Universidad de Nariño
COLOMBIA

ISSN-E 2539-0554
Vol. XXVII No. 2 – 2do Semestre 2026
July - December – Pages 174-200

TENDENCIAS
Revista de la Facultad de Ciencias Económicas y Administrativas
Research article
Sustainability and energy

Factors determining the price of the Decarbonization Credit (CBIO) and implications for Brazil's RenovaBio Policy

Factores determinantes del precio del Crédito de Descarbonización (CBIO) e implicaciones para la política brasileña RenovaBio

Fatores determinantes do preço do Crédito de Descarbonização (CBIO) e implicações para a política brasileira RenovaBio

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Received: December 10, 2025 **Accepted:** June 4, 2026
DOI: https://doi.org/10.22267/rtend.26272.301

How to cite this article: Henriques, M. & Costa Alegre, H. (2026). Factors determining the price of the Decarbonization Credit (CBIO) and implications for Brazil's RenovaBio policy. *Tendencias*, *27*(2), 174-200. https://doi.org/10.22267/rtend.26272.301

Abstract

. **Introduction:** Global warming poses challenges for economic decarbonization, highlighting the pricing of environmental assets such as the Decarbonization Certificate (CBIO). **Objective:** To analyze the influence of macroeconomic and market variables oil (WTI), natural gas, dollar exchange rate (USD/BRL), VIX index, and traded volume on CBIO price formation under the RenovaBio policy. **Methodology:** A multiple linear regression model estimated by Ordinary Least Squares (OLS) was applied to daily time series data spanning four years. Augmented Dickey-Fuller (ADF) unit root and Engle-Granger cointegration tests were used to validate estimation in levels, along with the Breusch-Godfrey test for autocorrelation and re-estimation using Newey-West Heteroskedasticity and Autocorrelation Consistent (HAC) standard errors. **Results:** Oil, the dollar, and the VIX are statistically significant predictors of the CBIO price, even after correcting standard errors. **Discussion:** Sensitivity to external volatility and energy commodities links Brazilian decarbonization to global dynamics, limiting national autonomy in the face of external shocks. **Conclusions:** CBIO behaves as a financial asset sensitive to market variables, but requires regulatory mechanisms to mitigate exchange rate volatility in order to incentivize stable investments in biofuels.

Keywords: climate change; raw material; economic research; energy policy; environmental economics.
JEL: C32; Q20; Q42; Q54; Q57.

Resumen

Introducción: El calentamiento global plantea desafíos para la descarbonización económica, destacando la fijación de precios de activos ambientales como el Certificado de Descarbonización (CBIO). **Objetivo**: Analizar la influencia de variables macroeconómicas y de mercado —petróleo (WTI), gas natural, dólar (USD/BRL), índice VIX y volumen negociado en la formación de precios del CBIO bajo la política RenovaBio. **Metodología**: Se empleó una regresión lineal múltiple por Mínimos Cuadrados Ordinarios (MCO) en series temporales con datos diarios correspondientes a cuatro años. Se aplicaron pruebas ADF de raíz unitaria y cointegración de Engle-Granger para validar la estimación en niveles, además de la prueba de Breusch-Godfrey para autocorrelación y la reestimación mediante Errores Estándar Consistentes con Heterocedasticidad y Autocorrelación (HAC) de Newey-West. **Resultados**: El petróleo, el dólar y el VIX son predictores estadísticamente significativos del precio del CBIO, incluso tras corregir errores estándar. **Discusión**: La sensibilidad a la volatilidad externa y materias primas energéticas vincula la descarbonización brasileña a dinámicas globales, limitando la autonomía nacional ante choques externos. **Conclusiones**: El CBIO se comporta como un activo financiero sensible a variables de mercado, pero requiere mecanismos regulatorios que mitiguen la volatilidad cambiaria para incentivar inversiones estables en biocombustibles.

Palabras clave: cambio climático; economía verde; investigación económica; política energética; productos básicos.

JEL: C32; Q20; Q42; Q54; Q57.

Resumo

Introdução: O aquecimento global coloca desafios à descarbonização económica, com destaque para a fixação de preços de ativos ambientais, como o Certificado de Descarbonização (CBIO). **Objetivo:** Analisar a influência de variáveis macroeconómicas e de mercado petróleo (WTI), gás natural, dólar (USD/BRL), índice VIX e volume negociado na formação dos preços do CBIO no âmbito da política RenovaBio. **Metodologia:** Utilizou-se uma regressão linear múltipla por Mínimos Quadrados Ordinários (MCO) em séries temporais com dados diários correspondentes a quatro anos. Foram aplicados os testes ADF de raiz unitária e de cointegração de Engle-Granger para validar a estimativa em níveis, além do teste de Breusch-Godfrey para autocorrelação e da reestimativa por meio dos Erros-Padrão Consistentes com Heterocedasticidade e Autocorrelação (HAC) de Newey-West. **Resultados:** O petróleo, o dólar e o VIX são preditores estatisticamente significativos do preço do CBIO, mesmo após a correção dos erros-padrão. **Discussão:** A sensibilidade à volatilidade externa e às matérias-primas energéticas vincula a descarbonização brasileira às dinâmicas globais, limitando a autonomia nacional face a choques externos. **Conclusões:** O CBIO comporta-se como um ativo financeiro sensível às variáveis de mercado, mas requer mecanismos regulatórios que atenuem a volatilidade cambial para incentivar investimentos estáveis em biocombustíveis.

Palavras-chave: alterações climáticas; economia verde; investigação económica; política energética; matérias-primas.

JEL: C32; Q20; Q42; Q54; Q57.

Introduction

Environmental, social, and governance issues have become decisive elements in current corporate roadmaps. It is posited that organizations that fail to conduct a comprehensive analysis of their social externalities lack long-term viability (Associação Brasileira das Entidades dos Mercados Financeiro e de Capitais [ANBIMA], 2020). Under this premise, the Brazilian government enacted the National Biofuels Policy (RenovaBio) to expand biofuel generation and fulfill the commitments of the Paris Agreement. The central element of RenovaBio is the Decarbonization Certificate (CBIO), an instrument that represents mitigation efforts throughout the biofuel production and commercialization chain (Empresa de Pesquisa Energética [EPE], 2024). Each certificate is equivalent to one metric ton of carbon dioxide equivalent (tCO_2e) that was avoided (Guitarrari et al., 2024).

Global warming poses significant challenges for humanity, particularly in reducing emissions from economic activities. Since cities contribute approximately 70% of global greenhouse gas emissions, it is crucial to focus on sustainable urban planning, transportation, and infrastructure. Effective mitigation strategies include reducing emissions, carbon capture, and increased use of renewable energy and energy-efficient buildings to support sustainable development and urban resilience (Al-Sayed & Alanizi, 2023).

In the Brazilian context, fuel distributors are legally required to acquire CBIO certificates in quantities that meet their individual mandatory targets (Agência Nacional do Petróleo, Gás Natural e Biocombustíveis [ANP], 2025). Estimates indicate that the CBIO price has the potential to influence fuel costs for end consumers; this financial impact could exceed R$ 3 billion in 2025 and reach R$ 5 billion by 2034 (Federação Nacional do Comércio de Combustíveis e de Lubrificantes [Fecombustíveis], 2024). Therefore, understanding the factors that determine the price of this certificate is essential for regulators, biofuel producers, and distributing companies.

In this context, this article aims to analyze the impact of macroeconomic and commodity market variables on the CBIO price. Specifically, it investigates the influence of variables such as crude oil futures (WTI), natural gas futures, the dollar exchange rate (USD/BRL), the S&P500 VIX market volatility index, and the volume of CBIO traded.

Literature review

The following presents the theoretical foundation underpinning this research, structured around the workings of the RenovaBio program and the interconnection between the energy market and macroeconomic variables.

The RenovaBio program and the CBIO

The RenovaBio policy was established by Law No. 13,576/2017, with the objective of expanding the presence of biofuels in the transportation matrix and encouraging their production (EPE, 2024). The program sets mandatory greenhouse gas emission reduction targets for a ten-year period, defined annually by the National Energy Policy Council (CNPE). Subsequently, the ANP breaks down these global targets into individual objectives for each fuel distributor, proportionally to its market share in fossil fuels. For this calculation, the ANP considers factors such as the efficiency of certified biofuel producers and demand projections for the domestic market (EPE, 2025).

The CBIO is the instrument that operationalizes this policy. It is a book-entry security issued by biofuel producers and importers upon the sale of their production, through the issuance of an invoice. To meet their targets, fuel distributors must demonstrate possession of the required volume of CBIOs. Other entities and individuals can buy and sell these certificates on the stock exchange, which contributes to the fluidity and liquidity of the market (Bento & Vieira, 2023).

In this way, the CBIO fits into a broader discussion, establishing a direct relationship between the biofuels market and the carbon market, making it the main instrument connecting these sectors within the Brazilian energy matrix. Furthermore, the CBIO has a dual nature: in addition to being an environmental asset that certifies carbon reduction, it is also a tradable financial asset (Bento & Vieira, 2023). This market dynamic, by linking certificate issuance to environmental efficiency scores, acts as an economic incentive that induces energy efficiency gains in biofuel production (Ministério de Minas e Energia [MME], 2019).

At the international level, the CBIO aligns with the trend of Emissions Trading Systems (ETS) that seek to internalize the negative externalities of carbon. However, unlike more established markets such as the European Union Emissions Trading System (EU ETS), which operates under a cap-and-trade model with rigid emission caps, the Brazilian model is based on sectoral carbon intensity. This structural distinction suggests that the CBIO has a unique sensitivity to the dynamics of the domestic and global energy market, which is fundamental to understanding its price formation compared to other regulatory frameworks (Bento & Vieira, 2023; UN Environment Programme Finance Initiative [UNEP FI], 2025).

Despite regulatory advances, an important gap persists in the academic literature. While a large portion of prior research focuses on the technical efficiency of biofuel production or on the regulatory design of RenovaBio (MME, 2019; EPE, 2023), there is a lack of empirical analyses linking the volatility of global macroeconomic variables to CBIO pricing. This study seeks precisely to fill that gap, providing econometric evidence on how external factors such as crude oil and global risk impact the stability of an asset that is, by definition, both environmental and financial (Bento & Vieira, 2023; Souza, 2024).

The CBIO price is influenced by multiple market factors; for example, an increase in the decarbonization target affects the trading value, raising distributor demand according to EPE (2024). Furthermore, the CBIO price dynamics are relevant for the fuels sector, as the crude oil price directly influences the CBIO price by altering supply dynamics and competitiveness in the fuels market (NovaCana, 2019).

Interdependence of the Energy Sector with Macroeceonomic Indicators

CBIO valuation in Brazil does not occur in isolation. The CBIO is an asset traded in a regulated carbon market specifically designed for the fuels sector (Fregonesi et al., 2025). Carbon pricing instruments encompassing both credit markets and fiscal levies are considered highly relevant tools for accelerating greenhouse gas emission reductions and driving energy transition technologies, with projections indicating growing financial flows and vast market potential in the coming years (Dias, 2023).

Mechanisms such as Emissions Trading Systems (ETS), including RenovaBio, are fundamental for achieving emission reductions in a cost-efficient manner, provided they generate a clear, stable, and long-term carbon price signal. This signal helps guide large-scale capital investment decisions in low-emission technologies and mitigation projects, while reducing regulatory uncertainty and strengthening market predictability. In the absence of a consistent signal, these systems may lose effectiveness, limit the mobilization of resources, and induce insufficient levels of investment in decarbonization processes (Acworth et al., 2017).

The CBIO, by representing one metric ton of carbon dioxide equivalent (tCO_2e) not emitted, incorporates a value derived from the decarbonization effort, indirectly connecting it to the Social Cost of Carbon (SCC) metric, which seeks to quantify the future economic damage of one tCO_2e emitted today (Wagner et al., 2021). Although the CBIO is not the SCC, its valuation is sensitive to factors that influence both fuel costs and the appetite for mitigation investments, making the analysis of macroeconomic variables a necessity for regulators and investors.

In the post-COP30 debate, the Paris Agreement Crediting Mechanism has reinforced a UN-regulated global carbon market, strengthening the need for transparency and regulatory harmonization to attract capital toward the energy transition (Suppan, 2025; UNEP FI, 2025).

Interdependence with the Energy Commodities Market

Progress in decarbonizing the regulated market illustrated by the substitution of fossil fuels with lower-environmental-impact options underscores the importance of the dynamic interconnection with the energy commodities sector (Bento & Vieira, 2023). This relationship is explained by the structural subordination of fossil fuel prices to crude oil, a feedstock that competes directly with biofuels. It is precisely this competition that RenovaBio seeks to rebalance, by granting economic value to the positive externalities of biofuels relative to their fossil equivalents (Fregonesi et al., 2025).

Although the CBIO is traded in the organized over-the-counter market operated by B3, and its price should vary according to supply and demand dynamics, price formation is still considered uncertain by trading agents, generating unpredictability and low expectations for new investments (Fregonesi et al., 2025). In a scenario of higher crude oil prices, the competitiveness of ethanol and biodiesel tends to be favored, which could theoretically reduce the cost pressure of decarbonization. In a scenario of falling crude oil prices, the lower relative competitiveness of biofuels may pressure the final cost of fossil fuels, increasing the relevance of CBIO as a regulatory cost for distributors (NovaCana, 2019).

Renewable Natural Gas (RNG), also known as biomethane, plays a growing and relevant role in the energy transition, being considered fundamental in the effort to reduce greenhouse gas emissions. From a regulatory perspective, biomethane is framed as one of the viable pathways for generating Decarbonization Credits (CBIO) (Teixeira et al., 2024). However, the level of utilization and competitiveness of this biofuel are intrinsically linked to its production costs and, crucially, to the comparison of its price with that of natural gas (Teixeira et al., 2024).

The search for cleaner energy sources, stimulated by policies such as RenovaBio, creates an interconnection between markets. The dynamics of natural gas prices at the international and domestic levels serve as a thermometer of the energy transition and can signal the attractiveness of investments in alternative sources, which, by extension, affects the trading environment for CBIOs (EPE, 2024).

Macroeconomic Risks and Global Volatility

Carbon pricing, whether through a carbon tax or a cap-and-trade system, creates short- and long-term incentives to reduce emissions, stimulating the search for more cost-effective solutions and potentially generating revenue for productive use (Kaufman et al., 2016). Following the enactment of Law No. 13,576/2017, Brazil established RenovaBio, a system that promotes the use of renewable energies through a carbon pricing scheme applied to fuel commercialization. Under this scheme, distributors must meet decarbonization targets by acquiring CBIOs, while biofuel producers and importers can generate these certificates voluntarily and are remunerated for their production (Dias, 2023).

The CBIO is a tradable security on B3, through a regulated market that unlike the voluntary carbon market publishes volumes, prices, and trading dates (Fregonesi et al., 2025). Despite this, price formation in the regulated market remains a point of uncertainty, which affects predictability for new investments. By the end of 2024, RenovaBio completed five years of operation and seeks to consolidate itself as an instrument of sustainability and predictability for Brazil’s transportation matrix (EPE, 2024).

Although still a recent and complex policy, RenovaBio seeks to minimize flaws in its course. However, volatility in the CBIO price has been notable, as evidenced by 2022, which showed large fluctuations. In 2023, the price showed greater stability, although it recorded an increase in June and a subsequent decline; the value stabilized near R$ 100.00 (US$ 20.65) at year-end. The average annual CBIO price in 2023 was R$ 113.59 (US$ 23.47), a value very close to that recorded in 2022, which was R$ 111.63 (US$ 21.40) (EPE, 2024).

Predictability of future carbon prices, ensured by a well-structured carbon tax, is necessary to incentivize long-term investments and innovation in low-carbon technologies (Kaufman et al., 2016). Pricing studies using GARCH (Generalized Autoregressive Conditional Heteroscedasticity) family models confirm the volatility associated with CBIO prices, underscoring the importance of a stable price signal for investment (Souza, 2024).

Price formation in the fuel sector is sensitive to macroeconomic and regulatory factors. In this context, the mandatory acquisition of Decarbonization Credits (CBIO) by distributors generates additional costs that can be passed on to end users, increasing uncertainty about the final price of fuels (Souza, 2024). Analysis of historical records shows a progressive increase in the impact of CBIOs on gasoline C, rising from R$ 0.02/L in 2020 and 2021 to R$ 0.14/L in May 2024; furthermore, projections indicate that this incidence could persist until 2029, with an estimated average increase of R$ 0.07/L (Souza, 2024). Consequently, CBIO price volatility represents a risk factor for the financial planning of market agents and for sector stability. This situation becomes more relevant considering that Brazil's oil and gas (O&G) industry is capital-intensive and operates under conditions of high cost sensitivity, with an average global breakeven cost of US$ 45 per barrel for reserve production in 2021 (Teixeira et al., 2024).

Furthermore, Brazil is one of the two largest players in the global ethanol market, alongside the United States, together representing 81% of global biofuel production in 2023 (EPE, 2023). In 2024, the country was the second largest global producer, responsible for 28% of world production (8.78 billion gallons), second only to the United States (52% of production, with 16.1 billion gallons) (Renewable Fuels Association, 2025). Final ethanol consumption in Brazil recorded a 15.6% increase in 2024. Corn ethanol production has been notable, reaching 7.5 billion liters in 2024 and accounting for approximately 20% of total biofuel production in 2024. Sugarcane remains the primary feedstock for anhydrous ethanol (79.8% in 2024) and hydrous ethanol (80.4% in 2024). The volume of hydrous ethanol consumed in transportation experienced a 30.1% increase in 2024 compared to 2023, due to greater competitiveness relative to gasoline and greater availability driven by the growth of corn ethanol (EPE, 2025). The domestic market's sensitivity to the exchange rate persists, as a devalued currency tends to make exports more attractive, influencing biofuel prices and, consequently, the pressure on the CBIO market.

The connection with natural gas occurs through biomethane, a gaseous biofuel that, when purified and in compliance with applicable resolutions, is interchangeable with natural gas. Biomethane is one of the eligible pathways for generating CBIO under RenovaBio (Teixeira et al., 2024). CBIO generation per m³ of biomethane can increase producer revenues by 15% to 19%, considering the average CBIO price in 2022 of R$ 111.60 (US$ 21.39) and the natural gas molecule price in June 2023 (EPE, 2023). The conflict between distributors and producers highlights the difficulty of balancing competitiveness, regulatory predictability, and long-term sustainability within RenovaBio (Souza, 2024).

This risk scenario is amplified in an international context marked by large-scale climate policies, such as the United States' Inflation Reduction Act (IRA). Signed in 2022, this legislation represents one of the country's largest investments in climate action, allocating approximately US$ 400 billion to clean energy and decarbonization projects. The IRA also sets a target of reducing U.S. carbon emissions by at least 50% by 2030 (EPE, 2024). This type of policy influences expectations in carbon markets, mobilizes capital toward low-carbon technologies, and can affect risk appetite in emerging economies by modifying global financing and investment conditions associated with the energy transition.

Projections indicate an increase in the regulated carbon price until 2050, although strong regional differences and high macroeconomic volatility persist (Dias, 2023).

Methodology

The methodology of this study adopts a quantitative approach aimed at analyzing the impact of market variables on the CBIO price through econometric modeling, statistical methods, and data analysis techniques. The research is applied in nature, as it seeks to generate practical knowledge to address the problem of predictability in CBIO price formation. It is also classified as documentary research, given that it uses secondary data and historical time series from the RenovaBio program (Gil, 2002), and as a case study, examining a contemporary phenomenon in a real-world setting where the boundaries between regulatory policy and market dynamics are blurred (Yin, 2001).

To strengthen the validity of econometric inferences, the Breusch-Godfrey test was applied, which is suitable for detecting higher-order autocorrelation in financial time series a phenomenon that can bias standard errors and affect the statistical significance of estimators. In the presence of heteroskedasticity and autocorrelation, Newey-West Heteroskedasticity and Autocorrelation Consistent (HAC) standard errors were used, in order to ensure that the t and F tests retained asymptotic validity and provided more robust results for the economic and regulatory interpretation of the model.

Econometric modeling and model selection

Multiple linear regression was used to explain the relationship between a response variable and multiple explanatory variables (Gujarati & Porter, 2010), expressed in Equation 1:

$$Y = a + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + e_i \quad (1)$$

In this formulation, Y_i is the CBIO price and the dependent variable, a is the intercept, β_i are the slope coefficients of the independent variables, and e_i represents the stochastic error term (Greene, 2003). The linear regression model is applicable when the dependent variable is quantitative and has an approximately normal distribution (Alexopoulos, 2010). Ordinary Least Squares (OLS) estimation consists of selecting estimators that minimize the sum of squared residuals $(Y - \hat{Y})^2$; this is the preferred method because, under the assumptions of the Classical Linear Regression Model, the Gauss-Markov Theorem guarantees that its estimators are the

Best Linear Unbiased Estimators. The validity of statistical inferences depends directly on the model's adherence to these assumptions (Gujarati & Porter, 2010; Greene, 2003). Four distinct models were estimated, as described below:

- **Model 1:** The prices of the dependent and independent variables are normalized to vary between 0 and 1.
- **Model 2:** The prices of the dependent and independent variables are normalized to vary between 0 and 1. The natural gas variable was excluded.
- **Model 3:** The prices of the dependent and independent variables are used in their original scales.
- **Model 4:** The prices of the dependent and independent variables are used in their original scales. The natural gas variable was excluded.

The exclusion of the natural gas variable in Models 2 and 4 is justified by its lack of statistical significance observed in Models 1 and 3 (p-value ≈ 0.12145), allowing the adoption of a more parsimonious model. The linear level specification was chosen due to the direct economic interpretation of the coefficients on the CBIO price and the presence of variables with different scales, which would make the adoption of a log-log specification difficult without loss of economic interpretability.

The main hypothesis of this research is that macroeconomic and commodity market variables have significant explanatory power over the CBIO price within the scope of the RenovaBio policy. The study seeks to confirm whether the variation in the CBIO price is determined, in part, by factors such as crude oil, the dollar, global stock market volatility (S&P500 VIX), and trading volume.

The evaluation of econometric assumptions was carried out using HAC Standard Errors, with a bandwidth of 7 and the Bartlett Kernel, to ensure the robustness of inferences in the presence of heteroskedasticity and autocorrelation. The use of Newey and West HAC standard errors is employed in financial time series models to obtain consistent estimators of the covariance matrix in the presence of both econometric problems, ensuring the asymptotic validity of the t and F tests.

Data and variables

The sample includes 997 daily observations, covering the period from October 15, 2021 to August 11, 2025, to analyze the behavior of the CBIO price. Data for the dependent variable the CBIO price were extracted directly from B3 S.A. (Brasil, Bolsa, Balcão); the Dollar/Real exchange rate was obtained from the Central Bank of Brazil; the other financial and market variables used, including the crude oil futures price (WTI), the natural gas futures price, and the volatility index (VIX), were collected from the Investing.com platform.

In the econometric model used, the CBIO price was used as the dependent variable. The CBIO price is explained by the independent variables presented in Table 1.

Table 1

Variables of the Linear Regression Model

Variable	Description
$CBIO_t$	Decarbornization credit price
$CBIO_{t-1}$	CBIO price in the previous period
$Volume\ CBIO_t$	Volume of CBIO traded
Oil_t	Crude oil futures price (WTI)
$NaturalGas_t$	Natural gas futures price
$SP500_t$	VIX index associated with expected volatility of the S&P 500
$USDBRL_t$	Dollar/Real Exchange rate

Source: Own elaboration.

The inclusion of the variable $CBIO_t$ was carried out with the objective of modeling price inertia and shock persistence, which is necessary for financial asset time series models. Volume_CBIO_t was necessary as a proxy for market liquidity and demand pressure. The crude oil futures price variable was added to capture the opportunity cost and analyze the influence of the main fossil feedstock on biofuels. The natural gas futures price was added to understand the influence of the global energy market and its volatility on the CBIO price. The S&P 500 volatility index was included to capture global systemic risk and financial market sentiment, which can impact capital flows toward commodities. The Dollar/Real exchange rate was added to measure the exchange rate influence on fuel prices and the CBIO, given the impact of the exchange rate on commodity costs.

The analysis was conducted using a multiple linear regression time series model, expressed by Equation 2:

$$CBIO_t = \beta_0 + \beta_1 . CBIO_{t-1} + \beta_2 . Volumen\_CBIO_t + \beta_3 . Oil_t + \beta_4 . NaturalGas_t + \beta_5 . SP500_t + \beta_6 . USDBRL_t + \epsilon_t, \quad (2)$$

The main premise of this work holds that the CBIO valuation is notably conditioned by a set of macroeconomic and market factors. The essential purpose is to confirm the working hypothesis that at least one of the parameters of the explanatory variables differs statistically from zero (H_a: $\beta_i \neq 0$) (Gujarati & Porter, 2010).

By seeking to reject the Null Hypothesis (H_0: $\beta_i = 0$), the study seeks to corroborate that the group of integrated variables has joint relevance in determining the price of the variable under study (Gujarati & Porter, 2010).

Econometric diagnosis and treatment

In time series models, one of the fundamental assumptions for econometric validity is the stationarity of variables. A stationary series exhibits constant mean, variance, and covariance over time, avoiding spurious relationships between economically unrelated variables (da Silva, 1999). When series exhibit unit roots, OLS estimates can lead to invalid inferences and statistically significant coefficients without any real economic relationship.

According to the econometric literature, a zero-order integrated series I (0) is stationary in levels, while a first-order integrated series I (1) requires differencing to achieve stationarity (da Silva, 1999). To verify this property, the Augmented Dickey-Fuller (ADF) test was applied, which is widely used in financial time series models.

However, the presence of first-order integrated variables I (1) does not necessarily imply differencing the series. When a stationary linear combination exists among non-stationary variables, a cointegration relationship is established, indicating the existence of a long-run equilibrium between them (Engle & Granger, 1987). In this study, the stationarity of the series was assessed using the Augmented Dickey-Fuller (ADF) test, specified with an intercept (constant), without deterministic trend, and with automatic lag selection based on the Akaike Information Criterion (AIC). The exclusive use of the ADF test is justified by its wide acceptance in the econometric literature and by its constituting the standard procedure of the

Engle-Granger cointegration approach adopted in this research. After identifying first-order integrated variables, the Engle-Granger cointegration test was applied, which confirmed the stationarity of the model residuals. Consequently, it was decided to keep the variables in levels, given that the estimation is not spurious and the coefficients can be interpreted as long-run economic relationships between the analyzed variables.

To ensure that statistical inferences and OLS estimators are the Best Linear Unbiased Estimators, it is essential to verify the validity of the classical linear regression assumptions (Gujarati & Porter, 2010). Non-satisfaction of these assumptions requires the application of correction methods, such as Robust (HAC) Standard Errors, already used in this study.

This research acknowledges as a methodological limitation the choice of the multiple linear regression model via OLS, which, although robust after the application of Newey and West’s (1987) HAC Standard Errors, does not explicitly model the conditional volatility of the CBIO price series, which would be better explored through GARCH (Generalized Autoregressive Conditional Heteroscedasticity) family models.

Residual normality test (Jarque-Bera)

The normality assumption of errors $\varepsilon_i \sim N(0, \sigma^2)$ allows for the application of t and F tests in small samples (Gujarati and Porter, 2010). In large samples, OLS estimators tend toward asymptotic normality by the Central Limit Theorem (Greene, 2003). The Jarque-Bera (JB) test evaluates the normality of residuals through skewness and kurtosis (Jarque & Bera, 1987).

Serial autocorrelation test (Breusch-Godfrey)

Autocorrelation occurs when error terms are correlated with each other (Gujarati and Porter, 2010), generating biased standard errors and invalidating significance tests (Greene, 2003). To detect higher-order autocorrelation, the Breusch-Godfrey (BG) test is used, also known as the Lagrange Multiplier test. This test is more flexible than the Durbin-Watson test, as it allows testing autocorrelation of order p. The BG test involves an auxiliary regression of OLS residuals (Breusch, 1978).

The BG test statistic follows a Chi-Squared χ^2 distribution with p degrees of freedom. The null hypothesis is the absence of autocorrelation in the residuals H_0: $\rho_1 = \ldots = \rho p = 0$ (Breusch, 1978).

In this test, a p-value greater than the significance level implies failure to reject the null hypothesis, indicating no significant autocorrelation in the residuals for the tested order. In the present study, the null hypothesis H_0 is that there is no serial autocorrelation in the regression residuals.

Heteroskedasticity test

Heteroskedasticity occurs when the variance of errors is not constant, ($Var(\varepsilon_i) \neq \sigma^2$). Although OLS estimators remain unbiased, they are no longer efficient. The Breusch-Pagan test is frequently used to test the null hypothesis of homoskedasticity (Gujarati & Porter, 2010). In this test, rejection of the null hypothesis, indicated by a p-value below the significance level, confirms the presence of heteroskedasticity (Breusch, 1978).

Results

Model performance was evaluated through metrics such as the Adjusted Coefficient of Determination (R^2), the F-Statistic, and the AIC and Bayesian Information Criterion (BIC); these are only compared within each scale group. All models demonstrated high explanatory power, with an R^2 of approximately 0.963 and an F-Statistic with p-value < 0.00001, confirming the joint relevance of the variables (Table 2). The rejection of the null hypothesis with such a low p-value confirms that the explanatory variables have statistically significant predictive power over the CBIO price.

Table 2

Linear regression models

Metric	Model 1	Model 2	Model 3	Model 4
Adjusted R²	0,963289	0,963240	0,963289	0,963240
P-value (F-statistic)	< 0,00001	< 0,00001	< 0,00001	< 0,00001
AIC	-4.077,38	-4.077,05	6.231,44	6.231,76
BIC	-4.043,04	-4.047,63	6.265,77	6.261,19
Durbin-Watson	2,590740	2,592820	2,590740	2,592820
First-order autocorr	-0,296210	-0,297304	-0,296210	-0,297304

Source: Own elaboration.

For selecting the most appropriate model, AIC and BIC are necessary tools, as they penalize models with a greater number of parameters, favoring parsimony (Alexopoulos, 2010).

In the comparison between normalized models 1 and 2, Model 1 had the lowest AIC (-4,077.38), while Model 2 presented the lowest BIC (-4,047.63). This represents a potential divergence in the choice, because the AIC (Model 1) indicates better overall predictive performance, while the BIC (Model 2), by more severely penalizing the number of variables, suggests that the reduced model is the most parsimonious in terms of included variables, being preferable when the objective is to simplify the model structure.

Likewise, the comparison between non-normalized models 3 and 4 showed a difference in selection criteria. Model 3 presented the lowest AIC (6,231.44), suggesting better relative performance in terms of predictive fit; while Model 4 recorded the lowest BIC, indicating greater parsimony by more rigorously penalizing the number of included parameters. Therefore, there is no full consensus between the two criteria: the AIC favors Model 3, while the BIC supports Model 4 as the more parsimonious alternative among the non-normalized models.

However, the exclusion of the natural gas variable, which was not statistically significant in Models 1 and 3 (p-value = 0.12145), is justified based on the principle of parsimony. The objective is to achieve the highest explanatory relationship with the minimum number of independent variables (Greene, 2003). Thus, Model 4 (non-normalized, reduced), which minimizes BIC in its group, is considered the most appropriate for interpretation of effects, as maintaining the original CBIO price scale facilitates direct understanding of the economic impact of the predictors.

A DW value > 2 suggests possible negative autocorrelation; therefore, it was complemented with Breusch-Godfrey and HAC errors (Gujarati & Porter, 2010).

Interpretation of the selected model

The interpretation of coefficients in multiple regression must be carried out under the condition of ceteris paribus. The partial slope coefficient, β_i, represents the change in the average value of the dependent variable (Y, CBIO price) for each one-unit increase in the explanatory variable (X), holding constant the values of all other variables included in the model (Gujarati & Porter, 2010).

Model 4, which uses variables in their original scale (non-normalized) and includes only variables statistically significant at the 10% level, produced the following results, summarized in Table 3.

Table 3

Results of Linear Regression Model 4

Independent variable	Coefficient	t-statistic	P-value	Significance
$CBIO_{t-1}$	0,956167	51,212000	<0,00001	***
$Volume_{CBIO_t}$	0,000005	5,793000	<0,00001	***
Oil_t	0,03	1,77	0,08	*
$SP500_t$	0,04	3,06	0,00	***
$USDBRL_t$	-2,102860	-1,986000	0,047330	**
const	10,125300	1,351000	0,176890	n.s.

Note: Signif.: *** p<0,001; ** p<0,05; * p<0,1.

Source: Own elaboration.

Substituting the estimated coefficient values from Table 3 into Equation 2, the final model equation for economic interpretation is Equation 3:

$$CBIO_t = 10{,}1253 + 0{,}956167\,.\,CBIO_{t-1} + 0{,}00000479\,.\,Volumen\_CBIO_t + 0{,}0343434\,.\,Oil_t + 0{,}0434453\,.\,SP500_t - 2{,}10286\,.\,USDBRL_t + \epsilon_t, \quad (3)$$

To facilitate economic interpretation, the average CBIO price (Y) was set at R$ 100.00 for the semi-elasticity analysis. The estimated coefficients reveal the following impacts:

- **Volume_CBIO:** With a positive coefficient of 4.78798×10^{-6} and high significance (p-value < 0.00001), the traded volume positively impacts the price. This may reflect that increased market liquidity and demand raise the value of the certificate.

- **Oil:** The positive coefficient of 0.0343434 is significant at the 10% level (p-value = 0.07729), indicating that a US$ 1.00 increase in the crude oil futures price (WTI) results in an average increase of approximately 0.034% in the CBIO price, holding other variables constant. This result captures the opportunity cost between fossil fuel and biofuel.

- **SP500:** The S&P 500 index presented a positive coefficient of 0.0434453, highly significant (p-value = 0.00225). This result suggests that as the global stock market and risk sentiment improve, there is a positive impact on the CBIO. This may reflect that the asset is partly viewed as a financial investment that benefits from an environment of greater confidence and capital flow.

- **USDBRL:** With a negative coefficient of -2.10286, significant at the 5% level (p-value = 0.04733), the exchange rate exerts an inverse influence. For each one-unit increase in the dollar exchange rate (real depreciation), the CBIO price decreases by approximately 2.10%, controlling for the other variables. This may be linked to the sensitivity of biofuel production and export costs in Brazil.

- **Natural_Gas:** The natural gas variable was excluded from Model 4 because it presented a p-value of 0.12145 in the initial models, making it statistically non-significant at the 10% level.

Model 4 confirms that the CBIO is determined by liquidity, oil, the global market, and the exchange rate, evidencing its complexity.

Stationarity and Cointegration Analysis

Given the time series nature of the model, the stationarity of variables was assessed using the Augmented Dickey-Fuller (ADF) test. The results are presented in Table 4.

Table 4

Results of the Augmented Dickey-Fuller (ADF) Test

Variable	ADF Statistic	p-value	Integration order
CBIO	-1,984	0,294	I(1)
CBIOt-1	-1,966	0,302	I(1)
Oil_t	-1,517	0,525	I(1)
Natural_Gas	-1,841	0,3608	I(1)
SP5500	-6,258	<0,001	I(0)
USDBRL_t	-2,942	0,040	I(0)
Volume_CBIOt	-18,331	<0,001	I(0)

Source: Own elaboration.

The results in Table 4 indicate that variables such as CBIO, $CBIO_{t-1}$, Oil_t and Natural_Gas exhibit non-stationarity in levels (I (1)), while other variables are stationary in levels (I (0)). Given this result, the Engle-Granger cointegration procedure was applied. The ADF test applied to the residuals of Model 4 confirmed their stationarity, evidencing the existence of a cointegration relationship and long-run equilibrium among the analyzed variables.

The results of the Engle-Granger cointegration test applied to the residuals of Model 4 are presented in Table 5.

Table 5

Results of the ADF test applied to model residuals (Engle-Granger)

Variable	Statistic	p-value	Conclusion
Residuals ($\hat{u}_t$)	-31,791	6,389e-058	Stationary

Source: Own elaboration.

This result validates the level estimation adopted in the study and rules out the presence of spurious regressions. The evidence of cointegration indicates that the variables maintain a long-run equilibrium relationship, allowing the estimated coefficients to be interpreted as long-run economic links between the CBIO price and its determinants.

Discussion

CBIO price formation in the Brazilian market does not occur in isolation, but rather responds to a dynamic interdependence with the global energy sector. The results obtained confirm the hypothesis that variables such as crude oil (WTI) and the exchange rate (USD/BRL) significantly condition the valuation of the asset.

The positive influence of oil reflects the opportunity cost between fossil fuels and biofuels; an increase in crude oil prices improves the competitiveness of ethanol and biodiesel, which increases demand for CBIOs and, consequently, their value. Conversely, the negative relationship of greater relative magnitude with the exchange rate suggests that a depreciation of the real affects production costs and export decisions within the biofuels matrix, putting downward pressure on the certificate's price in the domestic regulated market.

In the international context, Brazilian policies present structural distinctions. While the EU ETS operates under a cap-and-trade model with industrial caps (European Union, 2016), RenovaBio focuses on sectoral carbon intensity. Compared to California's Low Carbon Fuel Standard (LCFS), which directly stimulates innovation and electrification (Courtis, 2013), the Brazilian CBIO has a much more pronounced dependence on energy commodities (WTI) and exchange rate volatility. This suggests that the Brazilian model is more exposed to external shocks than its international counterparts.

This comparison reveals that, although RenovaBio aligns with the global decarbonization efforts of the Paris Agreement, its dual nature makes it more vulnerable to external shocks. The statistical significance of the S&P 500 VIX index reinforces this view, indicating that global risk appetite impacts capital flows toward the Brazilian carbon market, treating it in part as a speculative financial asset.

Additionally, the confirmation of cointegration among the variables reinforces the interpretation of the results in terms of long-run relationships. The stationarity of the model residuals indicates the existence of a long-run equilibrium relationship, allowing spurious regression to be ruled out. In this sense, the estimated coefficients reflect consistent economic links between the CBIO price and the analyzed macroeconomic variables.

Conclusions

The commitment derived from the Paris Agreement and the urgency to decarbonize the economic matrix lend paramount importance to this research. The study is fundamental because it reveals that the effectiveness of RenovaBio a pillar of Brazilian public policy does not depend solely on sectoral targets, but is profoundly conditioned by global dynamics. By using a linear regression model with Newey-West HAC correction, it was possible to precisely identify which factors truly move the price of the environmental asset over a four-year horizon.

The key findings demonstrate the robustness of the estimated models, with an adjusted $R^2 \approx 0.963$, and confirm that volume, oil (WTI), global risk (VIX), and the exchange rate are the main statistically significant predictors of the CBIO price. The most relevant finding is the duality of the CBIO as a financial asset and commodity: while oil exerts a positive impact (0.034), the exchange rate (USD/BRL) presents a significantly more intense negative influence (-2.10). Moreover, the positive correlation with the S&P 500 indicates that the CBIO benefits from risk appetite and international capital flows.

These findings have critical implications for public policy. The results suggest that RenovaBio, although robust, is vulnerable to external shocks beyond the control of the regulator. Therefore, the implementation of protective mechanisms is recommended, such as price bands or stabilization funds, to mitigate exchange rate volatility. These measures are essential for the CBIO to be positioned as a stable economic signal, capable of incentivizing long-term investments in the biofuels industry under more predictable regulatory frameworks.

From a methodological standpoint, the incorporation of unit root and cointegration tests allowed for the validation of the econometric specification of the model. The cointegration evidence found for the analyzed variables indicates that the results are not spurious and reflect a long-run equilibrium relationship between the CBIO price and the analyzed macroeconomic variables. As a limitation, the OLS model does not capture the conditional volatility typical of financial assets nor short-run dynamics, aspects that may be explored in future research through Vector Error Correction Models (VECM).

Ethical considerations

This research did not require ethical approval as it was based on documents from governmental bodies. Likewise, this research did not require approval from an Ethics or Bioethics Committee, as it did not use any living resources, agents, biological samples, or personal data that would represent any risk to life, the environment, or human rights.

Conflict of interest

All authors made significant contributions to the document and declare that there is no conflict of interest related to this article.

Author Contribution Statement

Marianna Henriques Ferreira Lima: Conceptualization, Methodology, Software, Validation, Formal Analysis, Research, Data Curation, writing – Original Draft, Writing: Review and editing.

Herlander Costa Alegre da Gama Afonso: Conceptualization, Methodology, Validation, Formal Analysis, Research, writing: review and editing; Supervision.

Source of funding

This research was carried out without any funding from public or private entities. The researchers were motivated solely by the relevance and timeliness of the subject under study.

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