critical aspect to consider in the analysis is the impact of land-use change in the increment of CO₂ emissions. This aspect is relevant for Colombia, where there has

been a significant increase in cultivated areas for palm production in the food and biofuel industries. For example, in ten years, the cultivated area has expanded by approximately 150%, reducing forests, particularly in tropical countries [41]. Another important factor to consider is the GWP associated with productive processes. Previous studies have indicated that the overall impact of JB is lower than that of PO.

Additionally, the carbon footprint of JLC production is on average 25% better than that of fossil fuel in terms of the lifecycle carbon footprint [5]. A reduction in the carbon footprint is particularly relevant for Colombia because the major emissions of greenhouse gases (GHG) occur in the agricultural sector, which is associated with changes in land use, and land use [42]. For example, in 2012, the farm sector accounted for 43% of the total GHG emissions [43].

Finally, JCL has great potential for sustainable development compared to palm because JCL improves soil properties. After five years of JCL crops, the soil increases organic carbon, organic nitrogen, and microbial biomass, among others, according to Singh et al. [34]. Moreover, an improvement in the structural stability of the soil was found [44]. Additionally, these research studies found that JCL crops contribute to maintaining carbon and nitrogen stocks and carbon sequestration rates. In contrast, palm plantations showed a decrease in carbon content, an increase in soil density, and a strong reduction in ecosystem services like carbon sequestration, water storage, and infiltration, etc. [45].

The land needed to produce the JB required for power supply in non-interconnected locations was estimated with productivity values reported by Abedin et al. [36]. In their research, they found that after six years, the productivity of JB reaches 1.85 Ton/ha, i.e., producing 10,891 tons of JB requires an area of 5887 ha. This area corresponds to nearly 1% of the land destined for palm crops nowadays [46]. On the other hand, JCL crops require temperatures between 15 to 35 °C, rainfall between 1000–2000 mm per year, and altitudes between 500–1200 masl.

Lozano-Castellanos et al. [35] studied the potential of oleaginous species in Colombia, and they found that, in Colombia, 18.65% (212,977.2 km²) of the territory has the agroclimatic compatibility needed to produce oilseeds such as JCL. This land is distributed mainly in 10 of the 32 departments of Colombia, some of which include many non-interconnected areas with excellent potential to use JCL for biodiesel production and thus attain self-sufficiency. Figure 11 shows the distribution of non-interconnected areas and the land areas with the potential to grow JCL.

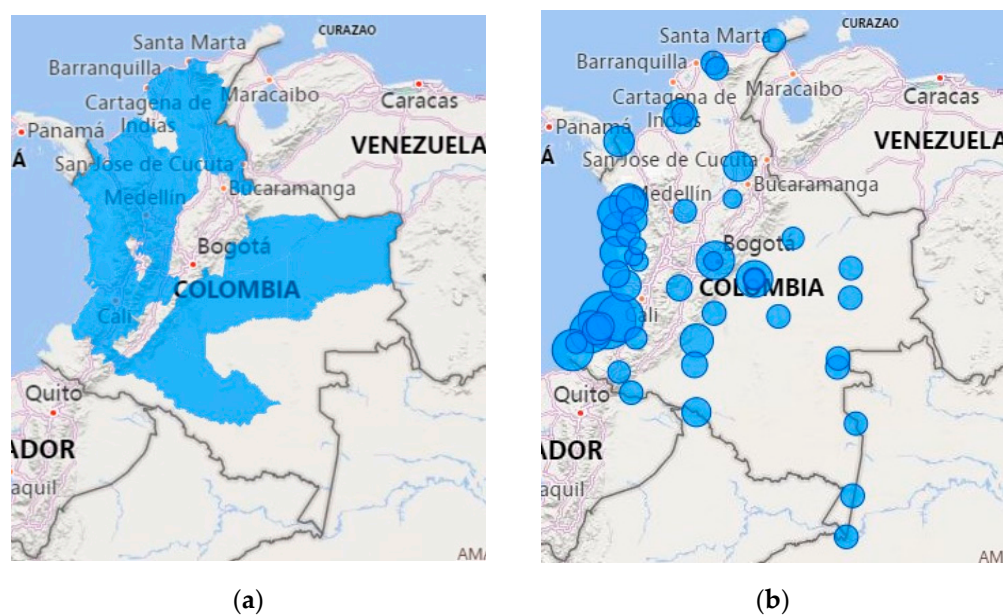


Figure 11. (a) Suitable areas for JCL crops; and (b) non-interconnected areas in Colombia.

To summarise, the replacement of PB10 for JB10 on rpm near 1900 rpm for power generation in non-interconnected areas can contribute to the goals of Colombia in reducing GHG emissions and soil deterioration, in addition to a reduction in fuel costs of 27,730 USD/day and a decrease in net CO₂ emissions of 1588 kg/day compared to pure diesel. Moreover, the use of JB10 produces a reduction in harmful emissions to human health, like CO, HC, and NO_x, which reduces the risk of disease. Table 4 summarises the main aspects considered in this section.

Table 4. Economic and environment assessment results between JB and PB.

Parameter	Unit	JB	PB	Ref.
BSFC	kWh/kg	320	363	[31]
Production	Ton/ha	1.85	4.16	[31,33]
Carbon Footprint	kgCO ₂ eq	1695,36	740.90	[33]
Soil Influence	NA	Positive.	Negative.	[34]
Potential of cultivation	NA	High for Colombia	High for Colombia	
Biodiesel density	kg/m ³	870	874	[47]
Biodiesel at 40 °C	mm ² /s	4,8	4,9	[20]

4. Discussion

This study explored the performance, emissions, and economic feasibility of using *Jatropha curcas* L. biodiesel blends compared to PO biodiesel in CI-ICE for power generation in rural Colombia. The results obtained in the experimental tests show that the performance and emissions parameters are similar to operations at sea-level and at high altitudes. According to the results, blends between 3 and 10% of JB have a performance result close to diesel operation.

The results show that the physical property that most affects the performance and emissions of CI-ICE is the LHV. The lower value of this property for JB produces an increase in the fuel mass flow that raises the value of the BFSC, which in turn, causes a reduction in thermal efficiency and an increase in the CO₂ emissions; despite the use of JB blends, this CO₂ is sequestered from the atmosphere by the JCL crop. Hence, the CO₂ footprint is reduced by an increase of JB in the blend. On the other hand, due to the oxygen content in the JB, the engine's combustion process improves, reducing BSHC, BSCO and BSPM. Nevertheless, the rise in exhaust gas temperatures increases BSNO_x.

The economic and environmental assessment showed that implementing JB in power generation in non-interconnected areas is feasible. In addition, this could have greater scope if other actors present in these areas are included, such as mining companies. This sector must comply with strong regulations to maintain air quality outside and inside the mines [48]. Several studies have shown the benefits of using biofuels in different mining activities [49,50]. Hence, the use of JB in Colombia can also be extended to this sector, which consumes large amounts of pure diesel, whereby using the JB could help improve the regulated emissions of CI-ICE, as shown in the previous results. Moreover, using JB would reduce their dependence on fossil sources for their operations and allow them to develop much more eco-friendly activities. Finally, biodiesel production can be carried out by these companies, which would lead to a higher employment rate in these areas and improve the economy of these regions.

Despite the promising results obtained with JB as an energy alternative for power generation, this must be integrated with hybrid solutions with non-conventional energy sources to ensure a constant and quality power supply [51]. However, non-conventional energy sources require a robust energy storage system for adequate operation. According to the literature, batteries are the most suitable among the numerous available storage technologies for a wide range of non-conventional energy source applications [52,53].

In future research, these hybrid solutions must be evaluated using techniques such as artificial intelligence neural methods or specialised software such as The Software

Hybrid Optimization Model for Electric Renewable (HOMER) [51,54]. Additionally, to reduce experimental test costs with ICE, software based on computational fluid dynamics should be used to ascertain the performance and emissions of an engine [4,55–57]. In some research studies, new mathematical models, machine learning, soft computing and artificial intelligence are used nowadays to predict the combustion, performance, and emissions parameters of ICEs [58–61].

5. Conclusions

The present study investigated the performance and emissions of a CI-ICE fuelled with JB blends and presented an economic and environmental assessment for implementing JCL crops for biodiesel production in non-interconnected areas. The following main conclusions can be drawn from this investigation.

- JB blends in proportions of up to 10% are suitable for power generation in CI-ICE in non-interconnected areas localised above 2000 masl because the performance and emissions of the CI-ICE do not differ significantly from diesel operations;
- The CI-ICE does not require modifications to operate, even with a blend of 20% of JB with diesel. The CI-ICE only requires a catalyser to tackle the increase in NOx emissions. This means that a power generation plant's operational and maintenance costs are hardly affected, which is beneficial for locations with a diesel engine as a generation plant;
- In the case of implementing JB blends as a fuel for power generation, this could represent some important improvements in economic, ecological, and health aspects. In the economic parameter, the use of JB blends could represent a reduction in fuel costs. Additionally, JCL crops require fewer agrochemical products. Therefore, an indirect reduction in agrochemical costs is also obtained;
- The replacement of PB by JB in the blend with diesel offers a favourable solution from economic and environmental perspectives. From an economic standpoint, JB has the potential to reduce overall fuel consumption (approx. 12%), leading to cost savings, in addition to being a good prospect for production in areas near consumption. Environmentally, the use of JB can help to mitigate direct CO₂ emissions by reducing fuel consumption, but an additional decrease in indirect emissions associated with the production cycle is better for JB than PB and fossil fuels.

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Abbreviations

The following abbreviations are used in this manuscript:

BMEP	Break Specific Mean Pressure
BSFC	Brake Specific Fuel Consumption
BSNO _x	Brake Specific Nitrogen Oxides
BSCO ₂	Brake Specific Carbon Dioxide
BSCO	Brake Specific Carbon Monoxide
BSHC	Brake Specific Carbo unburned hydrocarbon.
BSPM	Brake Specific Particulate Matter
CI	Compression Ignition
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
ICE	Internal Combustion Engine
LHV	Lower Heating Value
NO _x	Nitrogen Oxides
GHG	Greenhouse Gases
GWP	Global Warming Potencia
HC	Unburned Hydrocarbon
JCL	<i>Jatropha curcas</i> L.
JB	<i>Jatropha curcas</i> L. Biodiesel
JB3, JB5, JB7, JB10, JB20	Blends of diesel /biodiesel
PO	Palm Oil
PB	Palm biodiesel

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