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# Modelling São Paulo's Transport Sector Net-Zero Transition: Application of an Enhanced-FNN for HVO Biofuel Integration into the State's Energy Matrix.

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**Abstract**

This study evaluated the integration of hydrotreated vegetable oil (HVO, "renewable diesel") into São Paulo's transport energy matrix by quantifying $CO_2e$ emissions and avoided-emission potential from 2018 to 2023 and projecting pathways to 2050 under a business-as-usual (BAU) scenario. Using a distance-based fuel consumption model with a fleet efficiency of 3.60km/L and emission factors (2.70 kg $CO_2e$/L for diesel and 0.70 kg $CO_2e$/L for HVO), we computed emissions and avoided-emission credits for diesel, HVO, and intermediate blends (13–50% HVO). The results show that emissions decrease with increasing HVO content: average emissions decline from 39.105 MT (diesel) to 10.138 MT (100% HVO), a 74.1 % reduction, while avoided emissions increase to 28.966 MT for 100% HVO. For long-horizon forecasting for the years 2030, 2040, and 2050, an Enhanced Feedforward Neural Network (Enhanced-FNN; SiLU + MC-dropout; trained with training-only augmentation) outperformed quadratic regression ($R^2 \sim 0.65$) and provided stable nonlinear projections ($R^2$ ∼0.997, MAE ∼0.883 MT; MSE ∼1.286 $MT^2$). Increasing HVO blending consistently reduces projected emissions and strengthens avoided-emission benefits, thereby supporting progressive blending mandates in São Paulo.

**Keywords:** BioFuels, Hydrotreated Vegetable Oil, Artificial Intelligence, Neural Network, Net-Zero Emissions, Sao Paulo

# 1 Introduction

With the global population projected to reach approximately ∼8.5 billion by 2030, the demand for biofuels is expected to increase substantially (WEF, 2022). Statistically, the worldwide demand for biofuels is expected to rise by approximately ∼41 billion liters, representing a 28% increase between 2020 and 2030. Renewable energy sources are the cornerstone of any energy transition aimed at achieving zero emissions. With climate targets established and energy transition underway, the use of fossil fuels is expected to decline in absolute terms (IEA, 2021). In this context, the importance of fuel flexibility and independence has grown significantly in heat and power production. Advanced biofuels, such as Hydrotreated Vegetable Oil (HVO), represent promising renewable fuel options for addressing these requirements.

Green fuels, including biodiesel, bio-kerosene, and bio-LPG, along with other sustainable biofuels such as HVO, can significantly contribute to the decarbonization of power and heat. In particular, whereas Fatty Acid Methyl Ester (FAME, commonly known as traditional biodiesel) has lower compatibility with diesel engines, HVO can serve as a "drop-in" fuel substitute for fossil diesel, as shown in Table 1. Biodiesel produced via transesterification processes (FAME) can be used up to approximately ∼15% in a blend with fossil diesel, whereas HVO can be blended at much higher concentrations or even used as a complete alternative without the need for costly mechanical adjustments (Bohl et al., 2018; Valeika et al., 2022). This is because HVO has a chemical composition that is very similar to that of conventional fossil diesel fuel, enabling comparable performance characteristics without engine modifications (Heymi et al., 2022; Aatola et al., 2009; Nogueira et al., 2020). Beyond operability, recent life-cycle evidence continues to report substantial greenhouse gas (GHG) reductions for renewable diesel/HVO pathways relative to fossil diesel, although outcomes remain strongly dependent on feedstock origin, land-use effects, and system boundaries, reinforcing the need for context-specific, policy-aligned accounting when discussing "carbon credits" (Xu et al., 2022; Ajeeb et al., 2025).

Hydrotreated Vegetable Oil (HVO) can be synthesized from various organic materials, including diverse vegetable oils and animal fats, representing a third-generation biofuel production pathway, as illustrated in Figure 1. Furthermore, HVO has the potential to power the transportation and industrial sectors, including commercial agriculture, owing to its high quality as a diesel substitute and its compatibility with existing engines and infrastructure (Neupane, 2023; Bridgwater, 2012). The policy significance of Hydrotreated Vegetable Oil (HVO) has been enhanced by the increasing implementation of decarbonization frameworks that facilitate fuel switching through certifications and tradable instruments. In Brazil, this is exemplified by the RenovaBio system, wherein decarbonization credits (CBIOs) represent verified emissions avoidance, in accordance with regulatory guidelines (ANP, 2018; B3CBIO, 2023).

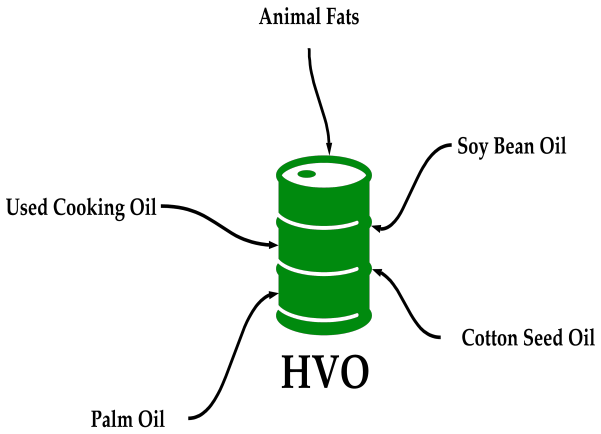



**Fig. 1: Hydrotreated Vegetable Oil (HVO). As shown, potential feedstocks for the production of HVO are Animal fats, Soy bean oil, Cotton seed oil, Palm oil and Used cooking oil.**

Given the beneficial properties of HVO, there has been an increased emphasis on its global production and adoption. It is essential to assess how HVO aligns with the prevailing trends in biofuel production globally and within key regions. Concurrently, it is imperative to differentiate between (**I**) descriptive market growth narratives and (**II**) quantitative, reproducible frameworks that connect demand, emissions factors, and policy crediting rules under conditions of uncertainty. This distinction directly impacts the interpretation of long-term projections (Alhindawi et al., 2020; Franckx, 2017).

Global biofuel production has steadily increased, with regional variations in growth rates and contributions. Prior to the COVID-19 pandemic, the International Energy Agency (IEA) reported that Latin America had a biofuel production capacity of approximately 39 billion liters per year (BLPY), primarily consisting of ethanol and biodiesel, aimed at reducing $CO_2$ and other greenhouse gas (GHG) emissions. In the post-2020 period, Latin America has observed a consistent annual growth in biofuel demand of approximately ∼10.4 BLPY, a rate surpassed only by Europe (approximately ∼13.4 BLPY) and North America (approximately ∼15.9 BLPY). Projections suggest that by 2026, Latin American biofuel demand will increase to approximately ∼49.0 BLPY, ranking second only to North America and accounting for approximately ∼26.8% of global biofuel demand (IEA, 2021; Heymi et al., 2022). Moreover, studies have shown that HVO improves compatibility and reduces particulate emissions compared with EN590 diesel. However, nitrogen oxide (NOx) emissions vary by engine and calibration because of HVO's paraffinic composition, low aromatics, and high cetane number of HVO, which affect the ignition delay and soot formation (Bugarski et al., 2016).

**Table 1**: **Combined Physical, Chemical, and Performance Properties of HVO, Fossil Diesel, FAME (Biodiesel), and Hydrous Ethanol. Adapted from (Dimitriadis et al., 2018; Herndon et al., 2022; Happonen et al., 2013; Lapuerta et al., 2011; Aatola et al., 2009; Crown Oil, 2025; ANP, 2023, 2022; McCormick and Moriarty, 2023; DOE-AFDC, 2024; NIST, 2025).**

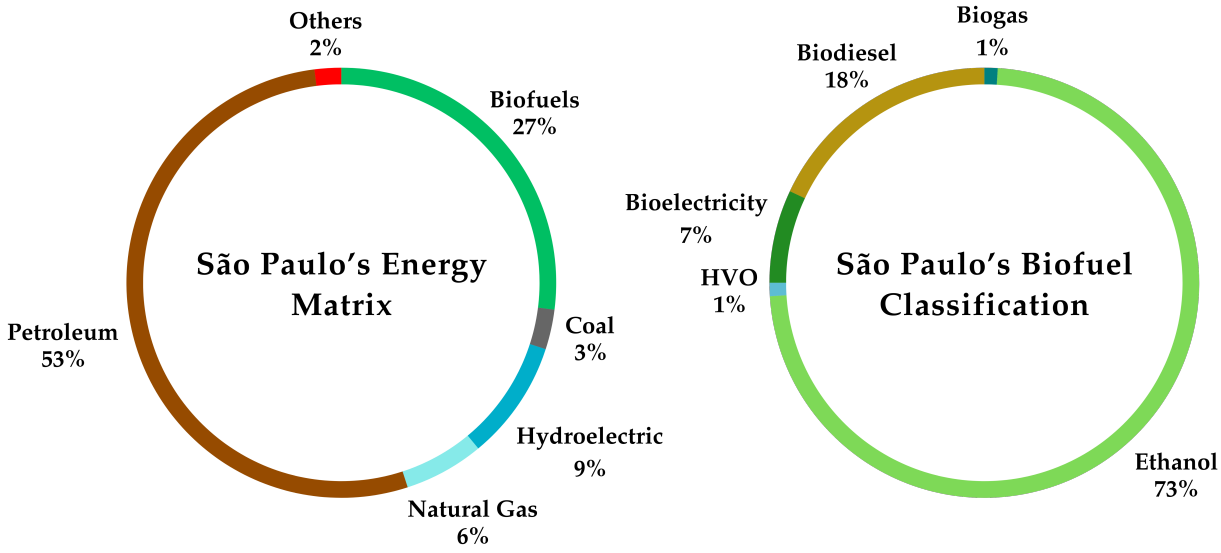
| Property | HVO | Fossil Diesel | FAME (Biodiesel) | Hydrous Ethanol |
|---|---|---|---|---|
| **PHYSICAL PROPERTIES** | | | | |
| Density (kg/m$^3$) °C | 775–790 | 830–845 | 850–900 | 805–811 |
| Boiling Point (°C) | 300–350 | 163–357 | 330–357 | 78.5 |
| Cloud Point (°C) | -10 to -15 | -40 | -3–16 | -117.3 |
| Pour Point (°C) | $<$ -20 | 3–15 | -15–10 | -117.3 |
| Flash Point (°C) | 83 | 59 | 100–170 | 12.8 |
| Cold Filter Plugging Point (CFPP, °C) | -21 | -5 | 5–14 | - |
| Water Content | 20 mg/kg | 160 mg/kg | $\leq$ 200 mg/kg | $\leq$ 7.5% (m/m) |
| Distillation Range (°C) | 189–301 | 191–357 | 330–360 | 78.5 |
| **CHEMICAL PROPERTIES** | | | | |
| Carbon Chain Range (C-number) | $C_{15}$–$C_{18}$ | $C_{12}$–$C_{20}$ | $C_{12}$–$C_{22}$ | $C_2$ |
| Chemical Formula | $C_nH_{2n+2}$ | $C_nH_{2n}$ | mixture (FAME) | $C_2H_6O$ |
| Hydrogen Content (% wt) | 15.4 | 12.0 | 11–12 | 13.0 |
| Oxygen Content (% wt) | 0.00 | 0.77 | 10–12 | 34.7 |
| Sulphur Content | $<$ 5.0 ppm | 9.1 ppm | $\leq$ 10 mg/kg | low |
| Ash Content (% wt) | $<$ 0.001 | 0.002 | $\leq$ 0.020 (sulfated ash) | $\approx$ 0 |
| Oxidation Stability (hr) | $>$ 22 | $>$ 6 | $\geq$ 13 | - |
| Aromatics Content (% vol) | $\leq$ 1 | 15–30 | $\approx$ 0 | $\approx$ 0 |
| **COMBUSTION AND PERFORMANCE PROPERTIES** | | | | |
| Cetane Number (Ignition Quality) | 76.3 | 56.5 | 47–65 | $\sim$110 (Octane number) |
| Lower Heating Value (LHV, MJ/kg) | 44.0 | 43.0 | 37.8 | 26.8 |
| Hydrogen-to-Carbon Ratio (H/C) | 1.90–2.00 | 1.80–1.85 | 1.75–1.85 | 3.00 |
| Soot Formation Tendency | Very low | Moderate to high | Low | Very low |
| Engine Ignition Delay | Shorter | Longer | Shorter | Not Applicable |
| Cold Start Performance | Improved | Standard | Cold-flow limited | Calibration-dependent |
| Carbon Footprint (tonnes $CO_2$/kL) | 0.195 | 3.6 | 0.96–1.32 | 0.7–1.5 |

**Table 2: Global Biofuel Demand Projection by Continent. Adapted from (IEA, 2021, 2019b).**

| Continent | Annual Growth | 2020 Demand | 2026 Demand |
|---|---|---|---|
| Asia | 10.8 | 20.9 (14.5%) | 31.3 (17.1%) |
| Europe | 13.4 | 25.5 (17.7%) | 28.5 (15.6%) |
| Latin America | 10.4 | 39.0 (27.1%) | 49.0 (26.8%) |
| North America | 15.9 | 58.3 (40.5%) | 73.6 (40.2%) |
| Rest of the World | 0.1 | 0.3 (0.2%) | 0.4 (0.2%) |
| **Total** | **40.6** | **144** | **182.8** |

As detailed in Table 2, these comparative trends underscore Latin America's increasing significance in the global biofuel market. This prominence is primarily attributed to Brazil, which is distinguished by its robust biofuel industry, particularly the production of bioethanol from sugarcane feedstock. Brazil's sustained investments in bioethanol infrastructure and technology have positioned it as a global leader in biofuel utilization and production. This regional context serves as a foundation for exploring specific locations within Latin America that may spearhead the development of the next generation of biofuels. The state of São Paulo in Brazil is particularly noteworthy because of its substantial energy consumption and existing biofuel ecosystem, which makes it an ideal case study for advanced biofuel integration. Concurrently, methodological frameworks developed for São Paulo hold broader scientific interest if they can be transparently applied to other subnational contexts with similar characteristics (such as large fleets, legacy diesel dependence, and expanding biofuel supply chains). This is the core motivation for emphasizing reproducible modelling and uncertainty treatment (Franckx, 2017; Alhindawi et al., 2020).

As shown in the donut chart in Figure 2 below, São Paulo has an existing diverse and robust energy matrix, with biofuels occupying approximately ∼27% of the state's energy matrix, second only to petroleum with approximately ∼53%. Again, from the donut chart on the right of Figure 2, it can be seen that ethanol is the predominant biofuel, consumed mostly as a "standalone" fuel with approximately ∼73% of the entire biofuel classification in the state's energy matrix (See also Figure 2(b)). In addition, HVO and biogas are novel introductions into the energy matrix, representing approximately ∼1% of the entire biofuel classification, as shown in Figure 2b.




(a) (b)

**Fig. 2: The donut charts illustrate the classification of energy sources in the state of São Paulo. As depicted in Subfigure (a) on the left-hand side, the energy source classification for São Paulo is presented. Currently, the state is predominantly powered by fossil fuels, specifically petroleum, followed by biofuels in terms of demand. Subfigure (b) further delineates the subclassification of the biofuels matrix within São Paulo's energy market. Ethanol emerges as the most consumed or highly demanded biofuel, followed by biodiesel. Adapted from (SEMIL, 2025; Hayashi and Degreenia, 2024; Costa et al., 2023)**

Given that São Paulo is recognized as the commercial hub of Latin America, the integration of an additional "drop-in" renewable diesel, such as Hydrotreated Vegetable Oil (HVO), into its pre-existing biofuel matrix could accelerate the state's transition towards net-zero emissions and its alignment with the COP 21 Paris Agreement. Despite existing market constraints, the blending of HVO with conventional fossil diesel has the potential to contribute to the achievement of Environmental, Social, and Governance (ESG) objectives while simultaneously reducing $CO_2$ emissions. With appropriate legislative measures, the biofuel market in São Paulo has been poised to expand, thereby facilitating the transition to green energy (Menezes et al., 2021; Heymi et al., 2022). In Brazil, such expansion is increasingly linked to the operationalization of decarbonization targets through RenovaBio, where CBIO issuance and trading depend on certified lifecycle performance and compliance rules, strengthening the need for transparent emissions-and-credit computations

(rather than purely descriptive claims) (ANP, 2018; B3CBIO, 2023).

Previous research has explored (I) the properties of fuel and engine performance evidence for HVO in comparison to fossil diesel (Table 1) (Dimitriadis et al., 2018; Herndon et al., 2022; Happonen et al., 2013; Lapuerta et al., 2011; Aatola et al., 2009; Crown Oil, 2025), (II) the general trajectories of the biofuel market (Table 2) (IEA, 2021, 2019b), and (III) the reductions in life-cycle emissions for renewable diesel pathways (Xu et al., 2022; Ajeeb et al., 2025), a notable gap persists at the subnational level. Specifically, there is a scarcity of studies that integrate (A) a region-specific transition narrative, such as São Paulo's energy matrix (Figure 2), (B) policy-aligned carbon-credit logic, exemplified by CBIO-style avoided emissions, and (C) uncertainty-aware long-term projections suitable for decision support under data constraints (ANP, 2018; B3CBIO, 2023). Furthermore, long-term projections of transport emissions are often highly sensitive to factors such as fleet structure, turnover, and efficiency trends. Many methodologies explicitly recommend disaggregation by vehicle class and age, as well as sensitivity analysis, to mitigate overconfidence when utilizing aggregated averages (Franckx, 2017; Alhindawi et al., 2020).

Accordingly, this study presents a reproducible, data-driven framework for São Paulo that (I) quantifies blended fuel emissions and avoided emissions through a transparent accounting methodology, (II) generates long-term projections utilizing an Enhanced-FNN with Monte Carlo dropout for uncertainty-aware inference, and (III) documents assumptions and limitations in a format adaptable to other regions with similar diesel reliance and biofuel policy instruments (e.g., other Brazilian states or analogous subnational markets in Latin America). The framework deployed in this study is adaptable for application to other Brazilian states or comparable regions. This adaptability is achieved by modifying parameters such as local fleet activity (distance travelled), fleet efficiency, blend shares, and policy credit rules. Importantly, the modelling workflow and uncertainty-aware forecasting procedure remained consistent despite these modifications. The scientific significance of the São Paulo case study resides in its integration of high economic activity, a substantial legacy fleet, and a well-established biofuel ecosystem (See Figure 2), providing a transferable model for incorporating regional energy-matrix evidence with forecast models and policy crediting rules (SEMIL, 2025; Costa et al., 2023).

Consequently, this study investigated the feasibility of incorporating Hydrotreated Vegetable Oil (HVO) into the existing biofuel energy framework of São Paulo. By employing São Paulo as a case study, we examine the global production of HVO and current technological advancements, and provide a forward-looking perspective on the transition to sustainable energy in Section 2. In Section 3, we delve into the Enhanced-FNN methodology utilized for calculating emissions and avoided emissions, situating this approach within the broader spectrum of modelling strategies for long-term transportation and energy forecasts (Alhindawi et al., 2020; Franckx, 2017). In addition, we present and analyze the findings in Section

4. Finally, in Section 5, we offer conclusions and potential policy recommendations that could facilitate the proposed blending ratios of HVO, thereby advancing the transition towards achieving net-zero emission objectives.

# 2 Production and Potential Consumption of HVO in the State of Sao Paulo as a Case Study: Global Overview, Synopsis of the Current Challenges, Production Technologies and Recommendations.

The global commissioning of large-scale standalone Hydrotreated Vegetable Oil (HVO) plants is anticipated to increase substantially, with full operational capacity projected by 2030 driven by prevailing demand trends. This development is further supported by ongoing retrofitting projects at petrochemical refineries. While the biodiesel market and its supply chain continue to expand, the need for enhanced HVO production is highlighted by relatively low barriers to reducing carbon emissions and low capital costs (Nurdiawati and Urban, 2022). These trends align with recent technical reviews that attribute near-term scale-up to both (I) standalone capacity additions and (II) refinery conversions/co-processing routes, while emphasizing that lifecycle benefits depend on feedstock sustainability and certification regimes (Ajeeb et al., 2025; Bonomi et al., 2023).

As illustrated in Table 1, HVO shares similar chemical properties with fossil diesel, and its technological application is straightforward, with production feasible from a diverse range of feedstocks (See Figure 1), making it a preferred choice among biofuels (OECD-FAO, 2019). Furthermore, HVO-derived products, such as hydroprocessed esters and fatty acid synthetic paraffinic kerosene (HEFA-SPK), produced at standalone HVO facilities, exhibit similar feedstock diversity and contribute to the reduction of $CO_2$, $NO_X$, and other greenhouse gas emissions. Moreover, HEFA-SPK is particularly valued as an aviation biofuel because of its superior storage stability and cold-flow characteristics. As shown in Figure 4, additional products include bio-naphtha and bio-LPG, which are utilized in the production of green plastics and olefin blendstocks, respectively (Slome and Dolan, 2021). Despite the substantial capital investments required for standalone HVO refineries, particularly in regions with less robust markets, such as Latin America, the sector holds promising long-term financial prospects. Significant global investments have been made in the transportation sector to mitigate carbon footprints by using biofuel production and carbon capture technologies. Additionally, the blending capabilities of HVO with fossil fuels aid in reducing the carbon footprint and advancing sustainable transportation objectives. Companies such as TotalEnergies, ENI, and Repsol are actively engaged in co-processing HVO products, and Petrobras is conducting pilot studies in Brazil. One such technology is the H-BIO, as shown in Figure 3.

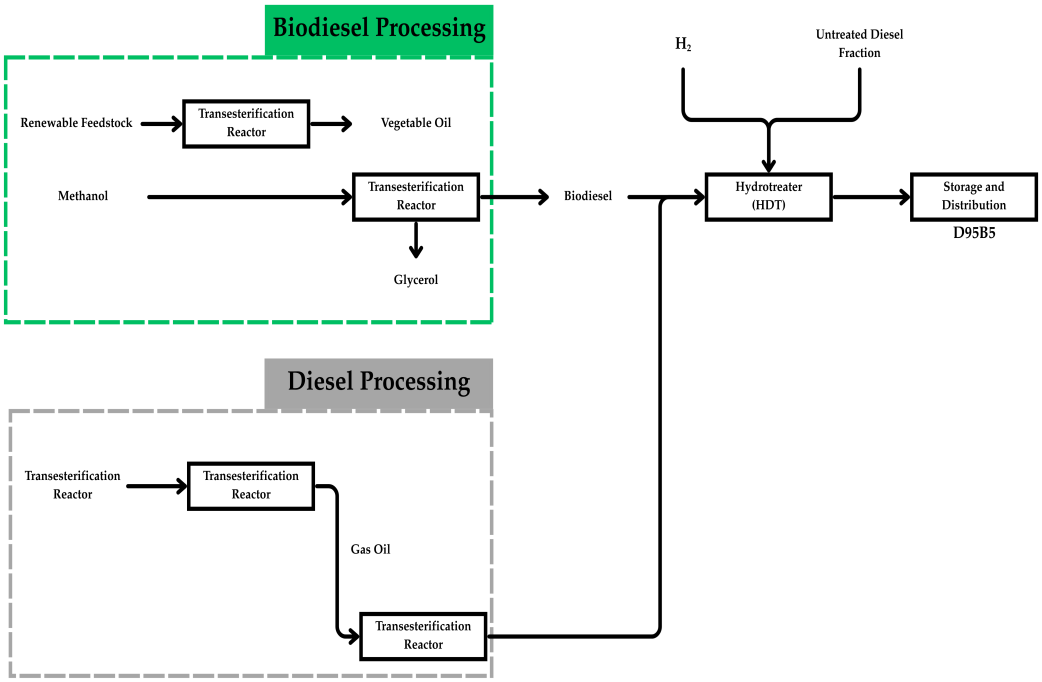



**Fig. 3: A schematic process flow diagram of the Petrobras H-BIO Technology. As shown, patented in 2006, the HBIO technology hydrogenates vegetable oil, which is in turn mixed with fossil diesels in a proportion of about 5-10% . Currently operational at the Presidente Bernardes Refinery, the goal is to produce renewable diesel through this retrofitted technology to lower sulfur and improve overall fuel quality.**

Government regulations requires that stakeholders decarbonize production processes while maintaining profitability, thereby encouraging the exploration of biofuel production alternatives such as bioethanol. This review introduces an innovative retrofitting process that incorporates additional process units into the existing petrochemical plants in Brazil, as illustrated in Figure 4. These technologies facilitate the processing of petrochemical byproducts, thereby enhancing energy efficiency and reducing capital expenditures. The scientific significance of such pathways is augmented when they are coupled with consistent life-cycle accounting tools and certification standards, as crediting mechanisms (e.g., CBIO-type instruments) require auditable emissions-intensity estimates rather than qualitative sustainability claims (Bonomi et al., 2023; ANP, 2018).

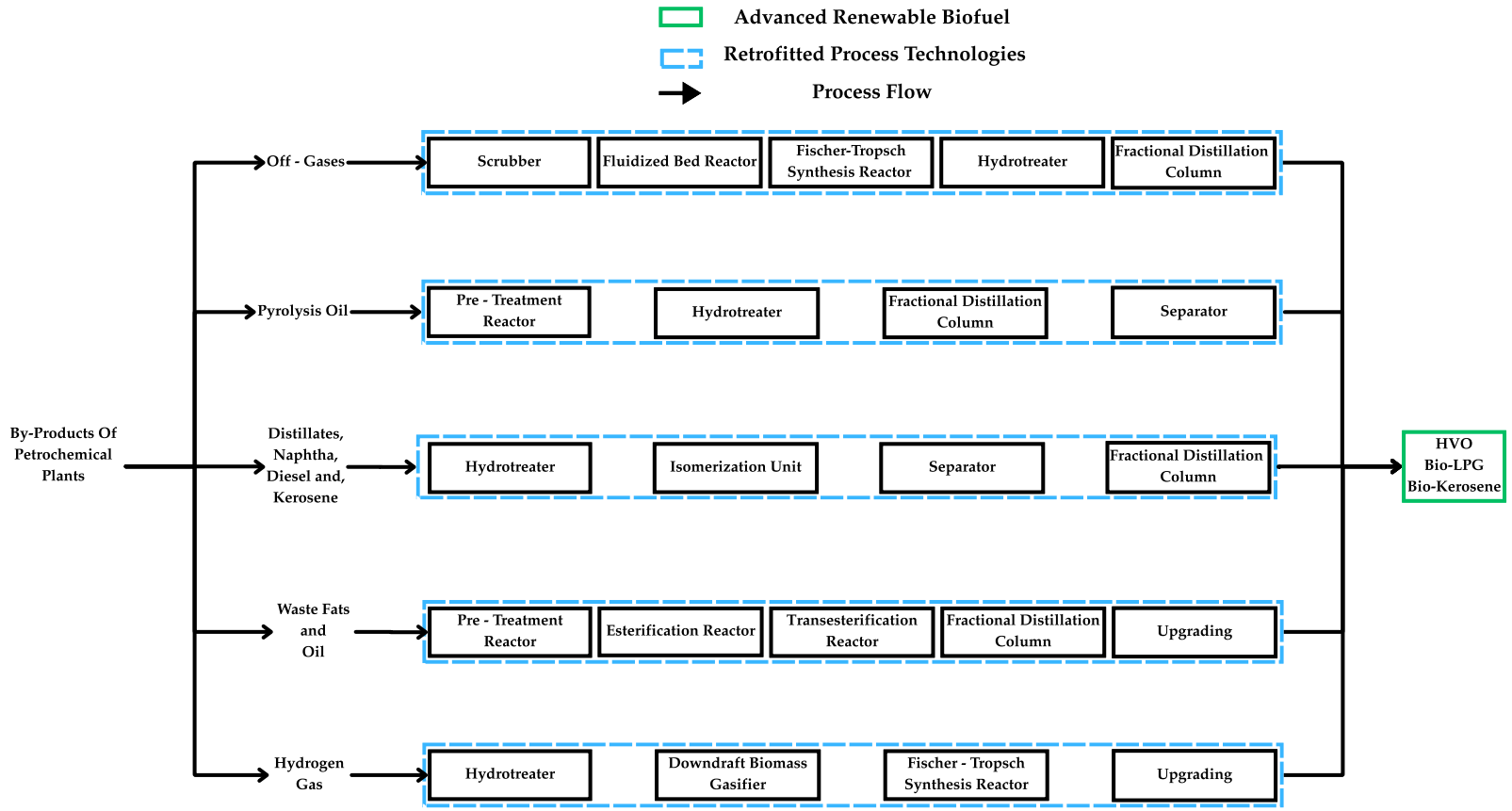



**Fig. 4: A complete recommended retrofitted process flow diagram for the production of HVO and other green fuels such as Bio-LPG and Bio-Kerosene from the by-products of pre-existing petrochemical plants. The upgrading processing step above denotes further hydrocracking, isomerisation, distillation, hydroprocessing, or hydrotreating processes. Adapted from** (Hopwood et al., 2019; Caretta et al., 2021; Boichenko et al., 2013; Neupane, 2023)

## 2.1 Global HVO and Biofuels Overview: Production, Demand, and Sao Paulo's Position

As previously noted, Hydrotreated Vegetable Oil (HVO) represents a significant advancement in the biofuel industry, distinguished from conventional biodiesel by its production through hydrotreatment rather than transesterification. This process yields a "drop-in" fuel that is chemically analogous to fossil diesel, thereby enabling seamless integration into existing infrastructure and engines, while offering improved cold-weather performance and greater potential for reducing greenhouse gas emissions. The global market for HVO is experiencing substantial growth, with projections indicating that it will reach approximately ∼USD 21.36 to ∼USD 21.83 billion by 2025 and potentially expand to ∼USD 36.86 to ∼USD 51.19 billion by 2032, reflecting a compound annual growth rate of 8.11% to 12.3% (IEA, 2019a; FMI, 2025; Moharir, 2025; Maia Research, 2025).

Moreover, the regional production capacity highlights this growth. Europe currently leads in HVO production, with an output of approximately ∼11.45 million tonnes (∼13.2 billion liters) projected for 2025, followed by North America at approximately ∼5.67 million tonnes (∼ 6.5 billion liters) (IEA, 2019a; FMI, 2025; Moharir, 2025; Maia Research, 2025). This production is set against the backdrop of increasing global demand for biofuels. As illustrated in Table 2, the total global biofuel demand is projected to grow from 144 billion liters per year (BLPY) in 2020 to 182.8 BLPY by 2026. Notably, North America and Latin America are the largest demand centers, accounting for over two-thirds of global consumption. This surge is driven by policies aimed at decarbonizing transport, particularly in sectors that are challenging to electrify, such as heavy-duty freight and aviation, where HVO and its derivatives, such as Sustainable Aviation Fuel (SAF), are critical solutions. In this context, a key methodological challenge for the literature is translating global trends into robust regional projections, as transport demand and fleet dynamics modeling choices (stock/turnover, survival curves, and segmentation by class) can significantly alter long-term results (Franckx, 2017; Alhindawi et al., 2020).

## 2.2 Latin American Context and Sao Paulo's Strategic Potential

In the global context, Latin America holds significant importance due to its large population, extensive market, established supply chains, and strong policy frameworks. The region represents 26.8% of the global biofuel demand and is anticipated to reach 49.0 BLPY by 2026 (See Table 2). Brazil, as the foremost biofuel producer in the region, plays a crucial role with its well-established sugarcane ethanol industry and biodiesel mandate. However, the production of Hydrotreated Vegetable Oil (HVO) is still in its nascent stages. São Paulo, recognized as Brazil's economic and agricultural hub, is strategically positioned to lead the development of the country's HVO industry. The state's abundant feedstock resources, including soy oil, animal fats, and non-edible oil, combined with its advanced biorefining infrastructure and logistics capabilities, provide a robust foundation for the production of biodiesel.

Notably, Brazil's regulatory environment is adapting to support the production of advanced biofuels. Specifically, in the context of São Paulo as a case study, the adoption of HVO production represents a strategic diversification of the existing bioeconomy. Integrating HVO into the state's current biofuel matrix offers a path to higher-value biofuels and potential export opportunities, particularly in Latin America, which, like Europe, enforces stringent sustainability criteria and provides significant environmental benefits for urban centers through enhanced air quality. The underlying demand and resource base, as highlighted in Table 2, indicate substantial untapped potential. With targeted investment and supportive policies, São Paulo is poised to become a key player in the Latin American advanced biofuel market, transitioning from being a leader in global biofuel demand to being a producer of next-generation renewable fuels. This positioning is strengthened when emissions and "credit" claims are aligned with formal certification rules (e.g., RenovaBio/CBIO definitions and issuance constraints), which improves reproducibility

and transferability to other regulated markets (ANP, 2018; B3CBIO, 2023).

## 2.3 Current Challenges, Production Technologies, and Recommendations For HVO

Expansion of the Hydrotreated Vegetable Oil (HVO) market presents several significant challenges. A primary obstacle is the substantial capital investment required to establish the production facilities. As illustrated in Table 3, "New Build" plants are crucial to both current and future HVO production, accounting for 49.47% of the projected 16.84 billion liters per year (BLPY) by 2024. This prevalence highlights the necessity for a considerable initial financial outlay, which acts as a barrier to rapid market entry and expansion. Furthermore, competition for sustainable feedstocks is intensifying, leading to increased prices and raising concerns about indirect land-use changes. In regions such as Latin America, where biofuel demand is anticipated to reach 49.0 BLPY by 2026 (as indicated in Table 2 ), this dynamic creates tension between the objectives of increasing production and ensuring its sustainability. Recent life cycle syntheses emphasize that the claimed climate advantage of renewable diesel/HVO can vary widely with feedstock sourcing and boundary assumptions, making transparent accounting essential when policy incentives and markets are involved (Xu et al., 2022; Ajeeb et al., 2025; Bonomi et al., 2023).

### 2.3.1 *Production Technology Landscape*

The evolution of production technologies is crucial to comprehending the trajectory of the sector. The data presented in Table 3 reveal a strategic shift away from exclusive dependence on "New Build" facilities. Although "New Build" remains predominant, its share is expected to decrease from 64.98% in 2020 to 49.47% in 2024. This trend is further supported by the consistent utilization of Fossil Refinery conversions and the growing importance of co-processing (or retrofitted plants), where renewable feedstocks are processed alongside fossil streams within existing refinery units, as illustrated in the recommended production pathway in Figure 4.

**Table 3: Global HVO Production and Projection by Plant Technology Type. Adapted from (IEA, 2019b, 2021)**

| Plant Type Technology | 2020 (BLPY) | 2022 (BLPY) | 2024 (BLPY) |
|---|---|---|---|
| Accelerated Case | – | 2.00 (14.53%) | 4.00 (23.75%) |
| Co-Processing | 0.48 (6.57%) | 0.48 (3.49%) | 1.06 (6.30%) |
| Fossil Refinery | 2.08 (28.45%) | 3.45 (25.07%) | 3.45 (20.47%) |
| New Build | 4.75 (64.98%) | 7.83 (56.90%) | 8.33 (49.47%) |
| **Total** | **7.31** | **13.76** | **16.84** |

Co-processing is a cost-effective strategy for integrating renewable content, although it is constrained by limitations concerning the renewable content of the

final product. As illustrated in Table 3, the "Accelerated Case" category is the most dynamic, projecting a swift increase from zero in 2020 to 23.75% of production by 2024. Additionally, an examination of existing refineries in São Paulo reveals their capacity to co-process Hydrotreated Vegetable Oil (HVO) or green diesel. This capacity may require minimal or no modification to the current process equipment to enhance the overall process efficiency and minimize energy penalties. Nonetheless, the integration capacity of the HVO process can secure future investments (IEA, 2019b, 2021; ECB Group, 2021). Given that downstream policy instruments, such as CBIOs, rely on certified life cycle performance, regional planning for co-processing and scale-up also benefits from alignment with emission accounting methods, data quality standards, and auditability (ANP, 2018; B3CBIO, 2023; Bonomi et al., 2023).

Currently, several refineries are anticipated to commence HVO co-production as part of their strategy to provide sustainable diesel and reduce the overall carbon footprint. These refineries represent 42% of Brazil's total capacity. Notably, most refineries owned by Petrobras have not yet engaged in HVO co-processing activities. In this context, refineries capable of co-processing HVO based on existing processing technologies or equipment are as follows:

1. **Replan refinery (Petrobras, Paulínia, SP).** Replan is Petrobras's largest refinery by throughput, with an installed crude processing capacity of approximately $\sim$66,000 $\mathrm{m^3\,d^{-1}}$ ($\sim$415,000 $\mathrm{bbl\,d^{-1}}$), accounting for $\sim$20% of Brazil's total refining capacity. Its main products include diesel, gasoline, Liquefied Petroleum Gas (LPG), fuel oils, jet fuel, asphalt, petrochemical naphtha, coke, propene, sulfur and hydrogenated fluids. There are plans to produce renewable-content diesel (Diesel R5) via co-processing, with a co-processing capacity of approximately $\sim$6 $\mathrm{kbbl\,d^{-1}}$, and an alcohol-to-jet (ATJ) SAF project with a capacity of $\sim$10 $\mathrm{kbbl\,d^{-1}}$ is under evaluation. (Petrobras, 2025e; Tolmasquim, 2025; Petrobras, 2024, 2022)

2. **Piracicaba complex (Raízen, Piracicaba, SP).** Raízen operates Parque de Bioenergia Costa Pinto in the Piracicaba refinery, which integrates sugar production, first- and second-generation ethanol (E2G), a solar plant, and a biogas/biomethane unit. The biometane plant built at this site is reported to have a production capacity of approximately 26 million $\mathrm{m^3\,yr^{-1}}$ of renewable natural gas, using vinasse and filter cake as feedstock. This confirms the role of Piracicaba as a major potential bioenergy hub. (Raizen, 2022; Costa et al., 2023)

3. **São Caetano do Sul facilities (Ipiranga/Transpetro, São Caetano do Sul, SP).** Rather than serving as a traditional refinery, the facility functions as a logistics and distribution hub. It accommodates Ipiranga's fuel and biofuel wholesale operations and includes a terrestrial terminal, which is responsible for the storage and transfer of petroleum products, alcohols, and biodiesel to other terminals

and refineries, such as Replan, Recap, RPBC, and Revap. (Transpetro, n.d.; IpirangaSCaetano, 2025)

4. **Henrique Lage refinery (REVAP, Petrobras, São José dos Campos, SP).** The Henrique Lage refinery (REVAP), situated on the São José dos Campos, has an installed crude processing capacity of $40{,}000\ \mathrm{m^3\,d^{-1}}$ (approximately $\sim 252{,}000\ \mathrm{bbl\,d^{-1}}$). Petrobras has designated REVAP as its third-largest refinery, accounting for approximately $\sim$14% of Brazil's oil derivatives. The primary products include diluted asphalt, asphalt cement, petroleum coke, sulfur, carbon dioxide, gasoline, liquefied petroleum gas (LPG), light refinery hydrocarbons, naphtha, fuel oil, diesel, propene, and aviation kerosene (QAV-1). These data and the product range are consistent with the information provided by Petrobras's official technical profile for REVAP. (Petrobras, 2025b, 2022, 2024)

5. **Presidente Bernardes refinery (RPBC, Petrobras, Cubatão, SP).** The Presidente Bernardes refinery (RPBC), situated in Cubatão,has a nominal crude processing capacity of approximately $\sim 178{,}000\ \mathrm{bbl\,d^{-1}}$ (equivalent to around $\sim 28{,}300\ \mathrm{m^3\,d^{-1}}$). Its primary products includes gasoline, petroleum coke, jet fuel, diesel, liquefied petroleum gas (LPG), petrochemical naphtha, natural gas, hydrogen, and petrochemical aromatics, such as benzene, xylene, and toluene. Petrobras has recently announced an initiative to establish its inaugural dedicated facility for the production of BioQAV (SAF blending component) and renewable diesel (HVO) at RPBC, with the capacity to process approximately $\sim 950{,}000\ \mathrm{t\,yr^{-1}}$ of vegetable oils and animal fats and to produce up to $\sim 16{,}000\ \mathrm{bbl\,d^{-1}}$ of renewable fuels (BioQAV and diesel renovável). This development confirms that RPBC serves as a pivotal site for HVO/SAF production within the state of São Paulo, although the refinery's conventional capacity is typically reported in $\mathrm{bbl\,d^{-1}}$ rather than in $\mathrm{m^3\,d^{-1}}$ specifically for HVO. (Petrobras, 2025c, a; Tolmasquim, 2025)

6. **Capuava refinery (Recap, Petrobras, Mauá, SP).** The Capuava refinery (Recap), located in Mauá within the Greater São Paulo region, has an installed crude processing capacity of approximately $8{,}500\ \mathrm{m^3\,d^{-1}}$ ($53{,}000\ \mathrm{bbl\,d^{-1}}$) and supplies approximately 30% of the fuel consumed in the São Paulo metropolitan area. The primary products of this process are gasoline, low-sulfur diesel (S-10), turpentine, propylene, liquefied petroleum gas (LPG), and special solvents. These capacities and product details are consistent with Petrobras's official description of Recap and are aligned with the original information provided. (Petrobras, 2025d, 2022, 2024)

The refineries in question are equipped with technologies that can be adapted or enhanced to comply with the production standards necessary for Hydrotreated Vegetable Oil (HVO). The critical processes include hydrotreatment, fractional distillation, and feedstock preparation. The potential challenges associated with HVO production in São Paulo include the cost and availability of feedstock, modification of existing process equipment, and catalysts. Nonetheless, the advantages of HVO,

particularly its ability to reduce carbon emissions, significantly outweigh technical challenges and stringent regulations (Petrobras, 2022; Battistella, 2021; ECB Group, 2021; Ajeeb et al., 2025).

## 2.4 Recommendations and the Blending Framework in the State of São Paulo

To fully harness its biofuel potential and transition to advanced biofuels, such as Hydrotreated Vegetable Oil (HVO), Brazil, particularly the state of São Paulo, requires a coordinated strategy. Figure 5 illustrates São Paulo's regulatory framework. At the federal level, the Conselho Nacional de Política Energética (CNPE) established overarching mandates, including biodiesel blending. The Agência Nacional do Petróleo (ANP) is tasked with the technical regulation, quality inspection, and authorization of the commercialization of all fuels, including Hydrotreated Vegetable Oil (HVO). Through rigorous quality control measures, the ANP ensures that any HVO produced or blended complies with stringent specifications, thereby protecting consumers and ensuring engine compatibility in Brazil. Simultaneously, the Instituto Brasileiro do Meio Ambiente (IBAMA) plays a pivotal role in the environmental licensing of new production facilities and certifies the sustainability of feedstock, which is essential for both domestic compliance and international market access. Concurrently, RenovaBio implements decarbonization targets through certification and the issuance/trading of CBIOs, linking blending strategies to measurable life cycle performance and auditable rules (ANP, 2018; B3CBIO, 2023).

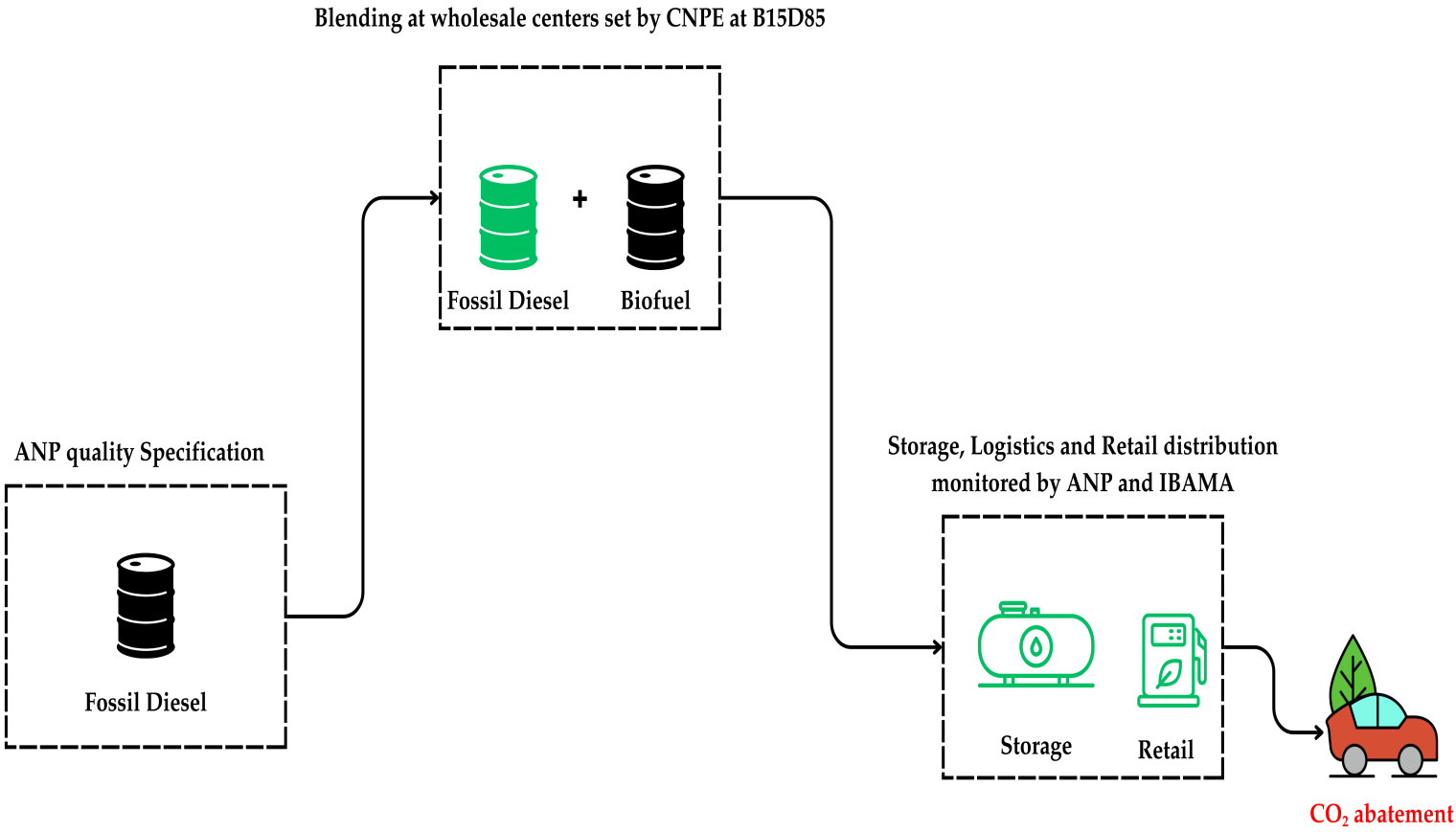



**Fig. 5: A visual representation of the existing blending process and the framework for the distribution of blended biodiesel in the state of São Paulo. As of February 21, 2026, Brazil requires a 15% biodiesel blend (B15) in diesel fuel. This increase from 14% was implemented on August 1, 2025, in accordance with the Fuels of the Future law, which outlines a gradual increase to 20% by March 2030. (Branco et al., 2025)**

To enhance the diversity of its biofuel matrix, the state of São Paulo should adopt the following recommendations to effectively engage with and benefit from this

framework while establishing incentives tailored to the state.

1. **Promote Technological Diversification**: Encourage investment not only in new HVO biorefineries, but also in retrofitting the state's existing fossil and biodiesel infrastructure for co-processing and dedicated hydrotreatment. This strategy aligns with the global trend of utilizing multiple technological pathways and reducing capital barriers while scaling certified low-carbon fuels (IEA, 2019b, 2021; Ajeeb et al., 2025).

2. **Streamlining environmental licensing**: Engaged in collaboration with IBAMA to develop a transparent and efficient licensing framework for HVO projects that utilize certified sustainable feedstocks, leveraging the state's abundant agricultural and agro-industrial residues. Aligning environmental licensing with life cycle accounting tools enhances transparency for stakeholders and bolsters eligibility under decarbonization crediting systems (Bonomi et al., 2023; ANP, 2018).

3. **Advocating for a Specific HVO Mandate**: Advocate to the CNPE for the establishment of a distinct "green diesel" or HVO mandate within the national biofuel policy (RenovaBio), separate from the conventional biodiesel (B100) mandate. This would provide a clear demand signal for producers and stimulate the technological transition necessary for São Paulo to emerge as a leader in the next generation of biofuels, while facilitating more consistent accounting of avoided emissions and credit generation under regulated frameworks (ANP, 2018; B3CBIO, 2023).

São Paulo can transform its substantial agricultural and industrial potential into a leading hub for advanced biofuels by addressing capital challenges through diversified technology adoption and establishing a stable and supportive regulatory environment.

# 3 Methodology

This section describes the computation of carbon dioxide equivalent emissions ($tCO_2e$) and the corresponding avoided emissions for the State of São Paulo, Brazil, using a distance-based fuel consumption framework. State-level emissions data were obtained from the Data Portal for Cities and Google Environmental Insights Explorer, while the annual diesel fleet size was obtained from SENATRAN (See Table 4) Data Portal for Cities (2025); GoogleInsights (2025); SENATRAN (2025). Using these data, historical emissions and corresponding avoided-emissions potential were computed for 2018–2023 via the analytical relationships presented in Section 3.2. Subsequently, future emissions and avoided-emission potentials for 2030, 2040, and 2050 were projected using an Enhanced Feedforward Neural Network (Enhanced–FNN), as described stepwise in Algorithm **??**. The Enhanced–FNN was trained using a train-only augmented version of the limited modelling dataset derived from Table **??**.

## 3.1 Scenario assumptions and blending context

All long-horizon projections are reported under a business-as-usual (BAU) scenario, in which diesel-powered fleet activity expands over time and current policy and operational patterns remain broadly unchanged. In practical terms, BAU assumes - (**I**) sustained growth in vehicle kilometres travelled (VKT/VMT), (**II**) increasing fuel demand driven by economic and population expansion, (**III**) slow fleet turnover, and (**IV**) limited near-term enforcement of more stringent tailpipe emission constraints.

At the time of analysis, Brazil's "Fuel of the Future" Law (Law No. 14.993/2024) established a renewable content trajectory consistent with an initial diesel-to-renewable blending reference of 85% fossil diesel (D) and 15% HVO (renewable diesel, R), while other blending fractions and a 100% HVO drop-in case were also assessed (see Section 4). In parallel, Brazil enacted the SBCE (Sistema Brasileiro de Comércio de Emissões), establishing a regulated carbon market framework that supports the interpretation of the avoided-emission credits reported herein (Planalto, 2024; MME, 2025).

## 3.2 Mathematical derivations

The following models were used to compute $CO_2$ emissions and avoided emissions potential using the dataset presented in Table 4. Unless stated otherwise, emissions are computed in tonnes $CO_2e$ ($tCO_2e$) and reported in mega tonnes (MT) where applicable.

**Table 4: Diesel $CO_2$ emissions and vehicle data (2018–2023). Adapted from (Data Portal for Cities, 2025; GoogleInsights, 2025; SENATRAN, 2025).**

| Year | Total Distance (km) | $tCO_2e$ per year | Total Vehicles |
|---|---|---|---|
| 2023 | 53,703,360,000 | 12,808,560 | 2,112,051 |
| 2022 | 52,694,160,000 | 12,512,920 | 2,050,750 |
| 2021 | 48,660,150,000 | 11,018,910 | 1,993,528 |
| 2020 | 38,118,800,000 | 9,243,400 | 1,921,329 |
| 2019 | 59,512,860,000 | 14,070,870 | 1,862,026 |
| 2018 | 60,145,050,000 | 14,811,230 | 1,784,731 |

1. **Total fuel consumption, $F_T$ (L)**
   The total fuel consumption is derived from the total distance travelled and fleet-average fuel efficiency, $f_E$. In this study, $f_E$ was assumed to be $3.6\ \mathrm{km/L}$. This value is consistent with the reported fuel-efficiency value from the Environmental Company of the State of São Paulo (CETESB) for diesel bus fleets (including AC and non-AC operation) (CETESB, 2025).

$$F_T = \frac{D_T}{f_E}, \tag{1}$$

   where $D_T$ is the total fleet distance (km) for a given year.

2. **Blend emission factor, $ef_B$ (kg $CO_2$e/L)**
   For a blend with $x\%$ HVO (renewable diesel, $R$) and $(100 - x)\%$ fossil diesel ($D$), the blend emission factor is:

$$ef_B = \left(\frac{x}{100}\right) \cdot ef_R + \left(1 - \frac{x}{100}\right) \cdot ef_D, \tag{2}$$

   where $ef_D \sim 2.7\ \mathrm{kg\ CO_2e/L}$ and $ef_R \sim 0.7\ \mathrm{kg\ CO_2e/L}$.

   The emission factors adopted in this study correspond to a well-to-wheel (WTW) system boundary, with values of 2.7 $kgCO_2e/L$ for fossil diesel and 0.7 $kgCO_2e/L$ for hydrotreated vegetable oil (HVO), as reported by the National Association of Automotive Vehicle Manufacturers (ANFAVEA), reflecting assumptions consistent with the Brazilian transport and energy context (ANFAVEA and BCG, 2021). The substantially lower WTW emission factor attributed to HVO is aligned with the assumption that domestic production would predominantly utilize waste cooking oil as feedstock, thereby reducing upstream lifecycle emissions relative to fossil diesel.

3. **Total blend emissions, $E_B$ ($tCO_2e$)**
   Total annual emissions for blend $B$ are computed as:

$$E_B = \frac{F_T \cdot ef_B}{1000}, \tag{3}$$

where division by 1000 converts kg $CO_2$e to tonnes $CO_2$e.

4. **Emissions per vehicle, $E_i$ ($\mathbf{tCO_2e/vehicle}$)**
   For completeness, per-vehicle emissions can be computed as:

$$E_i = \frac{E_B}{N_V}, \tag{4}$$

   where $N_V$ denotes the number of vehicles recorded in the corresponding year.

5. **Avoided Emissions, $C_B$ ($\mathbf{tCO_2e}$)**
   Carbon credit represents avoided emissions relative to the fossil diesel baseline:

$$C_B = \max\big(0,\ E_D - E_B\big), \tag{5}$$

   where $E_D$ is the diesel baseline emissions ($\text{tCO}_2\text{e}$) and $E_B$ is the blend emissions ($\text{tCO}_2\text{e}$).

   It is worth noting that Equation 5 pertains to avoided emissions rather than issued credits, as it quantifies the positive displacement of emissions relative to the fossil-diesel baseline in $tCO_2e$, with aggregated values reported in MT $CO_2$e.

### 3.3 Dataset, train-only augmentation, and futuristic predictions

Because the historical dataset was small (six years across multiple blend combinations), a conservative train-only augmentation strategy was adopted to stabilize neural-network training without compromising evaluation integrity. Specifically, only the training subset was augmented by a factor of $\times 1000$ using noise injection designed to preserve the empirical distribution, whereas the validation and test subsets were left unchanged.

As shown in Table 5, the mean fuel-consumption statistics were preserved with high fidelity (relative mean difference of 0.165%), well below the conventional thresholds used to justify distributional consistency (Wichern et al., 2019). Table 6 further indicates a modest reduction in dispersion, implying that the augmentation remains conservative while introducing sufficient variability to support machine learning applications (Rubin, 1987).

**Table 5**: **Statistical differences between datasets.**

| Metric | Value |
|---|---|
| Absolute Mean Difference | 34,394,399 L |
| Relative Mean Difference | 0.165% |
| Variance Reduction | 3.494% decrease in standard deviation |

**Table 6**: **Comparative statistics of raw versus augmented dataset.**

| Dataset | Mean Fuel Consumption* | Standard Deviation* | Coefficient of Variation |
|---|---|---|---|
| Raw | 20,855,625,333 | 3,008,078,167 | 14.42% |
| Augmented | 20,821,230,935 | 2,902,978,461 | 13.94% |

*Measured in liters.

Tables 7, 8 and 9 summarize the adopted Enhanced–FNN architecture and the variables used to construct the modelling dataset. In this study, the Enhanced–FNN was used to forecast the total blend emissions (MT) under BAU, while avoided emissions (or avoided emissions potential) were computed deterministically from Equation 5 using the corresponding diesel baseline.

**Table 7: The hyperparameter configurations or search space, as well as the training protocol deployed for the exploration of an optimized architecture for the Enhanced–FNN.**

| Parameter | Range Tested |
|---|---|
| Models Deployed | Enhanced–FNN |
| Hidden Layers | $[128, 64]$, $[128, 64, 32]$, $[256, 128, 64]$, $[512, 256, 128]$ |
| Activation Functions | ReLU, GeLU, SiLU, Tanh |
| Weight Decay | $0.0$, $1 \times 10^{-5}$, $1 \times 10^{-4}$ |
| Learning Rate | $1 \times 10^{-3}$, $3 \times 10^{-4}$, $1 \times 10^{-4}$ |
| Drop Out (BNN/H-BNN) | 0.0, 0.10, 0.20 |
| Batch Size | 32, 64 |
| Optimizer | Adam, Adamw, Rmsprop, Sgd |
| Maximum Epochs | 160, 220 |
| Early Stopping Patience | 25, 30 epochs |

**Table 8: Enhanced–FNN optimized architecture adopted in this study, including MC–Dropout uncertainty estimation for emission forecasting.**

| Model | Input Features | Hidden Layers | Output | Activation |
|---|---|---|---|---|
| Enhanced–FNN | 8 | [256, 128, 64] | 1 | SiLU (Swish)* |

*Uncertainty is estimated via MC-Dropout at inference (dropout $p = 0.10$), with an ensemble setting of $M = 5$ and BatchNorm disabled. The model forecasts the total blend emissions (MT) under BAU; carbon credits (MT $CO_2e$) are derived from Equation 5.

**Table 9: Input variables used for the Enhanced–FNN and derived targets.**

| Variable | Description |
|---|---|
| **Input Variables** | |
| Year | Calendar year |
| Blend | Blend type |
| HVO (%) | Blend fraction of HVO |
| Total Distance (km) | Total distance travelled |
| Total Vehicles | Registered vehicle count |
| Total Fuel Consumption (L) | Aggregate annual fuel usage |
| Blend Emission Factor (kg $CO_2e$/L) | Emission factor based on blend composition |
| Emission per Vehicle (t$CO_2e$/vehicle) | Average emissions per vehicle annually |
| **Model Output / Derived Quantities** | |
| Total Blend Emission (MT) | Computed from Equation 3 |
| Avoided Emission (MT) | Computed from Equation 5 |

To strengthen methodological transparency, a quadratic regression model was implemented as a simple parametric benchmark for long-horizon projection. The quadratic model was fitted to the same blend-specific historical emissions series

(2018–2023) used to train the Enhanced–FNN and was used to generate 2030, 2040, and 2050 projections under identical blend definitions and emission-factor inputs. The Enhanced–FNN is retained as the primary forecasting method because it captures nonlinear relationships more robustly and provides uncertainty estimates via MC–dropout (Gal and Ghahramani, 2016).

To report relative changes, the trend was computed with respect to the 2018–2023 mean baseline as follows:

$$\Delta_{b,t} = \frac{\hat{E}_{b,t} - \overline{E_b(2018\text{–}2023)}}{\overline{E_b(2018\text{–}2023)}} \times 100 \tag{6}$$

where $\overline{E_b(2018\text{–}2023)}$ is the average emissions for blend $b$ over 2018–2023.

# 4 Results and Discussions

Table **??** reports the computed $CO_2$-equivalent emissions and corresponding carbon credits for each blending case from 2018 to 2023, obtained using Equations 1–5. Specifically, the total blend emissions and credit values were computed from the diesel baseline dataset in Table 4 using the distance-based fuel consumption model (See Appendix **??**).

Based on a quadratic regression model adopted in this study, the results in Table **??** indicate a monotonic reduction in emissions as the share of renewable diesel increases. The fossil diesel baseline (D) exhibits the highest average emissions, with an average of 39.105 MT (Table **??**), whereas the 100% renewable diesel case (R) yielded the lowest value (10.138 MT), corresponding to an average reduction of 74.1%. Intermediate blends also demonstrated progressive reductions: D + R13 and D + R15 yielded average reductions of 7.4% and 8.4%, respectively, while D + R30 and D + R50 yielded reductions of 15.0% and 25.0%. Conversely, carbon credits increase with renewable share, confirming the expected inverse relationship between emissions and avoided-emission credit generation. This pattern is also illustrated in Figure 8, where the average emissions declined sharply across blends, while credits increased accordingly.

## 4.1 Sensitivity Analysis Framework: Analytical Sensitivity and Policy Implications.

Referring to Equation 1 through Equation 5, a robust sensitivity analysis is carried out in this section to introduce an explicit representation of total annual fleet distance as follows:

$$DT = N \cdot m \tag{7}$$

where $N$ denotes the number of vehicles and $m$ represents the annual mileage per vehicle (km/year). By substituting Equation 7 into Equation 3, the annual blend emissions in mega tonnes (MT) is obtained as follows:

$$E_B{}' = \frac{Nm}{f_E} \cdot \frac{ef_B}{10^9} \tag{8}$$

Similarly, substituting Equation 7 into Equation 4, the diesel baseline emissions are expressed as:

$$E_D' = \frac{Nm}{f_E} \cdot \frac{ef_D}{10^9} \tag{9}$$

From Equation 5, the carbon credit in mega tonnes (MT) obtained by replacing diesel with the blend is:

$$C_B' = \frac{Nm}{f_E} \cdot \frac{ef_D - ef_B}{10^9} \tag{10}$$

## Analytical Sensitivity:

Using Equation 8, the partial derivative of blend emissions with respect to total distance $DT$ is further obtained as follows:

$$\frac{\partial E_B^{'}}{\partial DT} = \frac{ef_B}{10^9 f_E} \tag{11}$$

Equation 11 confirms a linear relationship between emissions and the distance travelled. Similarly, the sensitivity of emissions to fuel efficiency $f_E$ is given by:

$$\frac{\partial E_B^{'}}{\partial f_E} = -\frac{DT \cdot ef_B}{10^9 f_E^2} \tag{12}$$

Thus, Equation 11 demonstrates an inverse non-linear relationship, indicating that improvements in fuel efficiency reduce emissions at a decreasing rate. Similarly, the sensitivity of carbon credits (Equation 9) is obtained as:

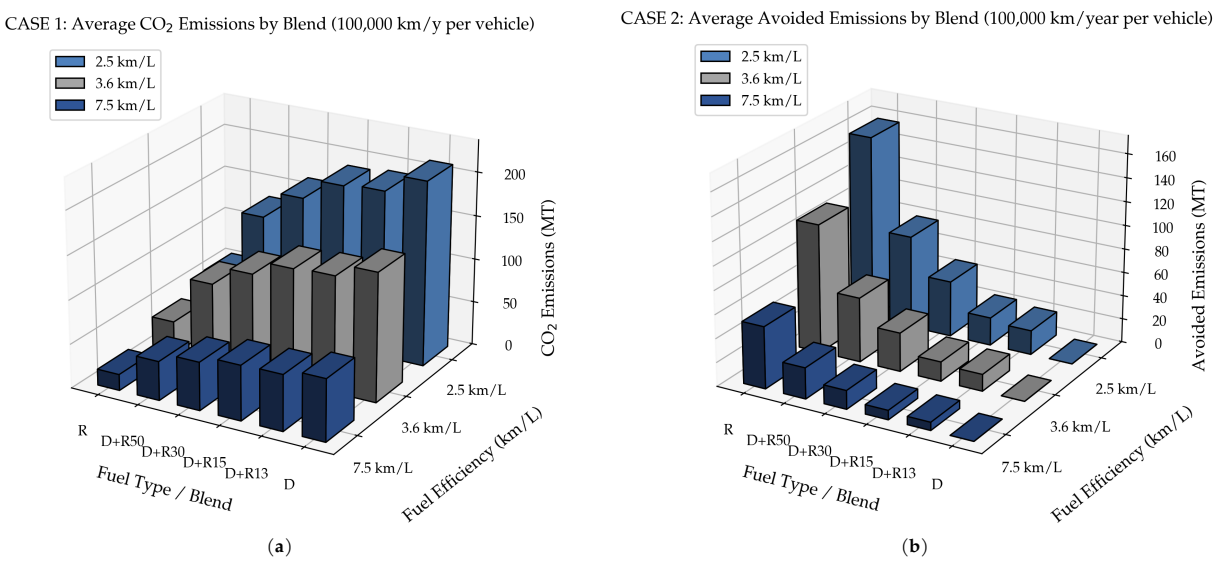
$$\frac{\partial C_B^{'}}{\partial DT} = \frac{ef_D - ef_B}{10^9 f_E} \tag{13}$$

Furthermore, by deploying Equation 7 and Equation 8, Equation 13 becomes:

$$\frac{\partial C_B^{'}}{\partial f_E} = -\frac{DT(ef_D - ef_B)}{10^9 f_E^2} \tag{14}$$

As shown, the histogram plots are fully consistent with Equations 10–13. In the annual mileage sensitivity cases (See Figure 7), the linear dependence of $E_B^{'}$ and $C_B^{'}$ on vehicle mileage $(m)$ explains the proportional increase in bar heights across all blends. Conversely, increasing fuel efficiency reduces emissions due to the inverse relationship in Equation 11, which accounts for the visibly lower emission bars at higher $f_E$ values (See Figure 6).

Furthermore, blends with higher renewable fraction exhibit lower emission factor $ef_B$, thereby reducing $E_B^{'}$ in Equation 8 and increasing $C_B^{'}$ in Equation 10. The widening separation between diesel and high-renewable blends observed in the histograms directly reflects the term $(ef_D - ef_B)$ governing carbon credit magnitude. As illustrated in the histogram plots of Figure 6, the hypothetical fuel efficiencies of 2.5 km/L and 7.5 km/L represent small vehicles and large trucks powered by diesel, respectively. These values were selected to offer a comprehensive perspective on sensitivity analysis.




(**a**) (**b**)

**Fig. 6: The multiple-bar histogram plots show the net $CO_2$ emissions and avoided emissions in megatonnes (MT) by blend type under different fuel consumption rates between 2018 and 2023 for the São Paulo diesel fleet. A fixed annual mileage of 100,000 km was used. As depicted in Subfigure (a) on the left-hand side, the Net $CO_2$ emissions for the stated years (2018 – 2023) are presented. The higher the fuel efficiency (km/L), the lower the projected emissions. Subfigure (b) further delineates the avoided emissions potential that can be accrued based on the value of the fuel efficiency. As shown, the amount of avoided emissions increases with a lower efficiency rate and a higher blend ratio. The histograms plots were generated following the methodological framework established by Pérez-Rangel et al. (2025).**

## Policy Implications

The analytical structure $E_B^{'} \propto \frac{N \cdot m}{f_E}$ highlights three primary decarbonization levers:

1. Reducing annual vehicle mileage $(m)$,
2. Improving fleet fuel efficiency $(f_E)$,
3. Increasing renewable blend share $(x)$ to lower $ef_B$.

The sensitivity derivatives indicate that enhancements in fuel efficiency result in nonlinear decreases in emissions, whereas the integration of renewable fuels leads to proportional emission displacement relative to diesel. Therefore, optimal strategies for fleet decarbonization should incorporate both operational efficiency measures and the gradual substitution of renewable fuels to maximize emissions reduction and avoided emissions potential.

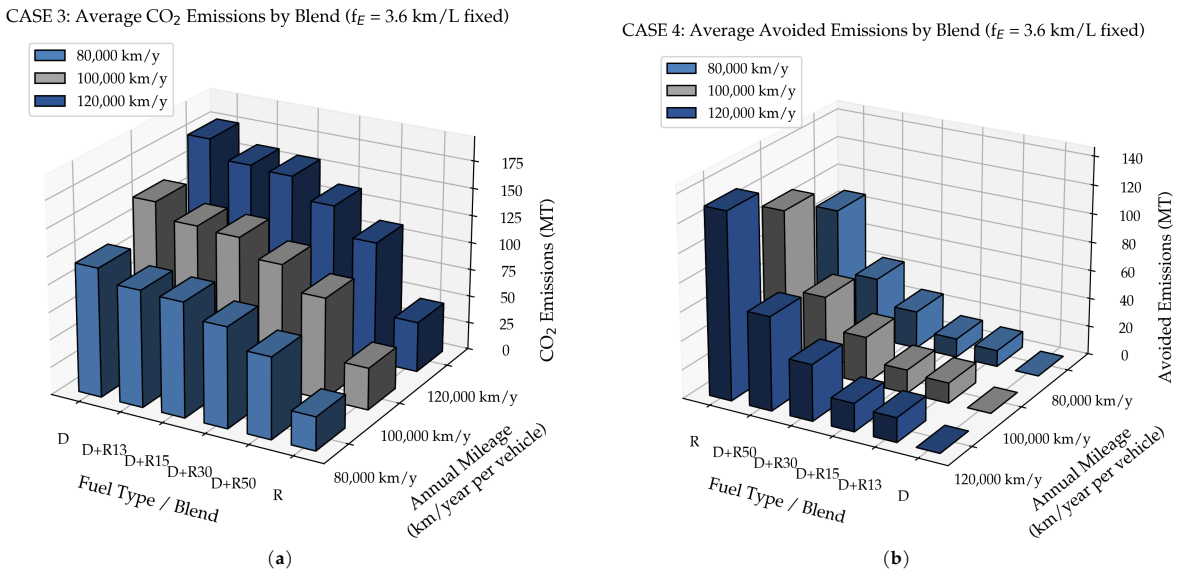



**Fig. 7: The multiple-bar histogram plots show the net $CO_2$ emissions and avoided emissions in megatonnes (MT) by blend type under different fuel consumption rates between 2018 and 2023 for the São Paulo diesel fleet. In cases considered, different annual mileages of 80,000 km, 100,000 km and 120,000 km were deployed. As depicted in Subfigure (a) on the left-hand side, the Net $CO_2$ emissions for the stated years (2018 – 2023) are presented. The higher the annual mileage (km per year per vehicle), the higher the projected emissions. Subfigure (b) further delineates the avoided emissions potential that can be accrued based on the value of the annual mileage. As shown, the amount of avoided emissions increases with a higher mileage and blend ratio. The histograms plots were generated following the methodological framework established by Pérez-Rangel et al. (2025).**

## 4.2 Long-horizon projections: Enhanced–FNN versus quadratic regression

Table 10 compares the benchmark quadratic regression (See Appendix **??** for computational steps deployed) projections against the Enhanced–FNN projections for 2030, 2040, and 2050. Both approaches were calibrated using the same historical emissions series (2018–2023) constructed from Table 4 and Equations 1–5. Under BAU, the Enhanced–FNN forecasts a smooth and internally consistent increase in emissions over time, with quantified uncertainty from MC–dropout. The 2020 "dip" visible in Figure 9 reflects the disruption in fleet activity during the COVID-19 period, which is preserved in the historical signal.

In comparison, quadratic regression provides only moderate explanatory power and exhibits high sensitivity under polynomial extrapolation, yielding rapidly accelerating trajectories outside the calibration range. This behaviour motivates the use of the Enhanced-FNN model as the primary forecasting model for BAU projections by 2050.

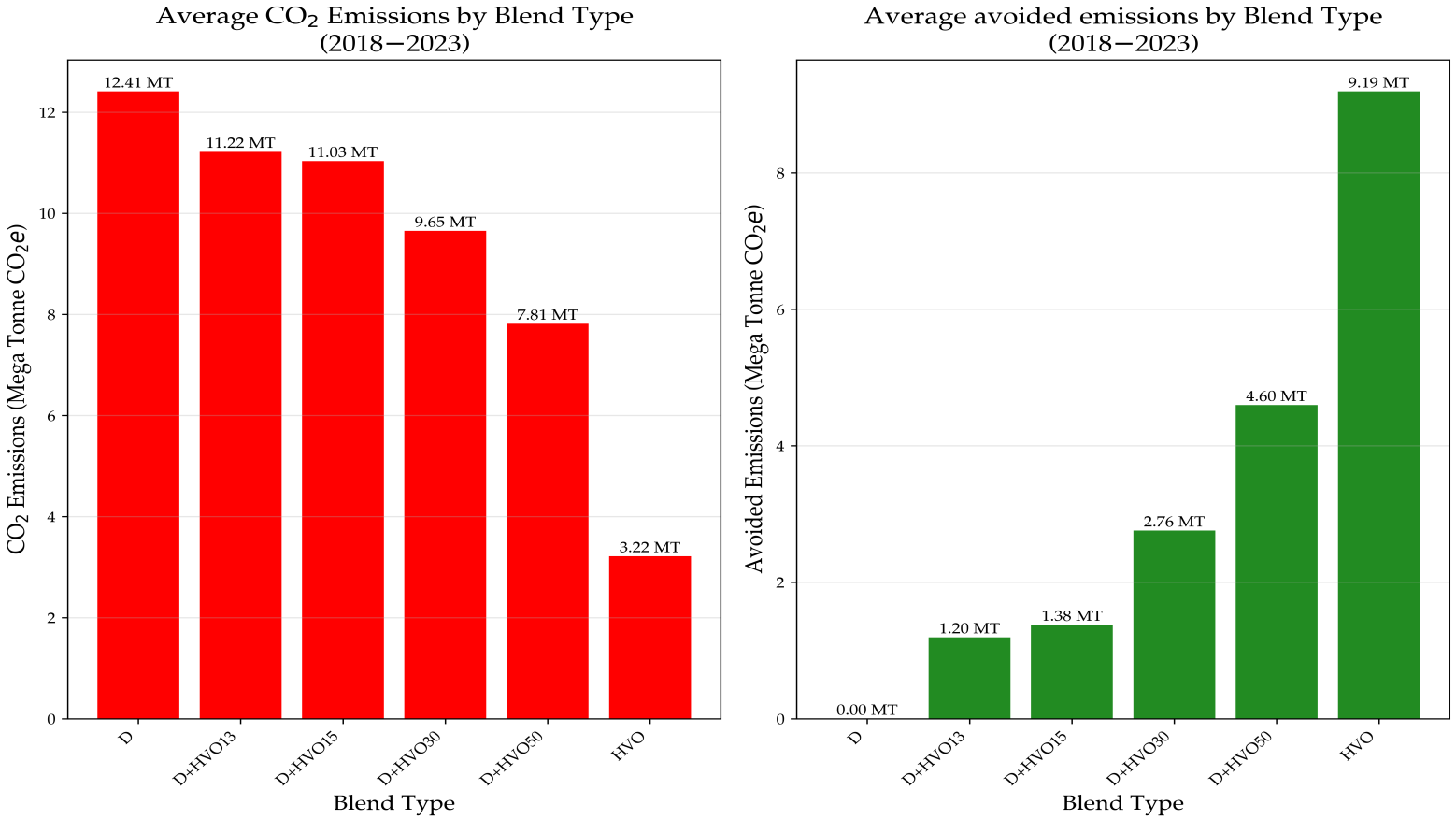



**Fig. 8: Average $CO_2$ emissions (red bars) and average avoided emissions (green bars) by blend type (2018–2023). All quantities are reported in megatonnes (MT).**

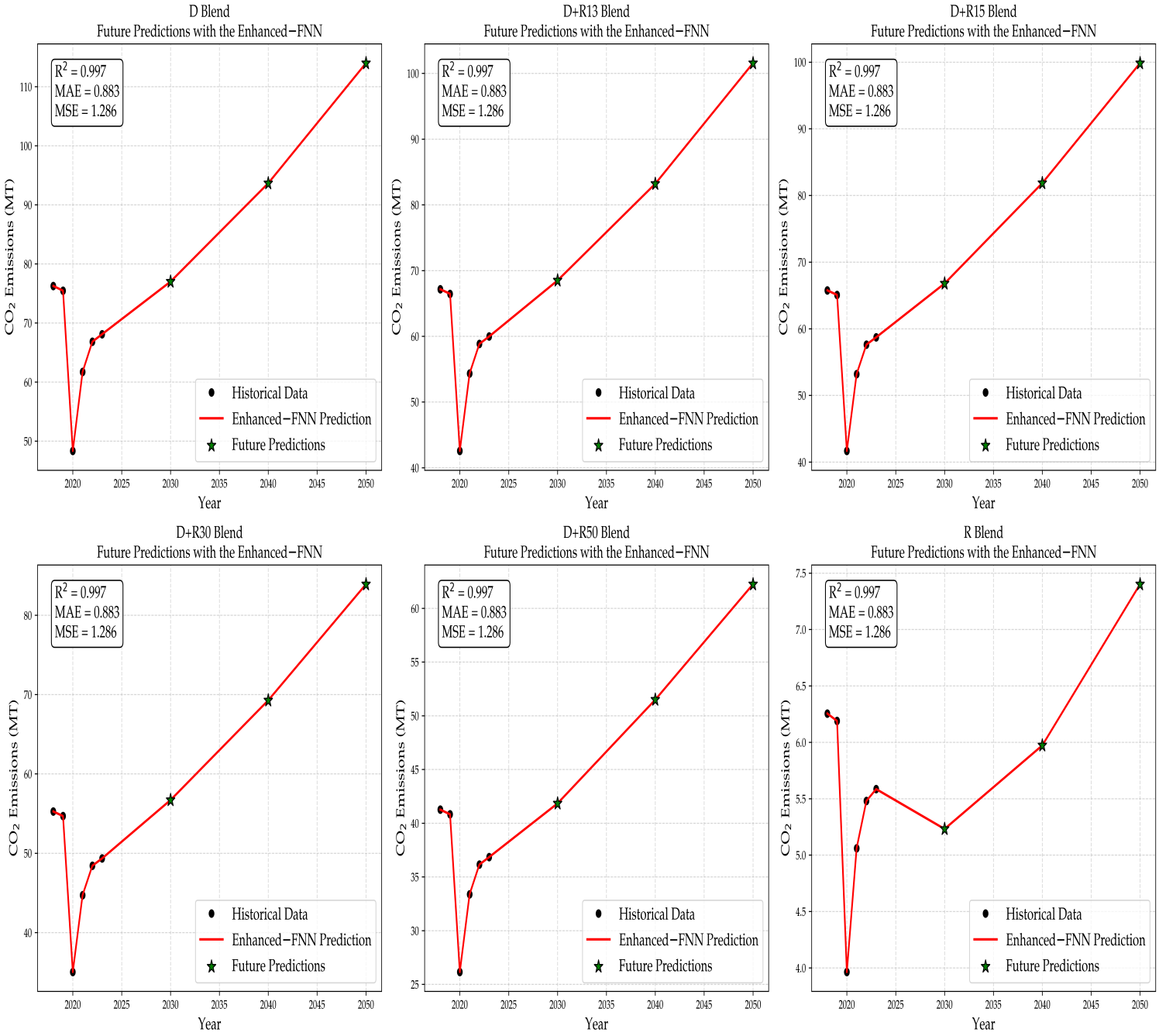



**Fig. 9: Predicted $CO_2$ emissions (MT) from 2018 to 2050 using the Enhanced–FNN (SiLU + MC–Dropout) trained with train-only augmentation. Projections follow a BAU scenario, and uncertainty is reported via MC–dropout sampling. The 2020 "dip" reflects the COVID-19 disruption in historical fleet activity.**

**Table 10: A comparative analysis of the predictive performance of the deployed Quadratic Regression model and the Enhanced–FNN (SiLU (Swish) + MC–Dropout) was conducted to forecast $CO_2$ emissions for the years 2030, 2040, and 2050. The Enhanced–FNN model projected outcomes based on each blend combination, utilizing trends from 2018 to 2023 as a baseline, while incorporating a Business-As-Usual (BAU) scenario within its framework.**

| Blend | Model | MAE | MSE | 2030 Pred. | 2040 Pred. | 2050 Pred. | Trend (%) |
|---|---|---|---|---|---|---|---|
| D | Quadratic | 0.910 | 1.204 | 56.42 | 210.50 | 473.39 | – |
| D | Enhanced–FNN | 0.883 | 1.286 | 77.37±3.22 | 93.68±3.72 | 114.78±4.36 | +48.4 |
| D+R13 | Quadratic | 0.822 | 0.983 | 50.99 | 190.23 | 427.80 | – |
| D+R13 | Enhanced–FNN | 0.883 | 1.286 | 68.56±2.46 | 83.73±2.73 | 102.55±3.48 | +49.6 |
| D+R15 | Quadratic | 0.809 | 0.951 | 50.15 | 187.11 | 420.79 | – |
| D+R15 | Enhanced–FNN | 0.883 | 1.286 | 66.66±2.27 | 81.11±2.94 | 99.40±3.59 | +49.1 |
| D+R30 | Quadratic | 0.708 | 0.728 | 43.88 | 163.72 | 368.19 | – |
| D+R30 | Enhanced–FNN | 0.883 | 1.286 | 56.42±1.82 | 68.94±2.46 | 83.99±3.33 | +48.9 |
| D+R50 | Quadratic | 0.573 | 0.477 | 35.52 | 132.54 | 298.06 | – |
| D+R50 | Enhanced–FNN | 0.883 | 1.286 | 42.44±2.41 | 51.39±2.99 | 63.10±3.63 | +48.7 |
| R | Quadratic | 0.236 | 0.081 | 14.63 | 54.57 | 122.73 | – |
| R | Enhanced–FNN | 0.883 | 1.286 | 5.48±5.08 | 6.38±6.85 | 8.67±6.78 | +58.3 |

**D** denotes fossil diesel (0% HVO), and **R** denotes renewable diesel (100% HVO). Enhanced–FNN projections were reported as mean ± standard deviation from the MC-dropout runs. Under BAU, total emissions increase over time owing to activity growth; within each year, emissions decrease monotonically with increasing renewable share. The trend (%) was computed using Equation 6.

## 4.3 Avoided-emission projections and implications

Table 11 reports avoided emission projections derived from the corresponding emissions scenarios using Equation 5. Avoided emission increase systematically with renewable share because they represent avoided emissions relative to the diesel baseline. For example, the D+R50 blend is projected to yield $42.44 \pm 2.41$ MT in 2030 and $51.37 \pm 5.67$ MT in 2050, while the 100% HVO case (R) is projected to yield $71.53 \pm 5.73$ MT in 2030 and $105.46 \pm 7.96$ MT in 2050. These outcomes highlight the strong coupling between physical decarbonization (lower tailpipe emissions) and the economic value of avoided emissions under regulated or voluntary carbon-market instruments.

Consistent with Equation 5, diesel (D) serves as the reference case with avoided emissions by definition and is therefore not reported in Table 11. Overall, the Enhanced-FNN provides a robust and uncertainty-aware framework for long-term emissions forecasting under BAU, whereas quadratic regression serves as a transparent benchmark demonstrating the limitations of polynomial extrapolation for long-horizon projections.

**Table 11: Combined comparison of avoided-emission projections (MT $CO_2e$) from Quadratic Regression and Enhanced–FNN under the BAU scenario.**

| Blend | Model | 2030 Projection | 2040 Projection | 2050 Projection |
|---|---|---|---|---|
| D+R13 | Quadratic | 5.43 | 20.27 | 45.59 |
| D+R13 | Enhanced–FNN | 8.46 ± 3.83 | 10.20 ± 4.23 | 11.81 ± 6.16 |
| D+R15 | Quadratic | 6.27 | 23.39 | 52.60 |
| D+R15 | Enhanced–FNN | 10.25 ± 3.49 | 12.96 ± 4.45 | 15.23 ± 5.85 |
| D+R30 | Quadratic | 12.54 | 46.78 | 105.20 |
| D+R30 | Enhanced–FNN | 20.58 ± 3.18 | 25.05 ± 4.43 | 30.99 ± 5.29 |
| D+R50 | Quadratic | 20.90 | 77.96 | 175.33 |
| D+R50 | Enhanced–FNN | 34.37 ± 3.79 | 42.66 ± 4.71 | 51.37 ± 5.67 |
| R | Quadratic | 41.79 | 155.93 | 350.66 |
| R | Enhanced–FNN | 71.53 ± 5.73 | 87.68 ± 7.58 | 105.46 ± 7.96 |

**Note:** Avoided emissions are computed relative to the diesel baseline and derived from emissions as $C_b(y) = \max(0, E_D(y) - E_b(y))$. The diesel (D) avoided emission is zero by definition and has not been reported. Enhanced–FNN avoided-emission values are reported as mean ± standard deviation from paired MC-dropout runs, propagating uncertainty in both $E_D$ and $E_b$.

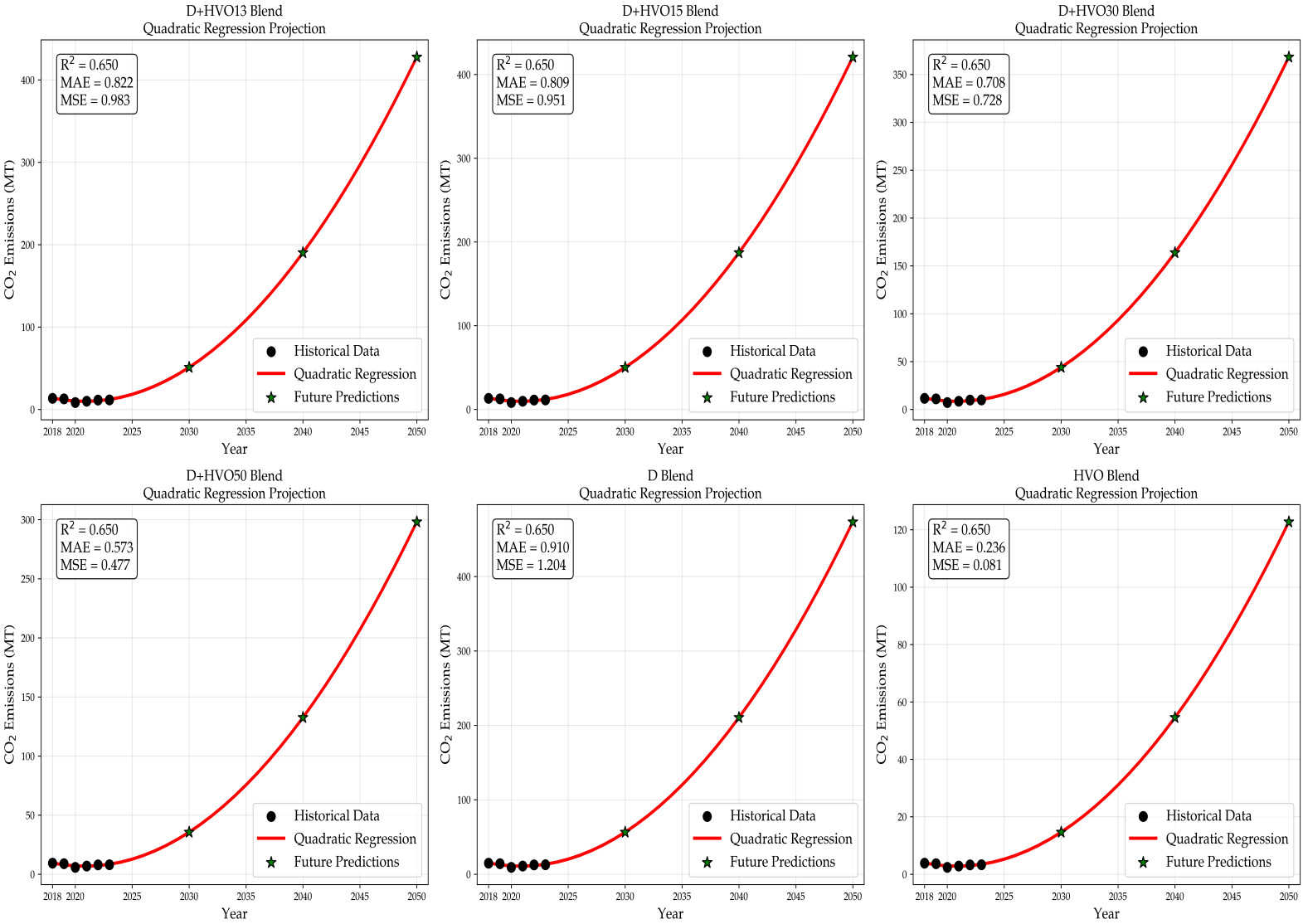



**Fig. 10: Quadratic regression projections of $CO_2$ emissions (MT) for 2030, 2040, and 2050 fitted to the historical blend-specific emissions series (2018–2023). The quadratic model exhibits moderate explanatory power and pronounced extrapolation sensitivity, producing rapidly accelerating trajectories outside the calibration domain.**

# 5 Conclusions

In this study, the historical and projected tailpipe $CO_2$-equivalent emissions and avoided-emission potentials associated with blending hydrotreated vegetable oil (HVO) with fossil diesel in the transportation sector of the State of São Paulo were investigated. Using a distance-based fuel consumption framework with a fleet-average fuel efficiency of $f_E = 3.6\ \mathrm{km/L}$, the empirical results for 2018–2023 demonstrate a clear monotonic decline in emissions as renewable diesel fractions increase, alongside a proportional rise in avoided-emission values. On average, the 100% renewable diesel case reduced emissions by approximately 74.1% (See Table **??**) relative to the fossil diesel baseline, while intermediate blends delivered progressively increasing reductions consistent with the blend composition.

For long-horizon projections under a business-as-usual scenario, the Enhanced-FNN (SiLU activation with MC-dropout) was conditioned on BAU indicators representing the current operating state, whereas future emissions were projected by scaling base-year model outputs using the BAU activity index. This produced smooth and internally consistent forecasts with approximate uncertainty quantification via paired MC-dropout and reproduced the expected blend ordering, whereby higher HVO shares corresponded to lower emissions. A quadratic regression benchmark was also assessed using the same historical calibration series, however, it exhibited limited explanatory power and instability when subjected to polynomial extrapolation, resulting in rapidly accelerating trajectories beyond the calibration window. These comparative findings support the Enhanced-FNN as a more robust tool for long-term forecasting in data-constrained environments, particularly when uncertainty estimation is necessary for policy interpretation.

From a policy perspective, the results suggest that increasing the penetration of renewable diesel can significantly reduce fleet emissions while increasing avoided-emission potential, thereby reinforcing the strategic importance of HVO within São Paulo's transport decarbonization pathway. As regulated market mechanisms such as the SBCE evolve, the quantified avoided-emission potentials reported in this study provide a defensible basis for evaluating the economic and environmental benefits of progressive blending strategies, including partial substitution scenarios (e.g., D + R30, D + R50) and full drop-in adoption (R). Future research should incorporate broader operational heterogeneity (e.g., fleet stratification by vehicle class and duty cycle) and include sensitivity analyses over fuel-efficiency and activity-growth assumptions to further refine scenario realism.

# Abbreviations

| | |
|---|---|
| **ANP** | Brazilian National Agency for Petroleum, Natural Gas and Biofuels |
| **ANFAVEA** | National Association of Automotive Vehicle Manufacturers |
| **Aprobio** | Brazilian Biofuel Producer's Association |
| **BAU** | Business-As-Usual |
| **bio-LPG** | Bio - Liquified Petroleum Gas |
| **BLPY** | Billion Litres Per Year |
| **CBE** | Brazilian Emission Quotas |
| **CBios** | Decarbonization credits |
| **CFPP** | Cold-Flow Plugging Point |
| **CI** | Carbon Intensity |
| **CNPE** | National Council of Energy Policy |
| **B100** | Conventional Biodiesel |
| **CRVEs** | Certificate of Verified Emission Reduction |
| **D** | Fossil Diesel |
| **EF** | Energy Fraction |
| **ESG** | Environmental, Social, and Governance |
| **EU** | European Union |
| **FAME** | Fatty Acid Methyl Ester |
| **Enhanced−FNN** | Enhanced Feed-Forward Neural Network |
| **GHGs** | Green House Gases |
| **HEFA-SFK** | Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene |
| **HFRR** | High-Frequency Reciprocating Ring |
| **HVO** | Hydrotreated Vegetable Oil |
| **IBAMA** | Brazilian Institute of Environment and Renewable Natural Resources |
| **IEA** | International Energy Agency |
| **LCA** | Life Cycle Assessment |
| **LCFS** | California's Low Carbon Fuel Standard |
| **OECD** | Organisation for Economic Co-operation and Development |
| **PlanClima SP** | São Paulo's Climate Law |
| **PM** | Particulate Matter |
| **R & D** | Research and Development |
| **RED II** | Renewable Energy Directive II |
| **RFS2** | Renewable Fuel Standard |
| **R** | Renewable Diesel |
| **UCO** | Used Cooking Oil |
| **WTW** | well-to-wheel |

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**Data availability**
Datasets used were obtained from public sources as indicated in the study.

**Code availability**
Available upon request.

**Author contribution**
**Edward Iwuchukwu**: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing—original draft preparation, Visualization and Writing - Review and Editing. **Thiago Brito**: Conceptualization, Methodology, Formal Analysis, Investigation, Visualization and Writing - Review and Editing. **Marilin Santos**: Supervision and Review. **Edmilson Moutinho dos Santos**: Supervision and Project Administration.

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