AN ANALYSIS OF PROMISING SOLUTIONS FOR THE DECARBONIZATION OF THE TRANSPORT SECTOR IN CONJUNCTION WITH THE DEVELOPMENT OF ULTRA-HIGH PRESSURE ETHANOL EXPERIMENTAL TEST BENCH

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Abstract. *In the context of global warming and its consequences such as temperature variations and elevated pollution levels, the transport sector is responsible for approximately one-quarter of total global pollution emissions. This underscores the critical need for a transition towards more sustainable technologies, particularly in the motors and propellants area. For this instance, this work presents a brief comparative analysis of potential alternatives to replace internal combustion engines powered by hydrocarbons. In this context, for spark ignition engines operating with ethanol injected at Ultra High Pressure (UHP) levels, it is important to understand the macro and microstructures of the ethanol plumes generated by such systems. Therefore, this study also proposes the development of an ultra-high pressure hydrous ethanol experimental test bench capable of consistently producing identical ethanol plumes to support further research and clearly demonstrate the expected benefits of the system. Previous results show that this setup allows ethanol atomization at pressure levels up to 1000 bar.*

Keywords. *Global Warming, Transport Sector, Hydrous Ethanol, Ultra High Pressure, Experimental Test Bench.*

Introduction

Since the second half of the 20th century, awareness of global warming and its effects has become a key topic in discussions on ecology and sustainability within governmental agendas. However, only in recent years has this issue been addressed with a heightened sense of urgency, as climate change and pollution have reached record levels (World Meteorological Organization, 2024).

In this context, the transport sector remains one of the largest contributors to global pollution, accounting for approximately 25% of total emissions (UNEP, 2017). To address this challenge, researchers have concentrated on developing alternatives to internal combustion engines (ICEs) propelled by hydrocarbons to enhance sustainability in the sector. These efforts have led to advancements in biofuels, electric vehicles (EVs), and hybrid electric vehicles (HEVs), as well as improvements in biofuel performance.

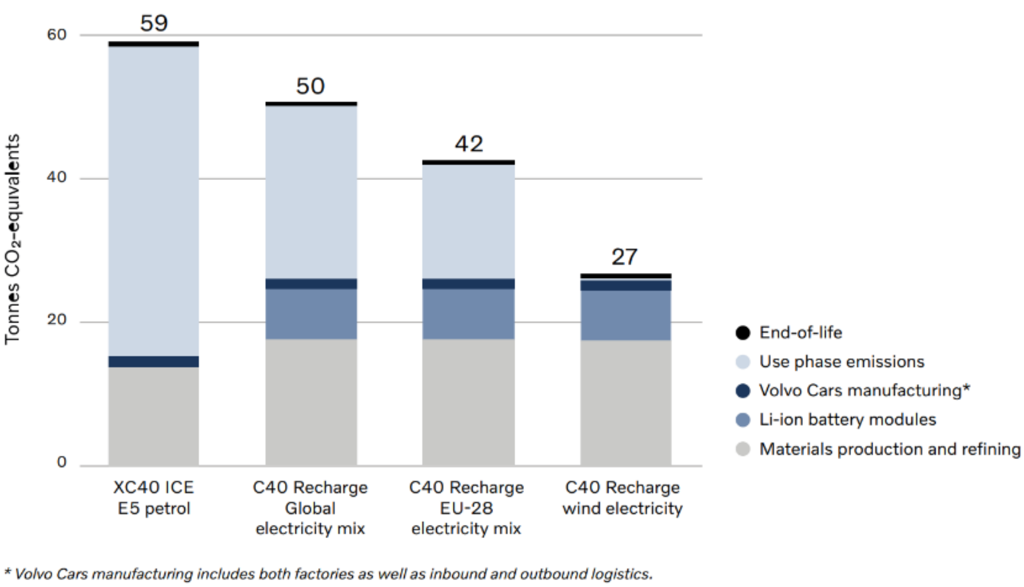
The EVs and HEVs have become very popular worldwide, especially in the United States and Europe, over the past few years as practical solutions to address pollution and climate change. In addition, fully sustainable fuels and technologies, such as ultra-high pressure (UHP) diesel engines and advanced biofuels, have been developed at a slower pace and complement to EVs and HEVs (Li, 2021) (Santos, 2021) (Onorati, 2022).

Firstly, this work aims to present a literature review of the current propulsion solutions for the transport sector worldwide, highlighting not only the main advantages and disadvantages of each but also providing an analysis of pollutant emissions throughout the vehicle's entire lifecycle. Subsequently, this paper will focus on the development of an ultra-high pressure hydrous ethanol test bench. Given that ethanol is a promising candidate for powering future vehicle fleets, the development of a dedicated test bench to study plumes at ultra-high pressure is essential.

Comparative Synthesis of Engine Propulsion Strategies

In the transportation sector, electrification has been driven by the growing popularity of electric vehicles and is seen as a possible solution to reduce greenhouse gas emissions (GHGs). The absence of internal combustion engines (ICEs), and therefore no reliance on fossil fuels, significantly helps reduce air pollution. However, saying that EVs produce no emissions is an oversimplification. While there are no direct emissions when driving, the production of batteries and the electricity needed to charge them can lead to indirect emissions, depending on how the electricity is generated. A study by Volvo (2021) shows that using non-renewable energy to charge an electric vehicle can create carbon emissions similar to those of a combustion vehicle, as shown in Figure 1.

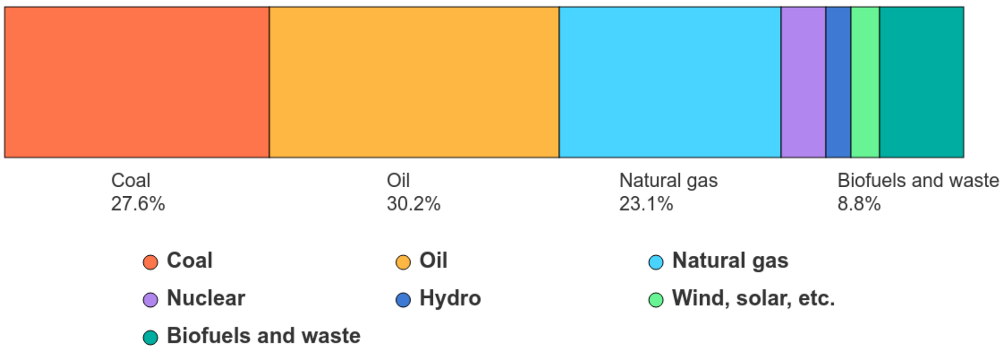
Figure 1 – CO_2 emissions emitted by vehicle type (Volvo, 2021).



The EVs technology offers benefits when it comes to emissions during use, but its production chain has a significant environmental impact. The batteries used in these vehicles are made of heavy metals like lithium, cobalt, nickel, and manganese, and extracting and processing these metals generate considerable pollution and waste (Ciclo Vivo, 2024). Also, the energy mix used to charge these cars is very important in determining their overall carbon footprint. The rapid growth in electric vehicle sales in areas that mainly use fossil fuels for electricity highlights a clear contradiction between trying to be more sustainable and the reality of energy production.

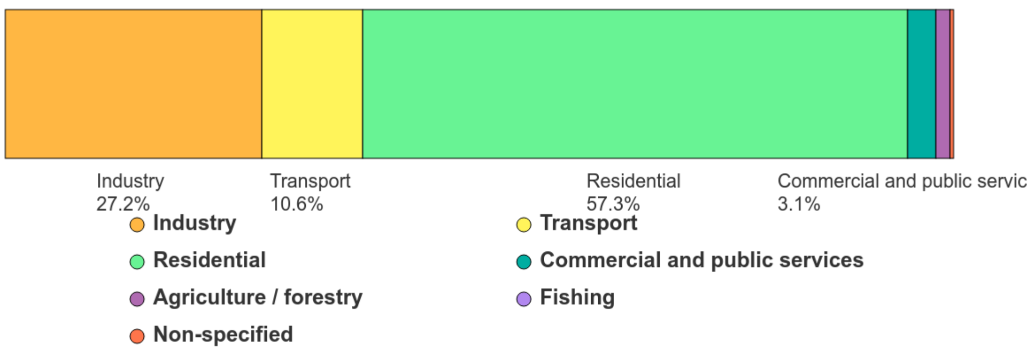
The growing need for electricity to power electric cars reveals the weakness of the global energy system, which still heavily relies on fossil fuels, as shown in Figure 2. This fact limits the environmental benefits of electrification, since emissions from electricity production may offset the benefits achieved by reducing local vehicle emissions. A complete transition to electric vehicles is not the sole solution for achieving sustainable mobility, especially given the limitations of the global energy system. However, a gradual shift, combined with other solutions, can bring significant benefits, particularly in countries with renewable energy sources. Brazil, for instance, relies heavily on renewable energy, which makes it well-suited for expanding the electric vehicle fleet in a more sustainable way.

Figure 2 – Electricity generation sources in worldwide (IEA, 2022).



In the search for sustainable energy alternatives in the transportation sector, biofuels offer a promising solution that has been getting more attention. This interest is due to several factors, including lower levels of pollution and the potential to fight climate change by capturing carbon. Despite the great potential of biofuels, their use in transportation is still very limited, as shown in Figure 3.

Figure 3 – Biofuels and waste final consumption by sector around the world (IEA, 2022).



While biofuels have many benefits, there are also important problems to consider, mainly the environmental impact linked to deforestation, driven by two main factors: the development of first-generation biofuels and the lack of large-scale production technologies for advanced biofuels. First-generation biofuels, such as biodiesel made from soybeans and palm oil, need large areas for cultivation, which leads to deforestation, especially in tropical forests and other fragile environments. For example, the expansion of palm oil plantations in Southeast Asia has resulted in the destruction of vast forest areas and loss of biodiversity (ECA, 2023).

The second challenge is the development of biofuels made from non-food sources like forest residues and cellulose, which is still at an early stage. Large-scale production technologies are new and not well-developed, which makes them inefficient and expensive, especially those that involve electrical hydrolysis. This high cost makes advanced biofuels less competitive compared to regular biofuels made from oilseeds and grains (IRENA, 2019)

Within the context of biofuels, ethanol stands out as having fewer challenges for large-scale use. Mainly produced from sugarcane and corn, ethanol has a favorable record concerning deforestation, unlike other biofuels like biodiesel, palm oil, and soybean oil. Brazil and the United States, the world's leaders in ethanol production according to official data (U.S. Department of Energy, 2024), demonstrate the viability of this biofuel for large-scale implementation. These countries have already achieved a high level of ethanol use, especially in light-duty vehicles used by most people daily. This practical experience proves the technical, economic, and social feasibility of ethanol as an important part of the energy mix.

Another advantage of ethanol compared to palm oil and soybean-based biofuels is that sugarcane, the main feedstock for ethanol, can be grown on land that is already deforested or degraded, thereby eliminating the need for new farmland. Despite its widespread use in Brazil and the United States, ethanol is still underused in most of the world, except in some Asian countries like China, India, and Thailand, which have followed the examples of Brazil and the United States in promoting large-scale ethanol use in recent years. This represents a significant growth opportunity for ethanol, which could help reduce carbon emissions in the transportation sector in many countries.

In Brazil, the majority of ethanol consumption comes from light-duty vehicles like passenger cars and the choice between ethanol and gasoline largely depends on their relative prices. This approach aims to encourage the use of sugarcane-based fuel, given that about 85% of light-duty vehicles in Brazil are flex-fuel, but only 30% use ethanol (Toledo, 2024). This highlights the need for incentives and measures to boost ethanol use. Trucks and buses can also run on ethanol, but to a lesser extent, with its use in heavy-duty vehicles being more common in specific situations like short-distance freight transport. Considering that more than half of carbon emissions in the transportation sector come from passenger cars, or light-duty vehicles, Brazil has been working towards reducing pollution levels and increasing ethanol consumption in recent years (Samora, 2024).

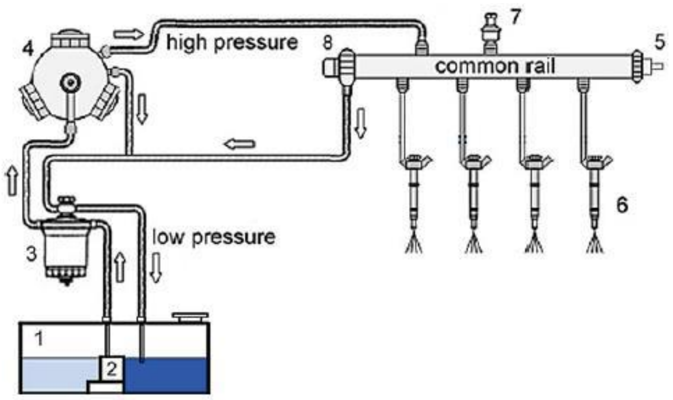
Based on the previously discussed content, hereafter this study is focused on the development of a device capable of simulating injection events to enable further characterization. A future paper will present the technical benefits of using ethanol in internal combustion engines (ICEs) to complement the advantages here discussed.

UHP-Ethanol test bench

The experimental test bench follows the working principle of the UHP diesel system, as shown in Figure 4. Its construction is based on the idea that fuel is first stored in a reservoir and then transferred to a high-pressure mechanical pump (HPP) using a low-pressure electric pump (LPP), which is powered by an electric motor controlled by a frequency inverter. Once pressurized, the fuel fills the rail, which is a component designed to keep the ethanol in an airtight condition, direct it to the injector for atomization, and include safety mechanisms and instruments needed to monitor pressure and fluid temperature during each injection cycle. Additionally, a pressure control valve (PCV) is connected to the rail to maintain the right fuel pressure in the gallery under different engine conditions.

Essentially, the PCV works as a valve controlled by pulse width modulation (PWM), regulating the flow of fuel returning from the rail to the storage tank. The rate of this return flow determines the relative pressure at which ethanol is kept in the diesel gallery.

Figure 4 - Components of a common rail system (Fiengo et al., 2013).



For controlling the test bench, an ESP32 microcontroller was employed to manage the input and output electric signals, as each one is presented in Table 1. Details about it are enounced in the work of Todaro *et al.* (2024). Furthermore, in consideration of the ESP32 microcontroller's limited capacity to handle high levels of electrical current and voltage, a current driver was employed. The drivers comprise boards equipped with transistors that activate solenoid valves in accordance with the signals transmitted by the ESP32.

Table 1 - Main signals of the experimental test bench control system (Todaro *et al.*, 2024).

Signal	Description	Signal	Description
E1	Input voltage from the high-pressure gallery pressure sensor.	S1	PWM output for actuation of the solenoid valve controlling the fuel inlet flow to the highpressure pump (180 Hz, if HPP-1; 250 Hz, if HPP-2).
E2	Input voltage, adjusted via potentiometer, proportional to the desired flow through the solenoid valve controlling the fuel inlet flow to the high-pressure pump	S2	PWM output for actuation of the solenoid valve controlling the fuel return flow from the highpressure gallery to the fuel tank (1000 Hz).
E3	Input voltage, adjusted via potentiometer, proportional to the setpoint pressure in the highpressure gallery.	S3	PWM output for actuation of the fuel injectors through the S070 PI Innovo current driver (frequency defined based on the test objective).

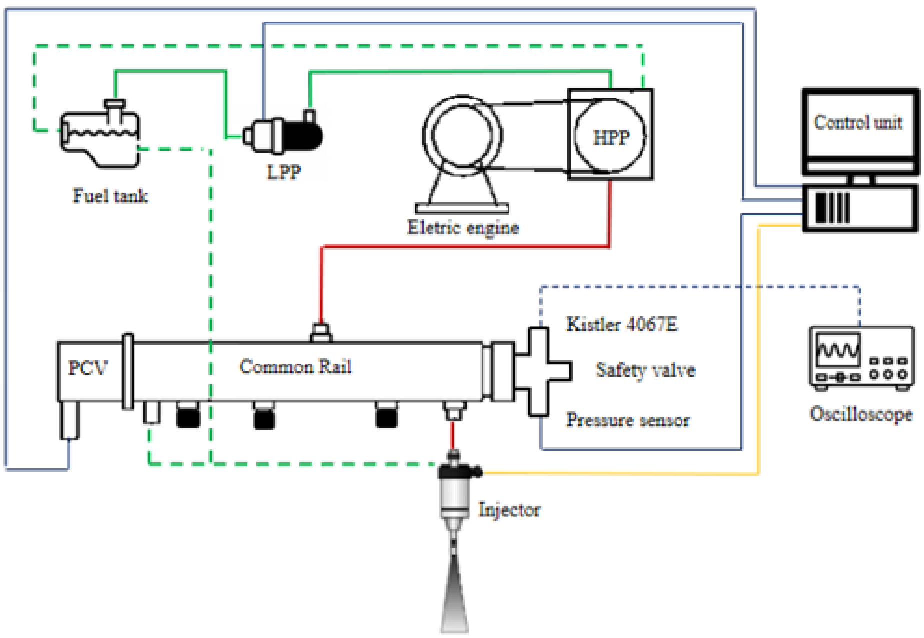
After installing the equipment and verifying that the system is sealed properly, work began on developing a dedicated control system to connect all the components of the experimental setup and their related systems. Figure 5 shows the arrangement of all devices and peripherals connected to the rail, demonstrating that only one fuel outlet in the gallery is used to supply the selected injector, while the other outlets are properly sealed.

Once the system is running, the voltage signal from the high-pressure gallery is converted based on the response curve of the sensor used (E1 – Original, Sensata). This value is then compared to the pressure setpoint that the operator sets using a potentiometer (referred to as E3). If the actual pressure is higher than the setpoint, the microcontroller will increase the opening of the solenoid valve that controls the fuel returning from the high-pressure gallery to the tank (PCV; shown as S2).

This action promotes increased ethanol discharge, resulting in a decrease in pressure within the gallery. On the other hand, if the actual pressure is below the setpoint, the microcontroller will reduce the opening of the PCV valve, limiting the ethanol flow and helping to increase the pressure in the gallery. The adjustment factor for the duty cycle, made through incremental or decremental changes, was set to 0.005.

The main control strategy works in a closed-loop system, unlike the open-loop control used to regulate input flow to the high-pressure pump, which is done with a potentiometer (see E2 and S1). Regarding the activation of the diesel injector installed on the bench, it can be triggered at set intervals and frequencies based on the relative pressure in the gallery (S3), which must be higher than the minimum activation pressure specified by the manufacturer. However, if the pressure in the gallery exceeds a safety threshold defined in the programming, the injection time and frequency are automatically doubled to ensure safe operation in the UHP system.

Figure 5 – Schematic illustration of the UHP-Ethanol test bench (Todaro *et al.*, 2024).



Results and Discussion

Before building the experimental test bench, the design of the setup was created using SolidWorks software. A detailed diagram of the components was also made. To make testing and optimization easier, a closed-loop fuel system was used. This setup removes the need for a conventional fuel tank since the fuel keeps circulating. The process starts with the frequency inverter providing the right voltage to the electric motor, which then pressurizes the fuel before sending it to the rail and distributing it to the four injectors. Figure 6 shows the 3D model created with the goal of replicating the actual setup, while Figures 7 and 8 shows the prototype of this apparatus and the control panel, respectively.

Figure 6 – Isometric perspective of the experimental test bench (left) and frontal view of the apparatus projected (right).

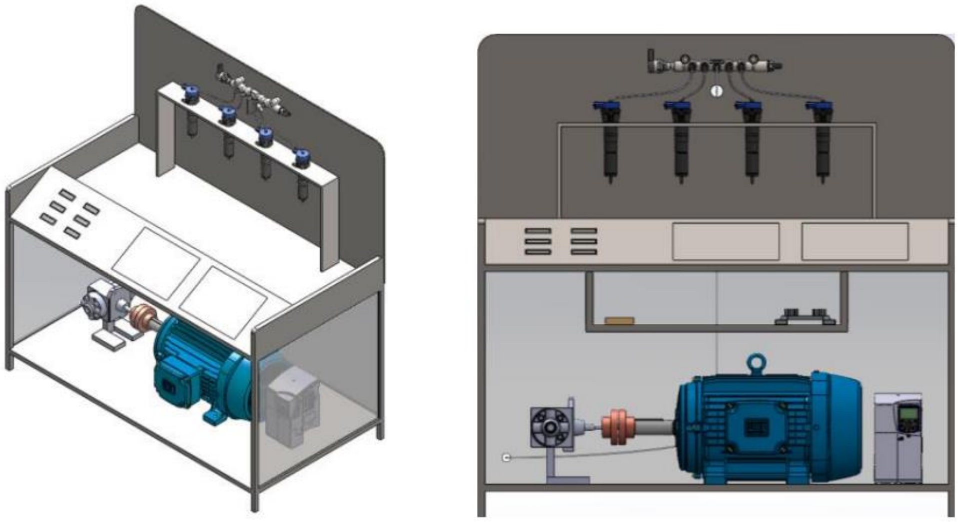


Figure 7 – Prototype of the experimental test bench (Friedrich *et al.*, 2023).

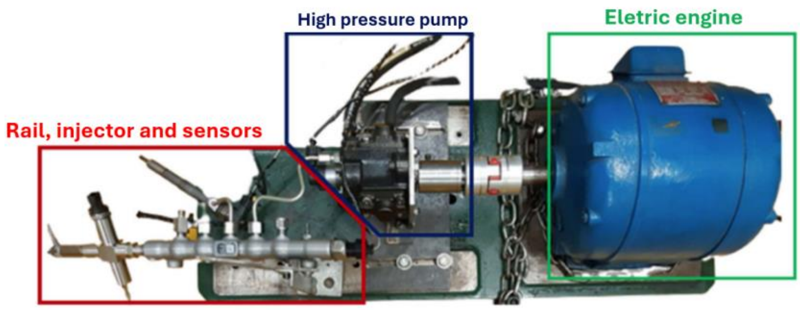
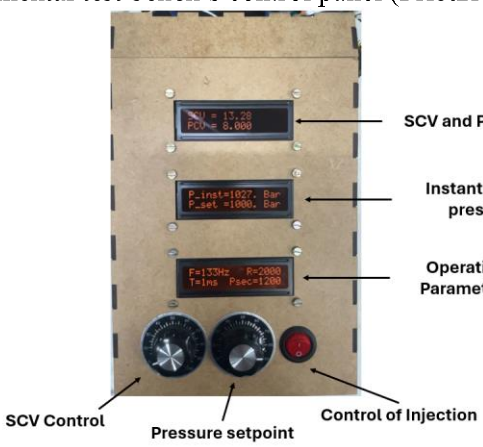


Figure 8 – Experimental test bench’s control panel (Friedrich *et al.*, 2023).



Since maintaining pressure levels is an important requirement for this test bench, an experimental test campaign was conducted in two phases, referred to here as cases 1 and 2 in Table 2. These cases involve measuring the relative pressure profiles of hydrated ethanol. In cases 1 and 2, the UHP system was pressurized by different high-pressure pumps (HPPs), and the injector was not energized. The goal of these experiments was to determine the system's pressure recovery time in the common rail based on the setpoint and injection time.

Table 2 - Experimental configurations for cases 1 and 2.

Cases	HPP / n (rpm)	Pressure (bar)	Injector
1	HPP-1 / 1200	300 | 700	Closed
2	HPP-2 / 1800	300 | 700	Closed

In the experiments conducted on the test bench with the injector closed, tests were performed at average pressures of 300 bar and 700 bar, with HPP-1 running at 1200 rpm. In both cases, the control system operated at a frequency of 1 kHz. The same pressure range was used to investigate similar effects when using HPP-2 at 1800 rpm. The minimum value of the pressure range for cases 1 and 2 was chosen based on the performance curve of the PCV, which shows that the device has a minimum operating pressure of around 200 bar (unstable operating condition). The upper limit was set based on the maximum torque provided by the electric motors dedicated to each HPP. In the tests with HPP-1, the normally open SCV valve was controlled with a duty cycle of 90%. For HPP-2, the duty cycle was 10%, as this pump has a normally closed SCV.

The duty cycle values defined for each HPP were chosen as the minimum flow value that ensures stable operation of the UHP system under the conditions suggested in Table 2. Additionally, it was initially decided to equalize both duty cycles in order to maintain the masses of fuel pressurized by each HPP equivalent. The instantaneous data recorded by the sensors were displayed and recorded by the digital oscilloscope with a resolution of 500 ms/division. Preliminary tests demonstrated that this resolution is optimal for capturing the effects that the devices comprising the experimental bench have on the pressure signals characteristic of the UHP system operating with ethanol.

In a future paper, the pressure recovery time data for the cases tested here will be presented. This information is important for researchers who will use this setup to study the properties of ethanol sprays produced by it.

Conclusion

This study explored the main alternatives for decarbonizing the automotive sector, particularly vehicle electrification and the use of biofuels, including ethanol. While electrification is a promising option, it faces significant challenges such as supply chain complexity and indirect emissions associated with battery manufacturing. The use of biofuels, on the other hand, presents limitations related to land use pressure, deforestation, and competition with food production.

Ethanol, in turn, stands out as a promising solution with a proven track record in several countries, particularly Brazil and the United States. Its production, based on sugarcane, offers advantages such as carbon sequestration, ease of cultivation, and the possibility of recovering degraded areas. Additionally, the development of new technologies, such as the use of ethanol in high-pressure diesel engines, further expands its potential.

Additionally, based on the results presented, it is concluded that the proposed solution provides a robust experimental bench capable of reproducing ethanol injection events under different conditions. This means that the system can be used to analyze fuel pressure behavior in the rail, considering (or not) the injector opening, and to study the influence of valve dynamics and other peripherals on the flow. Then, the bench is ready to be used in experimental tests for structural characterization of fuel plumes generated with a relative pressure difference of up to 1,000 bar. Therefore, future work can be developed based on this utility of the bench.

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