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# Evaluation of pollutant emissions from Diesel Vehicles Fueled with biodiesel under Real-World driving conditions

# Evaluación de las emisiones contaminantes en vehículos diésel alimentados con biodiésel en condiciones reales de conducción

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## Abstract

This study evaluates the impact of B10 and B20 biodiesel blends produced from waste frying oil on pollutant emissions when used in diesel-powered vehicles operating under real-world driving conditions at high altitudes, ranging from 2619 to 2877 meters above sea level, in the Metropolitan District of Quito, Ecuador. Comparative tests were conducted using two diesel vehicles: one equipped with a common rail direct injection (CRDI) system, designated as M2.5C, and another with an injection pump system, referred to as H2.5B. Both vehicles were initially fueled with conventional diesel to establish a baseline. Exhaust emissions were measured under hot-engine conditions using a Portable Emissions Measurement System (PEMS) along a 15.7 km route that included ascending, descending, and urban driving segments. The findings indicate that carbon monoxide (CO) emissions were lowest when pure diesel was used in both engine types. Hydrocarbon (HC) emissions were minimal when B20 biodiesel was employed, regardless of the vehicle. Nitrogen oxide ($NO_x$) emissions showed no significant differences across the fuels tested, and in urban driving conditions, $NO_x$ levels remained consistently stable.

***Keywords***: fuel consumption index, air conditioning, efficient driving, fuel, schedule, driving cycle

## Resumen

Esta investigación evalúa los efectos de las mezclas de biodiésel de aceite de fritura usado (B10 y B20) con combustible convencional, en términos de emisiones, a gran altitud (entre 2619 y 2877 m s. n. m.), bajo condiciones reales de conducción en el Distrito Metropolitano de Quito, Ecuador. Se realizaron ensayos comparativos con dos vehículos con motor diésel; el primer sistema CRDI de inyección directa de common rail denominado M2.5C; el segundo, con sistema de bomba de inyección, denominado H2.5B, ambos alimentados inicialmente con diésel puro como línea base. Las tasas de emisiones de escape se cuantificaron en caliente mediante el sistema portátil de medición de emisiones (PEMS), a lo largo de una ruta de 15,7 km que incluyó condiciones de ascenso, descenso por carretera y tramos urbanos. Los resultados permiten concluir que las emisiones mínimas de CO se registran al utilizar diésel convencional en ambos motores (H2.5B y M2.5C); las emisiones de HC son mínimas con la mezcla B20, y las emisiones de $NO_x$ no presentan variaciones significativas, independientemente del combustible utilizado. En el circuito urbano, tampoco se observa una variación significativa de las emisiones de $NO_x$ según el tipo de combustible.

***Palabras clave***: índice de consumo de combustible, aire acondicionado, conducción eficiente, combustible, horario, ciclo de conducción.

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## 1. Introduction

The combustion of petroleum-derived fuels produces emissions that are both toxic and harmful to public health. According to the World Health Organization (WHO), nine out of ten people worldwide are exposed to polluted air, contributing to the premature deaths of approximately seven million individuals each year [1]. In Latin America and the Caribbean, over 100 million people are exposed to air pollution levels exceeding WHO-recommended thresholds [2, 3]. Importantly, emissions from diesel engines have been classified as carcinogenic to humans [4, 5]. The transport sector has overtaken the energy sector as the leading contributor to carbon emissions and other pollutants that significantly exacerbate the greenhouse effect and global warming [6]. According to the International Transport Forum, carbon dioxide ($CO_2$) emissions from transport account for 23% of global totals and represent 30% of all $CO_2$ emissions resulting from fossil fuel combustion [7]. Moreover, the transport sector is the primary source of conventional air pollutants responsible for elevated concentrations of ozone and particulate matter in urban environments [8].

Although there is extensive literature on vehicular emissions, most studies have been conducted in cities located at or near sea level [9]. In Ecuador, air pollution resulting from hydrocarbon combustion has reached alarming levels in recent years. One major contributing factor is the country's topography, with cities such as the Metropolitan District of Quito situated at an average altitude of 2,850 meters above sea level [10]. At high altitudes, combustion becomes less efficient, leading to increased emissions of nitrogen oxides ($NO_x$) and particulate matter (PM) [11]. Additionally, the diesel fuel used in Ecuador contains approximately 350 ppm of sulfur, which restricts the import of vehicles equipped with after-treatment technologies designed to reduce $NO_x$ and PM emissions [11]. Higher altitudes are also associated with increased emissions of unburned hydrocarbons (HC), PM, and soot [12]. Furthermore, evidence suggests that real-world $NO_x$ emissions from diesel vehicles have shown little improvement over time and often exceed regulatory limits by a wide margin [13, 14]. Altitude affects both intake and exhaust pressures, which can lead to clogging of air filters and diesel particulate filters (DPFs). Moreover, variations in spray and combustion characteristics in diesel engines have been observed across altitudes ranging from 0 to 4,500 meters, with injection pressure playing a significant role [15]. According to Fontaras et al. [16], the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) provides $CO_2$ emission estimates that are more representative of real-world driving conditions than those from the New European Driving Cycle (NEDC). However, the Real Driving Emissions (RDE) test, designed to ensure regulatory compliance under on-road conditions, specifically targets the reduction of $NO_x$ emissions in diesel vehicles using Portable Emissions Measurement Systems (PEMS) [17].

Traditionally, vehicular emissions are evaluated using standardized dynamometer-based test cycles, such as the New European Driving Cycle (NEDC), the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), and the EPA Federal Test Procedure (FTP-75). However, studies have demonstrated that these laboratory protocols do not always capture the full range of emissions encountered under real-world operating conditions. As a result, on-road testing methodologies have gained prominence. These rely on Portable Emissions Measurement Systems (PEMS) to evaluate vehicle performance under everyday driving scenarios, including road gradients, traffic variability, ambient temperature fluctuations, and changes in driving speed. According to Kousoulidou et al. [18], real-world emissions of nitrogen oxides ($NO_x$) and particulate matter can be two to four times higher than those measured in controlled laboratory environments.

Diesel engines are widely recognized for their low installation cost, high energy efficiency, operational stability, and exceptional adaptability to diverse operating conditions [19, 20]. However, fossil fuel reserves are being rapidly depleted under current consumption trends [21]. This has spurred growing interest in the development of renewable, sustainable, and environmentally friendly alternative fuels. Among these, biofuels represent a promising energy source capable of enhancing energy, economic, and environmental security [22]. Biodiesel, in particular, has attracted global attention as both a blending component and a direct substitute for conventional fuels in internal combustion engines (ICEs) [23, 24]. To mitigate emissions of harmful pollutants, blends of diesel with biodiesel derived from oilseeds and other feedstocks have been proposed as viable alternatives [25]. Despite its potential, there is limited empirical evidence regarding the impact of biodiesel blends on the performance and emissions of diesel engines not originally designed for such fuels [26]. Furthermore, studies assessing the health impacts of biodiesel combustion must be interpreted in the context of rapid advances in diesel engine technology, which have evolved significantly in response to increasingly stringent emissions regulations [27, 28].

Biodiesel has emerged as a viable alternative to fossil fuels, garnering growing interest for its potential to reduce pollutant emissions and mitigate the environmental impact of compression ignition engines. Derived from renewable feedstocks such as vegetable oils, animal fats, and recycled cooking oils, this biofuel offers substantial advantages in terms of sustainability and greenhouse gas (GHG) mitigation [29, 30].

According to Demirbas [31], carbon dioxide ($CO_2$) emissions from biodiesel combustion can be reduced by up to 78% compared to conventional diesel. Addi-

tionally, biodiesel produces lower emissions of particulate matter, sulfur oxides ($SO_x$), and carbon monoxide (CO), thereby contributing to improved urban air quality [32]. However, its effect on nitrogen oxide ($NO_x$) emissions remains variable and depends on factors such ascombustion conditions and engine design.

This study aims to evaluate the impact of B10 and B20 biodiesel blends, derived from waste frying oil and mixed with conventional diesel, on vehicle emissions under high-altitude conditions ranging from 2,619 to 2,877 meters above sea level. The assessment was conducted through on-road testing to quantify emissions during real-world driving in the Metropolitan District of Quito, Ecuador.

## 2. Materials and Methods

The experimental work was carried out in two stages. The first stage involved the characterization of the base diesel fuel and its blends with biodiesel. The second stage consisted of evaluating the exhaust emissions from a diesel engine fueled with pure diesel and biodiesel–diesel blends (B10 and B20). All tests were performed at an altitude of 2,810 meters above sea level at the Laboratory for the Analysis of Vehicles and Sustainable Mobility (LIAVMS), located in Quito, Ecuador.

### 2.1. Characterization of waste cooking oil and biodiesel production.

A total of 100 liters of waste cooking oil was collected from a restaurant located near SEK University in Quito, Ecuador. The oil was centrifuged and filtered to remove suspended solids and then heated to reduce its water content. The collected oil had undergone at least ten frying cycles. Table 1 presents the physicochemical characteristics and selected fuel-related properties of the waste cooking oil [33].

The waste cooking oil was converted into fatty acid methyl esters (FAME) via base-catalyzed transesterification using potassium hydroxide (KOH) dissolved in methanol. The reaction was carried out in a thermal bath at 90 °C for 3 hours at a stirring rate of 900 rpm. Upon completion, the reaction mixture was filtered using Millipore equipment. To purify the filtrate, 5 mL of Milli-Q water was added for washing, followed by 2 mL of a hexane: diethyl ether mixture (80:20) to remove residual impurities, catalyst traces, and solvent. The mixture was then transferred to separating funnels and allowed to stand for 20 minutes to facilitate phase separation. The organic phase was subsequently collected in pre-weighed tubes and dried in an oven at 60 °C for 24 hours.

The production cost of one liter of biodiesel at the laboratory scale was approximately three U.S. dollars, a value that could be reduced under industrial-scale conditions. In comparison, the international market price for conventional diesel is around one dollar per liter, making biodiesel production economically unviable under laboratory-scale parameters. However, it is important to note that biodiesel is not typically used at 100% concentration (B100). The literature recommends blending levels of no more than 20% (B20) due to the associated reduction in engine torque and power output [3]. Therefore, one liter of biodiesel can be mixed with at least five liters of conventional diesel, which improves economic feasibility when applied under real-world blending practices.

**Table 1.** Physicochemical properties of waste cooking oil

| Property | Value |
|---|---|
| Acidity | 1,998±0,02 |
| Kinematic viscosity ($mm^2$/s, a 313 K) | 35,4±0,05 |
| pH | 2,9±0,0 |
| Density (kg/L, at 288 K) | 0,931±0,02 |
| Water content (%) | 0,46±0,01 |
| Saponification value | 124,31±0,03 |
| ÍIodine value | 30,85±0,01 |
| Cetane number | 47±0,1 |
| Free fatty acid (mg KOH/g oil) | 1,29±0,03 |

### 2.2. Characterization of diesel/biodiesel blends

Presents the physicochemical properties of the fuel samples, characterized in accordance with ASTM standards and compared against the limits established by Ecuadorian Technical Standard INEN 1489:2012 for diesel and biodiesel blends. All measured values complied with the specified requirements. According to the literature, a higher cetane number contributes to improved combustion performance in diesel engines [25], [32].

### 2.3. Test vehicles

Table 3 presents the technical specifications of the two test vehicles used in this study. The first vehicle, an MB-5 van from the 2015 model year, had an odometer reading of 55,000 km. The second, an H2.5 van also from 2015, had accumulated 143,365 km. Although the H2.5 is equipped with an older injection system, it was included in the study due to its continued presence in Ecuador's second-hand vehicle market. Moreover, this type of engine remains in use in certain heavy-duty applications, such as trucks, locomotives, and marine vessels, where durability and mechanical simplicity are critical.

**Table 2.** Physicochemical characterization of diesel and biodiesel blends.

| Fuel properties | Standard | Diesel Premium | Diesel / 10% biodiesel (B10) | Diesel / 20 % biodiesel (B20) | INEN Standard: 1489 2012 |
|---|---|---|---|---|---|
| Cetane number | ASTM D976 | 51.7 | 53.2 | 53.5 | 45 min. |
| Distillation curve T90 – 90 % evap„ (oC) | ASTM D88 | 336 | 336 | 343 | 360 max. |
| Flash Point (oC) | ASTM D93 | 61 | 63 | 66 | 51 min. |
| Sulfur content (ppm) | ASTM D4294 | 145.9 | 122.7 | 106.7 | 650 max. |
| Copper strip corrosion | ASTM D130 | 1A | 1A | 1A | 3 |
| Kinematic viscosity at 40 oC ($mm^2/s$) | ASTM D445 | 3.528 | 3.445 | 3.459 | 2-May |
| Water and sediment content (%) | ASTM D1796 | <0,05 | <0,05 | <0,05 | 0.05 max. |

**Table 3.** Main technical specifications of test vehicles.

| Model | Fuel system | Engine type | Displacement ($cm^3$) | Power | Torque | Compression ratio |
|---|---|---|---|---|---|---|
| M2.5C Double Cabin Pick up | CRDI Common Rail Diesel Electronic Injection EURO 3 | 4 cylinders in line, DOHC | 2499 $cm^3$ | 117.3 kW 3500 rpm | 330 Nm 1800 rpm | 18:01 |
| H2.5B Van | Injection pump, type of bypass EURO 3 | 4 cylinders in line, SOHC, TCi (Injecting timing control) | 2476 $cm^3$ | 73.08 kW 3800 rpm | 392 Nm 2000 - 2500 rpm | 21:01 |

Prior to the experimental tests, the vehicles underwent preventive maintenance, including oil changes, replacement of fuel filters, and injector cleaning. The selected vehicle model is commonly used in the mountainous regions of Ecuador due to the country's geographical variability and prevalence of third-order roads. Additionally, the vehicle brand ranks among the ten best-selling in Ecuador's national vehicle fleet, which adds relevance to its inclusion in the study [34]. Its engine displacement is representative of the average configuration for this class of vehicle, and it is equipped with a catalytic converter designed to reduce pollutant emissions.

### 2.4. Road circuit

The driving cycle used in this study was based on the route developed by Pisuña and Solís [35], with a total length of 15,673 meters, comprising 7,993 meters of suburban roadway and 7,680 meters of urban segments. Figure 1 illustrates the route selected for the on-board emissions tests, which was designed to evaluate vehicle performance in relation to altitude and pollutant emissions. The average elevation along the route is 2,610 meters above sea level [36]. The route is divided into two main sections. The first begins with an ascent along Avenida Rumiñahui, where data were collected for subsequent analysis, followed by a descent toward the Cloverleaf interchange, which provided a second set of measurements. The second section covers the urban portion of the route, extending from the Cloverleaf to Plaza Artigas. This phase of the study accounted for variables such as traffic density, number of circulating vehicles, ambient temperature, and weather conditions. The data collected enabled a comparative analysis of the different fuel alternatives and their environmental impacts under real-world driving conditions.

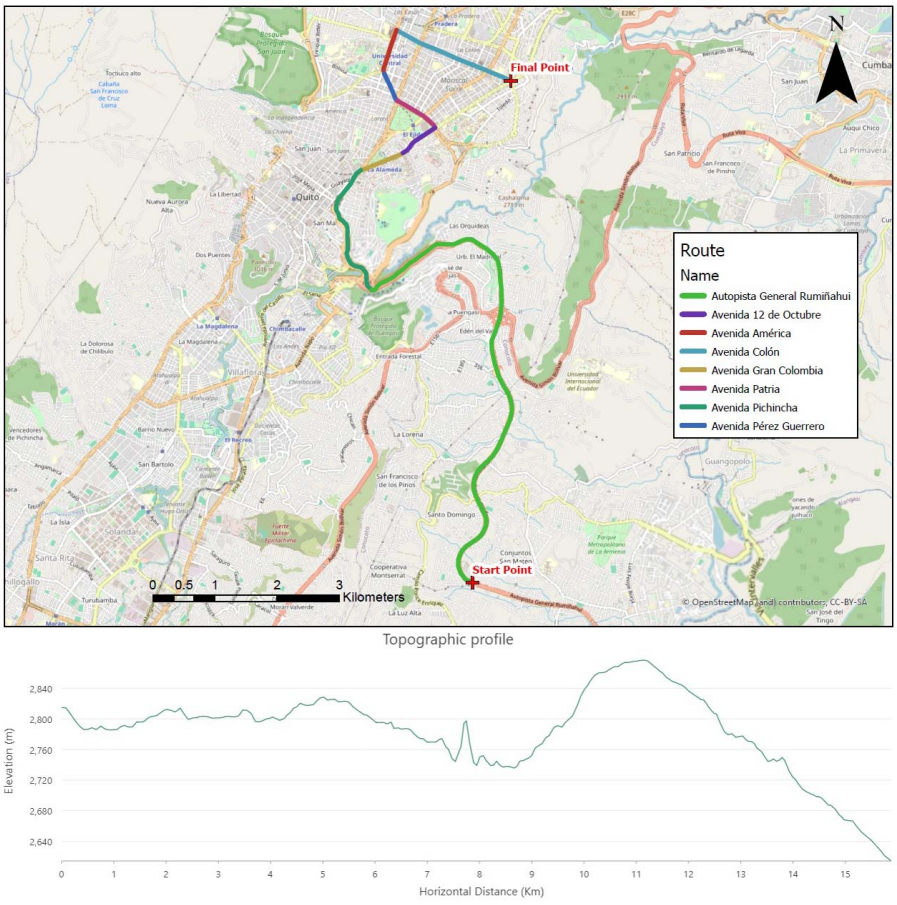


**Figure 1.** Driving route used for on-board emissions testing [35]

The study was designed to analyze the route in discrete sections rather than as a continuous whole, based on several technical considerations. These included variability in engine load, the need for accurate characterization of real-world driving behavior, improved calibration of simulation models, and the development of targeted mitigation strategies for segments associated with the highest emission levels, such as steep inclines or congested urban areas.

### 2.5. Portable emission data acquisition system

Exhaust gas measurements were conducted using the Axion OEM-2100AX model, which records volumetric concentrations of pollutants by interfacing with the vehicle's onboard diagnostic port (OBD2) [27]. Detailed technical specifications of the equipment are provided in Table 4.

**Table 4.** Especificaciones técnicas del sistema de medición de emisiones Axion OEM-2100AX

| Parameter | Measurement Range | Accuracy | Resolution |
|---|---|---|---|
| Measuring $O_2$ (sensor) | Greater than or equal to (0,01 a 25 % vol.) | Greater than or equal 0,1 % abs. | Greater than or equal 0,01 % vol. |
| Measurement CO (NDIR) | Greater than or equal to (0,001 a 10 % vol.) | Greater than or equal to 0,02 % abs. | Greater than or equal 0,001 % vol. |
| Measurement $NO_x$ (sensor) | Greater than or equal (0 a 4000 ppm) | Greater than or equal 25 ppm abs. | Greater than or equal 1 ppm |
| Measurement $CO_2$ (NDIR) | Greater than or equal to (0,01-16 % vol.) | Greater than or equal to 0,30 % abs. | Greater than or equal 0,01 % vol. |
| Measurement HC (NDIR) | Greater than or equal to (1 a 15 000 ppm) | Greater than or equal 4 ppm abs. | Greater than or equal 1 ppm |

### 2.6. Variable analysis

A multilevel factorial design was implemented to evaluate various fuel mixtures (diesel, B10, and B20) in two vehicles with distinct injection technologies: Common Rail Direct Injection (CRDI) and mechanical injection pump systems. Each vehicle was tested under three driving conditions, ascending, urban, and descending, resulting in multiple combinations for assessing emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides ($NO_x$), as well as oxygen ($O_2$) and carbon dioxide ($CO_2$) concentrations. Five repetitions were performed for each experimental condition. Control charts were applied to assess the reliability of the experimental data, ensuring consistency by identifying deviations that might cause excessive variability relative to acceptable thresholds [37]. The nomenclature used for the factorial combinations is presented in Tables 5 and 6. The statistical methodology follows the approach proposed by several authors, including that of [23]. According to Serrano et al. [38], the influence of independent variables on response variables can be effectively evaluated using response surface methodology (RSM) [39, 40]. Data analysis was performed using the educational version of Statgraphics Centurion XVI.

**Table 5.** Factor levels and designation codes

| Factors | Levels | Designation 1 | Designation 2 |
|---|---|---|---|
| Vehicle | M2.5C (2,5 $cm^3$ CDRI) | 1 | A2 |
| | H2.5B (2,5 $cm^3$ injection pump) | -1 | A1 |
| Fuel Type | Diesel | 1 | C1 |
| | B10 | 0 | C2 |
| | B20 | -1 | C3 |
| Driving condition | Ascent | 1 | AS |
| | Urban | 0 | UR |
| | Descent | -1 | DE |

**Table 6.** Experimental treatment combinations for response surface analysis

| Treatment | Vehicle | Fuel | Driving condition |
|---|---|---|---|
| 1 | A1 | C1 | AS |
| 2 | A1 | C2 | UR |
| 3 | A2 | C2 | UR |
| 4 | A2 | C1 | AS |
| 5 | A1 | C3 | UR |
| 6 | A2 | C2 | DE |
| 7 | A1 | C3 | DE |
| 8 | A2 | C3 | DE |
| 9 | A1 | C1 | DE |
| 10 | A2 | C3 | UR |
| 11 | A2 | C1 | UR |
| 12 | A1 | C2 | DE |
| 13 | A2 | C1 | DE |
| 14 | A1 | C3 | AS |
| 15 | A2 | C3 | AS |
| 16 | A1 | C2 | AS |
| 17 | A1 | C1 | UR |
| 18 | A2 | C2 | AS |

## 3. Results and Discussion

This section presents the results obtained from the experimental procedures. Tables 7 and 8 summarize the data used for response surface analysis of the two test vehicles. Across all cases, standard deviations were low, and the coefficients of variation remained below 20%, indicating moderate and acceptable levels of variability. The range values, defined as the difference between the maximum and minimum measurements, were also within acceptable limits for most variables.

Response surface methodology (RSM) has been

widely used in similar studies to evaluate the influence of multiple independent factors on dependent variables, as well as to construct predictive models of their interactions. This approach has been applied by authors such as Morales-Bayetero et al. [41], Guardia et al. [40], and Rocha-Hoyos et al. [25], among others.

**Table 7.** Statistical summary of emission measurements for H2.5B vehicle

| | Count | Average | Standard Deviation | Coefficient of Variation (%) | Range |
|---|---|---|---|---|---|
| $ADCO_2$ | 5 | 7.76 | 0.44 | 5.74 | 1.06 |
| $AB10CO_2$ | 5 | 9.03 | 0.28 | 3.13 | 0.62 |
| $AB20CO_2$ | 5 | 8.67 | 0.34 | 4.01 | 0.78 |
| ADCO | 5 | 0.02 | 0 | 0 | 0 |
| AB10CO | 5 | 0.02 | 0 | 0 | 0 |
| AB20CO | 5 | 0.018 | 0.002 | 11.29 | 0.004 |
| ADHC | 5 | 112.41 | 4.84 | 4.3 | 11.79 |
| AB10HC | 5 | 164.74 | 4.75 | 2.88 | 10.23 |
| AB20HC | 5 | 131.47 | 10.59 | 8.06 | 24.03 |
| $ADNO_x$ | 5 | 334.47 | 10.54 | 3.15 | 23.67 |
| $AB10NO_x$ | 5 | 352.89 | 7.8 | 2.21 | 17.66 |
| $AB20NO_x$ | 5 | 360.86 | 9.89 | 2.74 | 22.16 |
| $DDCO_2$ | 5 | 3.56 | 0.29 | 8.34 | 0.64 |
| $DB10CO_2$ | 5 | 4.22 | 0.57 | 13.52 | 1.26 |
| $DB20CO_2$ | 5 | 4.2 | 0.15 | 3.75 | 0.38 |
| DDCO | 5 | 0.017 | 0.002 | 16.49 | 0.005 |
| DB10CO | 5 | 0.015 | 0.002 | 18.85 | 0.006 |
| DB20CO | 5 | 0.011 | 0.0004 | 3.97 | 0.001 |
| ADHC | 5 | 129.63 | 3.8 | 2.93 | 9.06 |
| DB10HC | 5 | 169.55 | 2.62 | 1.54 | 5.82 |
| DB20HC | 5 | 141.45 | 5.98 | 4.23 | 13.68 |
| $DDNO_x$ | 5 | 157.18 | 4.03 | 2.56 | 9.65 |
| $DB10NO_x$ | 5 | 152.27 | 5.31 | 3.48 | 13.01 |
| $DB20NO_x$ | 5 | 182.86 | 12.96 | 7.08 | 30.92 |
| UDCO2 | 5 | 3.42 | 0.32 | 9.48 | 0.73 |
| $UB10CO_2$ | 5 | 3.92 | 0.1 | 2.58 | 0.22 |
| $UB20CO_2$ | 5 | 3.69 | 0.24 | 6.56 | 0.58 |
| UDCO | 5 | 0.011 | 0.0008 | 7.42 | 0.002 |
| UB10CO | 5 | 0.011 | 0.0012 | 11.22 | 0.003 |
| UB20CO | 5 | 0.011 | 0.0012 | 11.22 | 0.003 |
| UDHC | 5 | 75.06 | 2.47 | 3.29 | 5.33 |
| UB10HC | 5 | 126.15 | 7.11 | 5.63 | 16.31 |
| UB20HC | 5 | 112.26 | 3.33 | 2.97 | 8.17 |
| $UDNO_x$ | 5 | 167.52 | 6.13 | 3.66 | 14.39 |
| $UB10NO_x$ | 5 | 173.45 | 2.43 | 1.4 | 5.36 |
| $UB20NO_x$ | 5 | 179.53 | 8.01 | 4.46 | 18.69 |

**Note:** ADCO2 (Ascent Diesel $CO_2$ (%)), AB10CO2 (Ascent B10 $CO_2$ (%)), AB20CO2 (Ascent B20 $CO_2$ (%)), ADCO (Ascent Diesel CO (%)), AB10CO (Ascent B10 CO (%)), AB20CO (Ascent B20 CO (%)), ADHC (Ascent Diesel HC (ppm)), AB10HC (Ascent B10 HC (ppm)), AB20HC (Ascent B20 HC (ppm)), $ADNO_x$ (Ascent Diesel $NO_x$ (ppm)), $AB10NO_x$ (Ascent B10 $NO_x$ (ppm)), $AB20NO_x$ (Ascent B20 $NO_x$ (ppm)), DDCO2 (Descent Diesel $CO_2$ (%)), DB10CO2 (Descent B10 $CO_2$ (%)), DB20CO2 (Descent B20 $CO_2$ (%)), DDCO (Descent Diesel CO (%)), DB10CO (Descent B10 CO (%)), DB20CO (Descent B20 CO (%)), ADHC (Descent Diesel HC (ppm)), DB10HC (Descent B10 HC (ppm)), DB20HC (Descent B20 HC (ppm)), $DDNO_x$ (Descent Diesel $NO_x$ (ppm)), $DB10NO_x$ (Descent B10 $NO_x$ (ppm)), $DB20NO_x$ (Descent B20 $NO_x$ (ppm)), UDCO2 (Urban Diesel $CO_2$ (%)), UB10CO2 (Urban B10 $CO_2$ (%)), UB20CO2 (Urban B20 $CO_2$ (%)), UDCO (Urban Diesel CO (%)), UB10CO (Urban B10 CO (%)), UB20CO (Urban B20 CO (%)), UDHC (Urban Diesel HC (ppm)), UB10HC (Urban B10 HC (ppm)), UB20HC (Urban B20 HC (ppm)), $UDNO_x$ (Urban Diesel $NO_x$ (ppm)), $UB10NO_x$ (Urban B10 $NO_x$ (ppm)), $UB20NO_x$ (Urban B20 $NO_x$ (ppm)).

**Table 8.** Statistical summary of emission measurements for M2.5C vehicle

| | Count | Average | Standard Deviation | Coefficient of Variation (%) | Range |
|---|---|---|---|---|---|
| $ADCO_2$ | 5 | 8.71 | 0.62 | 7.13 | 1.42 |
| $AB10CO_2$ | 5 | 8.17 | 0.24 | 3.04 | 0.61 |
| $AB20CO_2$ | 5 | 8.85 | 0.46 | 5.3 | 0.99 |
| ADCO | 5 | 0.45 | 0.03 | 7.94 | 0.08 |
| AB10CO | 5 | 0.29 | 0.02 | 9.78 | 0.07 |
| AB20CO | 5 | 0.43 | 0.03 | 8.9 | 0.09 |
| ADHC | 5 | 143.02 | 1.33 | 0.92 | 3.03 |
| AB10HC | 5 | 107.46 | 1.89 | 1.76 | 4.01 |
| AB20HC | 5 | 86.82 | 2.82 | 3.25 | 6.48 |
| ADNOx | 5 | 469 | 15.71 | 3.34 | 32.97 |
| AB10NOx | 5 | 542.2 | 10.43 | 1.92 | 22.98 |
| AB20NOx | 5 | 494.52 | 3.22 | 0.65 | 6.7 |
| $DDCO_2$ | 5 | 4.32 | 0.311 | 7.219 | 0.55 |
| $DB10CO_2$ | 5 | 4.76 | 0.11 | 2.46 | 0.27 |
| $DB20CO_2$ | 5 | 5.13 | 0.19 | 3.84 | 0.46 |
| DDCO | 5 | 0.15 | 0.02 | 14.54 | 0.05 |
| DB10CO | 5 | 0.23 | 0.03 | 12.79 | 0.07 |
| DB20CO | 5 | 0.22 | 0.02 | 9.74 | 0.05 |
| ADHC | 5 | 219.93 | 5.7 | 2.59 | 13.38 |
| DB10HC | 5 | 234.55 | 4.43 | 1.88 | 9.7 |
| DB20HC | 5 | 136.5 | 3.6 | 2.63 | 6.68 |
| DDNOx | 5 | 299.88 | 8.18 | 2.72 | 15.29 |
| DB10NOx | 5 | 322.53 | 9.31 | 2.88 | 21.62 |
| DB20NOx | 5 | 256.29 | 9.19 | 3.58 | 20.72 |
| $UDCO_2$ | 5 | 4 | 0.06 | 1.51 | 0.14 |
| $UB10CO_2$ | 5 | 3.86 | 0.15 | 3.93 | 0.37 |
| $UB20CO_2$ | 5 | 4.39 | 0.16 | 3.74 | 0.39 |
| UDCO | 5 | 0.19 | 0.01 | 8.64 | 0.04 |
| UB10CO | 5 | 0.17 | 0.02 | 11.61 | 0.04 |
| UB20CO | 5 | 0.2 | 0.009 | 4.61 | 0.02 |
| UDHC | 5 | 145.08 | 7.86 | 5.41 | 17.98 |
| UB10HC | 5 | 174.43 | 1.71 | 0.98 | 3.71 |
| UB20HC | 5 | 122.78 | 2.39 | 1.94 | 5.7 |
| UDNOx | 5 | 275.74 | 8.52 | 3.09 | 19.18 |
| UB10NOx | 5 | 339.06 | 17.19 | 5.07 | 36.23 |
| UB20NOx | 5 | 322.82 | 11.51 | 3.56 | 24.1 |

### 3.1. Experimental Analysis of $CO_2$ and CO emissions

Figure 2 illustrates the carbon dioxide ($CO_2$) emission patterns of the H2.5B vehicle (2.5 L injection pump engine) across different fuel types and driving conditions. The lowest $CO_2$emissions were recorded during descent with conventional diesel fuel, reaching values of approximately 2.8% by volume, indicating improved combustion efficiency under reduced engine load and favorable operating conditions. Regarding carbon monoxide (CO) emissions, the most favorable results were also observed when using diesel during descent, as well as during ascent with B20 biodiesel, where CO concentrations dropped to approximately 0.0008% by volume.

In the case of the M2.5C vehicle (2.5 L CRDI engine), the $CO_2$ emission behavior is consistent with that observed in the H2.5B vehicle, as illustrated in Figure 3a. The lowest $CO_2$ concentrations were recorded under descent conditions when conventional diesel was used. However, for CO emissions, fuel type did not appear to be a significant influencing factor. Instead, driving conditions played a more critical role. The lowest CO values were again observed during descent, reaching approximately 0.0008%, identical to the minimum values recorded for the H2.5B vehicle (Figure 3b) [42].

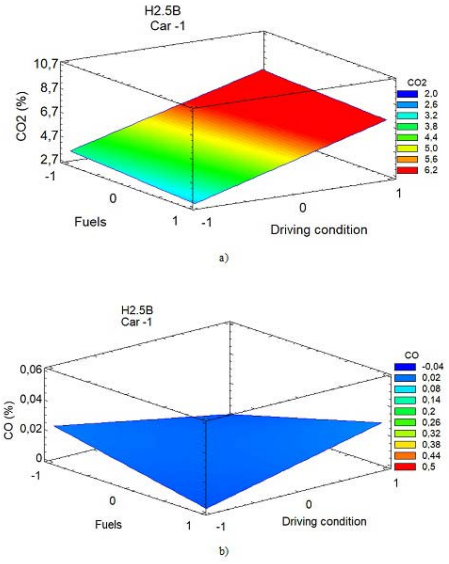


**Figure 2.** $CO_2$ emissions (a) and CO emissions (b) from the H2.5B vehicle as a function of fuel type and driving conditions.

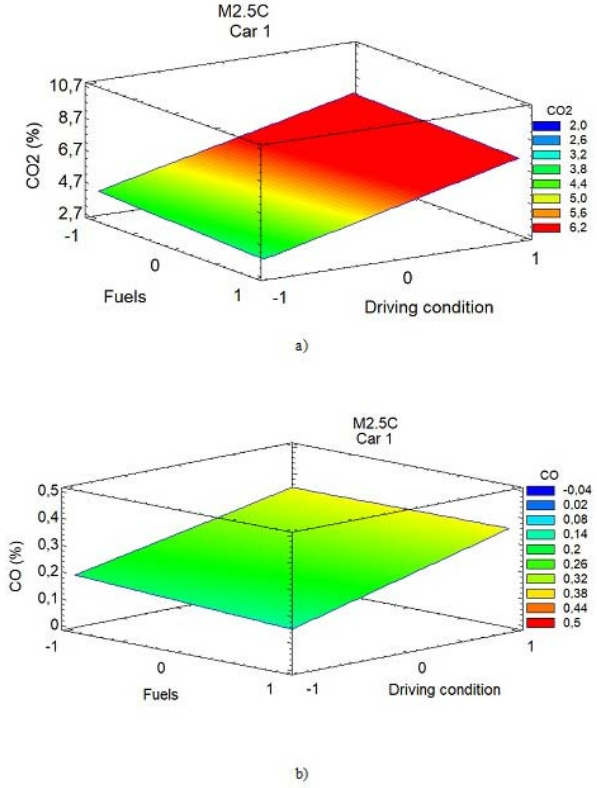


**Figure 3.** $CO_2$ emissions (a) and CO emissions (b) from the M2.5C vehicle as a function of fuel type and driving conditions.

The Pareto diagram presented in Figure 4 illustrates the relative influence of experimental factors on $CO_2$ emissions. The diagram includes the main effects and two-factor interactions: AC (Vehicle–Driving Condition), BC (Fuel–Driving Condition), and AB (Vehicle–Fuel). Among these, driving conditions emerged as the most significant factor affecting $CO_2$ levels. This result is further supported by the trends shown in Figure 5. In the case of CO emissions, the most influential variables were the vehicle type, driving conditions, and their interaction, as depicted in Figure 6.

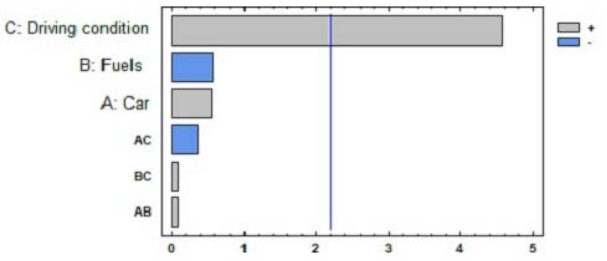


**Figure 4.** Effects of factors on $CO_2$ emissions.

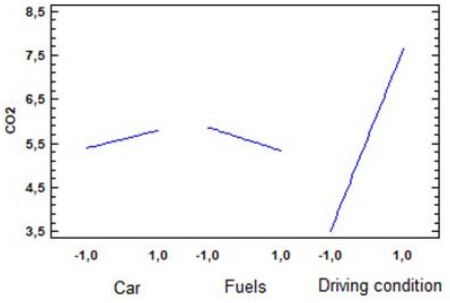


**Figure 5.** Main effects of factors on $CO_2$ emissions.

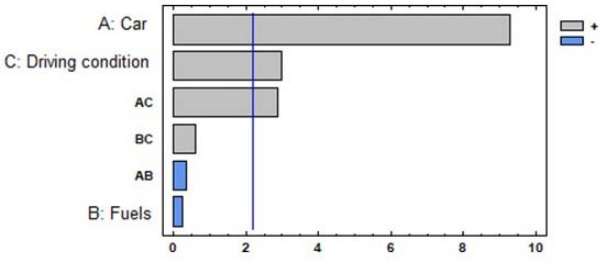


**Figure 6.** Effects of factors on CO emissions.

### 3.2. Experimental Analysis of HC emissions

Figure 7 presents the hydrocarbon (HC) emission behavior of the H2.5B vehicle (2.5 L injection pump engine) as a function of fuel type and driving condition. The lowest HC concentrations were observed when using conventional diesel, regardless of the driving condition, suggesting that in this vehicle configuration, fuel type has a greater influence on HC emissions than operating mode. In contrast, the M2.5C vehicle (2.5 L CRDI engine) exhibited a different trend, as shown in Figure 8.

The lowest HC emissions were recorded when operating with B20 biodiesel during ascent conditions.

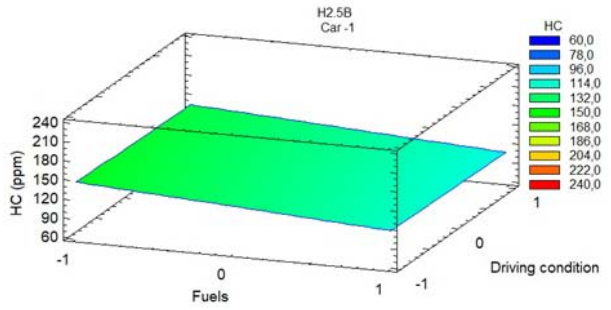


**Figure 7.** HC emissions from the H2.5B vehicle as a function offuel and driving conditions.

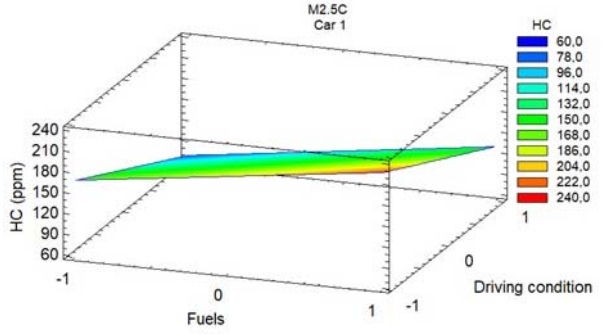


**Figure 8.** HC emissions from the M2.5C vehicle as a function of fuel and driving conditions.

The Pareto diagram in Figure 9 illustrates the influence of individual factors and their interactions on HC emissions. The most significant contributors were the driving conditions, followed by the interaction between vehicle type, fuel type, and driving conditions. In Figure 10, the main effects of each variable are shown independently, providing a clearer understanding of the relative impact of each factor on HC emissions.

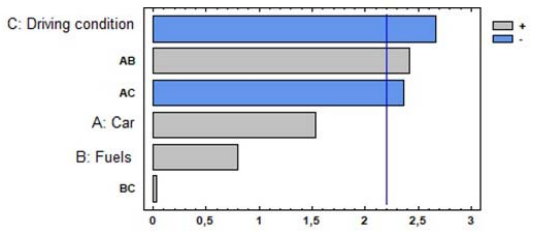


**Figure 9.** Effects of factors on HC emissions.

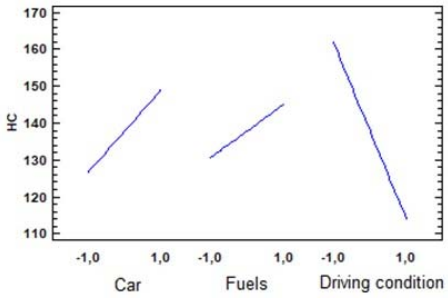


**Figure 10.** Main effects of factors on HC emissions.

### 3.3. Experimental Analysis of $NO_x$ Emissions

Figure 11 illustrates the nitrogen oxide ($NO_x$) emission behavior of both the M2.5C (2.5 L CRDI) and H2.5B (2.5 L injection pump) vehicles as a function of fuel type and driving condition. The lowest $NO_x$ emissions were observed during descent conditions, with fuel type showing no statistically significant effect in this context. Previous studies, such as that by Rocha-Hoyos et al. [25], have reported that biodiesel combustion tends to lower particulate matter, carbon monoxide, and smoke opacity, while slightly increasing $NO_x$ emissions relative to conventional diesel. Similarly, findings by Tesfa, Mishra, and Ball [28] suggest that biodiesel use generally results in increased $NO_x$ levels, irrespective of the feedstock source. However, in the present study, these increases were not statistically significant, likely due to the high-altitude driving conditions and real-world measurement approach, which reflect actual vehicle operation more accurately than laboratory conditions. Additional strategies, such as biodiesel–ethanol blending, have been proposed to mitigate $NO_x$ emissions more effectively [43].

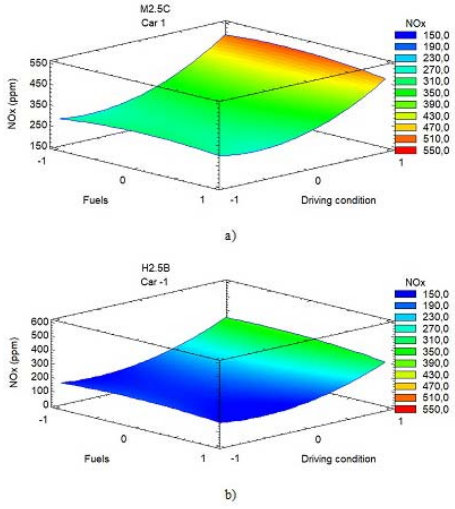


**Figure 11.** $NO_x$ emissions as a function of fuel type and driving conditions for the M2.5C vehicle (a) and the H2.5B vehicle(b).

## 4. Conclusions

The chemical characterization of waste frying oil revealed a cetane number of 47, confirming its suitability for biodiesel production through transesterification.

Biodiesel blends (B10 and B20) met the quality criteria outlined in INEN Standard 1489:2012, validating their potential use as alternative fuels in compression ignition engines.

$CO_2$ and CO emissions from both the H2.5B and M2.5C vehicles were lowest under descent conditions when fueled with conventional diesel. This is attributed to reduced engine load, operation in coasting or injection cutoff modes, and overall improved combustion efficiency in such scenarios.

HC emissions were minimized in ascent conditions when using B20 biodiesel in both vehicles. The increased oxygen content in the biodiesel likely enhanced combustion under high load, thereby reducing unburned hydrocarbons.

$NO_x$ emissions were also lowest during descent, regardless of the fuel type, due to the reduced combustion chamber temperature and lower engine load in these operating conditions.

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## Contributor Roles

- **Edilberto Antonio Llanes-Cedeño:** Conceptualization, supervision,data curation.
- **Andrés Cárdenas-Yánez:** Methodology.
- **Edwin Chamba:** Validation, data curation.
- **Juan Carlos Castelo:** Writing – original draft.
- **Juan Carlos Rocha-Hoyos:** Writing – review & editing.

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