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ORIGINAL ARTICLE

Dynamic impacts of economic growth, energy use, urbanization, tourism, agricultural value-added, and forested area on carbon dioxide emissions in Brazil

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Abstract
Global climate change caused by greenhouse gases (GHGs), particularly carbon dioxide (CO_2) emissions, poses incomparable threats to human life, the environment, and development. The present study empirically investigates the dynamic impacts of economic growth, fossil fuel energy use, renewable energy use, urbanization, tourism, agricultural value-added, and forested area on CO_2 emissions in Brazil. Time series data from 1990 to 2019 were utilized by applying the autoregressive distributed lag (ARDL) bounds testing approach followed by the dynamic ordinary least squares (DOLS) method. The DOLS estimate findings reveal that economic growth, fossil fuel energy use, urbanization, tourism, and agricultural value-added cause environmental degradation by increasing CO_2 emissions in Brazil while increasing renewable energy use and forested areas help to mitigate the CO_2 emissions in Brazil. The estimated results are robust to alternative estimators such as fully modified least squares (FMOLS) and canonical cointegrating regression (CCR). In addition, the pairwise Granger causality test is utilized to capture the causal linkage between the variables. This article put forward policy recommendations toward sustainable development by establishing strong regulatory policy instruments to mitigation of CO_2 emissions.

Keywords Climate change · Environmental degradation · CO_2 emissions · Sustainable development · Brazil

Introduction

Global climate change is a burning issue in the twenty-first century due to the atmospheric concentrations of GHGs dominated by CO_2 which is mostly released by human-caused activities such as fossil fuel combustion and deforestation (Jaafar et al. 2020; Raihan et al. 2021a; IPCC 2022;). In addition to CO_2, other GHGs with significantly lower emissions such as methane (CH_4) and nitrous oxide (N_2O) also influence global climate change. However, the present study's focus on CO_2 is justified because it forces most of the global warming leading to climate change. The continuous increase in CO_2 emissions is expected to have massive ramifications for the global climate system, with catastrophic consequences affecting all segments of society (Begum et al. 2020; Raihan et al. 2022a). Therefore, reducing CO_2 emissions and increasing environmental quality have become a global concern in order to ensure sustainable development and mitigate the negative effects of climate change (Raihan and Said 2021). Furthermore, the United Nations has proposed Sustainable Development Goals (SDGs) for 2030, which emphasize the need for affordable and clean energy, comprehensive and sustainable economic growth, and technological invention as urgently needed solutions to tackle climate change (SDGs 7, 8, 9, and 13). Global climate change is having a huge impact in Latin America, and it has already manifested itself in several countries (Azócar et al. 2021). Brazil plays a significant and unique role in climate change because it is one of the world's ten largest economies and home to one of the planet's most diverse ecosystems and forests. However, Brazil is the world's seventh-biggest CO_2 emitter, with fossil fuel burning coming in second after land use change and forestry-related activities (Adebayo et al. 2021a). In September 2016, Brazil accepted the Paris Agreement, pledging to reduce GHG emissions by 37% by 2025 and 43% by 2030, compared to 2005 levels, as stated in

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the Intended Nationally Determined Contribution (INDC). Overall understanding Brazil's vulnerability to climate change is becoming increasingly important for policymakers seeking to strike a balance between policies aimed at mitigating climate change and achieving sustainable development, as well as implementing measures that achieve both. The trade-off between pollution and development is the most difficult aspect of achieving this dual goal at the same time. As a result, it is a big question of sustainable growth and mitigation of CO_2 emissions as mutually exclusive aims. A significant question that arises is how Brazil might reduce CO_2 emissions, and this question can be answered by examining the country's environmental variables. If the functional relationship between natural resources and modern development processes cannot be prevented, environmental damage will unavoidably occur. Such issues are more common in developing countries like Brazil, where economic growth, energy security, urbanization, tourism, agricultural productivity, and mitigation of CO_2 emissions are simultaneously important.

Brazil's economy is the largest in South America, with a gross domestic product (GDP) and GDP per capita of USD 1.88 trillion and USD 8638, respectively, in 2019 (World Bank 2022). The Brazilian economy is primarily an industrial and investment-based economy that is heavily reliant on energy consumption (Adebayo et al. 2021a). To meet its growing energy demand, Brazil has to depend on the utilization of fossil fuels, such as oil, natural gas, and coal. The increase in fossil fuel energy use leads to a substantial rise in CO_2 emissions. The country is highly concerned about the growing emission intensity, especially from the energy sector. Brazil is the world's tenth-largest energy consumer and the Western Hemisphere's third-largest after the USA and Canada. As a result, increased energy efficiency is critical (Adebayo et al. 2021a). Moreover, the rising concern about energy scarcity, global climate change, and mitigation of CO_2 emissions has highlighted the significance of renewable energy (Sharif et al. 2021; Sohag et al. 2021). The rapid depletion of fossil fuels and their severe environmental effects are gradually causing international economies to move to more sustainable renewable energy sources (Sohag et al. 2019). The advantages of renewable energy minimize conventional energy use while preserving long-term global economic output (Raihan et al. 2022b). Compared to conventional energy, renewable energy is safe, clean, and abundant. Renewable energy is widely regarded as a carbon-free energy source with the potential to solve energy security and reduce emissions (Raihan and Tuspekova 2022a). Renewable energy plays a critical part in meeting the global emission reduction goal of 50% by 2050 (Raihan and Tuspekova 2022b).

Brazil's energy comes from two main sources: crude oil, whose pricing is controlled by the worldwide market, making the country vulnerable; and hydroelectricity, which is vulnerable to droughts, making the country's electrical supply worse. As a result, renewable energy diversity and enhanced supply are required (Lima et al. 2020). Hydropower, wind, biofuels, and solar power are all abundant renewable energy sources in Brazil (Lima et al. 2020). Brazil's energy policies, according to the international energy association, are well-positioned to address the world's most critical energy concerns. After China and the USA, Brazil has the world's third-largest renewable energy capacity. Brazil's renewable energy covers over 47% of energy consumption (World Bank 2022), making it one of the least carbon-intensive economies in the world. In general, Brazil's electricity output and consumption have increased, with major hydropower facilities accounting for 80% of domestic electricity generation (Adebayo et al. 2021b). The Itaipu Dam, located in Brazil, is the world's second-largest hydropower plant, supplying more than 20% of the country's electricity needs (Zambrano-Monserrate et al. 2016). Moreover, Brazil has high winds throughout the year, particularly during the dry season with limited rainfall, making wind power a viable supplement to Brazil's hydropower (Pao and Fu 2013). Brazil is now ranked ninth among the countries with the largest tangible wind energy capacity in the world. There are roughly 400 wind farms in operation, with a total installed power of 10 GW and a contribution of 6.5 to 7% to national electricity production (Lima et al. 2020). Brazil is one of the top five countries in the world when it comes to renewable energy (Jebli and Youssef 2019). According to the Brazilian government, renewable energy sources make for 83% of Brazil's electrical output. Hydropower (63.8%), wind (9.3%), biomass and biogas (8.9%), and solar (1.4%) are the most commonly used renewable energy sources in Brazil. The country has developed and implemented several policy tools to encourage renewable energy technology. Despite this, limited research has been conducted to examine the relationship between renewable energy use and the mitigation of CO_2 emissions. Hence, it is essential to explore the potential of renewable energy use to reduce CO_2 emissions in Brazil.

The procedure of urbanization may be recognized as an imperative aspect of economic growth and the structure of the economy. In 2020, 87.1% of Brazil's total population lived in urban areas and cities with an urban population growth of 1.1% per year (World Bank 2022). Brazil's rapid urbanization degrades the natural character of economic development by influencing the establishment of industries, residences, and other types of infrastructure, all of which contribute to environmental deterioration. Rapid urbanization is a threat to sustainable development, as it increases energy consumption as well as CO_2 emissions. According to Zhu and Peng (2012), urbanization has three major effects on CO_2 emissions: first, residential and industrial energy consumption; second, energy used by the construction industry to improve infrastructure, transportation, and residential dwellings; and third, forest conversion for urban development. Furthermore, increased use of residential household equipment (e.g., air conditioning, water heater) has consumed a lot of electricity and has a negative impact on CO_2 emissions. Urbanization, like the growth of cities, has a significant impact on the area's environment. Therefore, it is imperative to explore the relationship between urbanization and CO_2 emissions for sustainable development in Brazil.

Tourism in Brazil is a rapidly rising industry that is vital to the economies of several parts of Brazil. In 2019, the country had 6 million international visitors, placing it second in South America in terms of international tourist arrivals (World Bank 2022). Tourism generated 2.4% of the country's revenue from exports of goods and services in 2019 and accounted for 7% of the country's direct and indirect employment. According to the United Nations' World Tourism Organization (UNWTO), by 2030, the total number of international tourists would reach a new high of 2 billion, translating to a yearly worldwide income of 2 billion USD. These numbers show that tourism has a significant impact on worldwide economic growth (Raihan et al. 2022c). However, tourism is linked to an increased need for energy for transportation, food, lodging, support facilities, and the management of tourist sites, all of which are likely to degrade the environment (Katircioglu et al. 2018). According to the UNWTO, tourism accounts for over 5% of total global emissions, with transportation accounting for 75% of tourism-related emissions and lodging accounting for 20% (IPCC 2014). Thus, in the context of economic and transportation activities, the link between tourism development and CO_2 emissions is spelled out by domestic energy use. Nevertheless, tourism development has been glaringly disregarded in emission models, owing to the widespread belief that tourism contributes massively favorably to economic growth, particularly in Brazil.

Agriculture, one of the main drivers of environmental deterioration, was linked to CO_2 emissions and global climate change and was labeled ultrasensitive to climate change (Raihan et al. 2022a). Agriculture in Brazil has grown significantly during the previous four decades. Brazil's constant agricultural production has turned the country from a net importer of food to one of the world's top exporters of agricultural goods, pulling millions of Brazilians out of poverty (Jebli and Youssef 2019). Brazil is the world's second-largest agricultural exporter, an important exporter of soybeans, tobacco, and poultry, and the world's largest supplier of orange juice, sugar, and coffee. It is also a major producer of maize, rice, and beef, with a sizable domestic consumer market (Jebli and Youssef 2019). Brazil's total agricultural value-added has more than doubled since 2000, with animal production nearly tripling, owing to increased productivity. Agriculture accounted for 5.91% of Brazil's GDP in 2020 (World Bank 2022), and it employed over 13% of the country's workforce. However, agricultural productivity also benefits the environment (Raihan et al. 2022d). Agricultural productivity is linked to economic growth, which promotes demand for cleaner environments, commodities, and services, as well as the government's ability to enforce environmental legislation. On the other hand, the annual combustion of fossil fuels in agriculture puts billions of tons of GHGs into the atmosphere, contributing to global warming and climate change (Raihan and Tuspekova 2022a). Agriculture is responsible for 25% of Brazil's current emissions. Cattle account for half of the agricultural emissions, with farming operations accounting for the other half (Jebli and Youssef 2019). Thus, research on the relationship between agricultural value-added and environmental degradation is critical for the development of successful sustainable agriculture policies in Brazil.

Forest resources are under strain as the world's population grows, as does the demand for food, lodging, agriculture, transportation, and other infrastructures. The forestry sector and land use change are by far the largest sources of pollution in Brazil, which hosts the majority of the Amazon (Adebayo et al. 2021a). Rapid urbanization and the loss of forests are examples of land use change that can result in significant CO_2 emissions and climate change. However, forest ecosystems function as both sources and sinks of carbon through which they have a crucial influence on the global climate system (Raihan et al. 2021b). Forests play a significant role in climate change mitigation by absorbing the atmospheric CO_2 and storing it in tree biomass, which is called carbon sequestration (Raihan et al. 2019). About 300 billion tons of CO_2 emissions from the atmosphere are yearly absorbed by the global forest ecosystems, and about three billion tons of it are anticipated to leak into the environment annually due to deforestation (Raihan and Tuspekova 2022c). Deforestation causes long-term ecological problems by accelerating the effects of climate change, thus attributing to desertification, flooding, soil erosion, and loss of natural habitats (Raihan et al. 2022a). With temperatures anticipated to rise 1.5 °C above pre-industrial levels between 2030 and 2052 under the current global warming and climate change scenario, the role of forest resources in absorbing carbon from the atmosphere is becoming increasingly important (IPCC 2018). Brazil has a forested area of 60% of its total land area (World Bank 2022), which plays an important role in the global carbon balance. Therefore, it is crucial to investigate the potential of forested areas for CO_2 emission reduction in Brazil.

Over the last few decades, Brazil faces a big challenge in struggling to achieve high growth rates without deteriorating the environment and this raises the issue of the environment–growth nexus. However, there has been very little research in Brazil on the interaction of CO_2 emissions and its determinants, even though it has become a hot topic among contemporary researchers worldwide. Therefore, the present study aims to fill up this research gap by using econometric approaches to explore the dynamic impacts of economic growth, fossil fuel energy use, renewable energy use, urbanization, tourism, agricultural value-added, and forested area on CO_2 emissions in Brazil. This study is significant because it contributes to the recent literature and policymaking in Brazil in several directions. First, the present study estimated the impacts of both fossil fuel and renewable energy use on CO_2 emissions to compare their influences and provide recommendations for mitigation of CO_2 emissions in Brazil. Second, the novelty of this research is the evaluation of the impact of tourism, forested area, and agricultural value-added on CO_2 emissions in Brazil which is a ground-breaking attempt to reveal the nexus between tourism, agricultural value-added, forested area, and CO_2 emissions in the case of Brazil. Third, this study has used the most up-to-date and complete data over the period of 30 years (1990–2019). Fourth, several unit root tests (ADF, DF-GLS, and P-P), cointegration models (ARDL, DOLS, FMOLS, CCR), and diagnostic tests are employed to verify the precision of the results. In addition, the pairwise Granger causality test is utilized to capture the causal linkage between the variables. Finally, the study's findings would provide policymakers with more comprehensive and useful information for developing successful policies in the areas of low-carbon economy, promoting renewable energy use, sustainable urbanization, eco-friendly tourism, climate-smart agriculture, and sustainable forest management which would ensure emission reduction in Brazil. In addition, the findings from this investigation are useful for environmental policy evaluation and further policy formation to prepare Brazil for a 1.5 °C world by strengthening policy and action plan to reduce the climate change impacts, thereby ensuring sustainable development and mitigation of CO_2 emissions in the long term. This study's outcome could provide suggestions for other developing countries aiming at building successful strategies to achieve environmental sustainability through the mitigation of CO_2 emissions while strengthening the climate change mitigation and adaptation strategies.

Methodology (Appendix)

Data

The present study provides an empirical investigation of the dynamic impacts of economic growth, fossil fuel energy use, renewable energy use, urbanization, tourism, agricultural value-added, and forested area on CO_2 emissions in Brazil employing the DOLS approach of cointegration by Pesaran and Shin (1995) and Pesaran et al. (2001). Time series data from 1990 to 2019 for Brazil were obtained from the World Development Indicator (WDI) dataset. The WDI is the primary World Bank collection of development indicators, compiled from officially recognized international sources. It presents the most current and accurate global development data available and includes national, regional, and global estimates. The WDI is a compilation of relevant, high-quality, and internationally comparable statistics about global development and the fight against poverty. The database contains 1400 time series indicators for 217 economies and more than 40 country groups, with data for many indicators going back more than 50 years (World Bank 2022). In recent years, numerous studies used time series data for different countries around the world which are obtained from WDI to investigate the dynamic relationship between carbon emissions and its factors by utilizing several econometric approaches.

However, the utilization of the DOLS method by using time series data for 30 years (a small sample size) has been justified by similar kinds of previous studies which have already been published in reputed journals, for example, Dogan et al. (2017), Streimikiene and Kasperowicz (2016), Uddin et al. (2017), Rasoulinezhad and Saboori (2018), Salim and Rafiq (2012); and Hafner and Mayer-Foulkes (2013), who applied the DOLS approach by using annual time series data for 16, 18, 22, 23, 26, and 28 years, respectively. This research considers CO_2 emissions as the dependent variable while economic growth, fossil fuel energy use, renewable energy use, urbanization, tourism, agricultural value-added, and forested area as explanatory variables. This study measures CO_2 emissions as kilotons (kt); economic growth as GDP (constant Brazilian real); fossil fuel energy use and renewable energy use as Joules per capita; urbanization as the total population; tourism as the number of international tourist arrivals; agricultural value-added as constant Brazilian real; and forested area as square kilometers (sq. km). Lastly, the variables are transformed into a logarithm to make sure that data are normally distributed. The variables with their logarithmic forms, measurement units, and data sources are presented in Table 1. Moreover, the annual trends of the study variables in Brazil are presented in Fig. 1.

Empirical model

Theoretically, CO_2 emission is associated with income and fossil fuel energy use. Assuming the market clearing condition, where CO_2 emissions equal economic growth and fossil fuel energy use, the following function is written within the framework of the standard Marshallian demand (Friedman 1949) function at time *t*:

Table 1 Variables with their logarithmic forms, units, and data sources

Variables	Description	Logarithmic forms	Units	Sources
CO_2	CO_2 emissions	LCO2	Kilotons	WDI
GDP	Economic growth	LGDP	Constant Brazilian real	WDI
FFE	Fossil fuel energy use	LFFE	Joules per capita	WDI
RNE	Renewable energy use	LRNE	Joules per capita	WDI
URB	Urbanization	LURB	Total population	WDI
TR	International tourism	LTR	Number of tourist arrivals	WDI
AVA	Agricultural value-added	LAVA	Constant Brazilian real	WDI
FA	Forested area	LFA	Square kilometers (sq. km)	WDI

$$CO_{2t} = f\left(GDP_t; FFE_t\right) \tag{1}$$

where CO_{2t} is the CO_2 emissions at time t, GDP_t is the economic growth at time t, and FFE_t is the fossil fuel energy use at time t.

This study intends to estimate the impacts of renewable energy use, urbanization, tourism, agricultural value-added, and forested area on CO_2 emissions to compare their influences on environmental quality. Hence, Eq. (1) can be as follows:

$$CO_{2t} = f\left(GDP_t; FFE_t; RNE_t; URB_t; TR_t; AVA_t; FA_t\right) \tag{2}$$

where RNE_t is the renewable energy use at time t, URB_t is the urbanization at time t, TR_t is the international tourism at time t, AVA_t is the agricultural value-added at time t, and FA_t is the forested area at time t.

The next equation depicts the empirical model:

$$\begin{aligned} CO_{2t} = {} & \tau_0 + \tau_1 GDP_t + \tau_2 FFE_t + \tau_3 RNE_t \\ & + \tau_4 URB_t + \tau_5 TR_t + \tau_6 AVA_t + \tau_7 FA_t \end{aligned} \tag{3}$$

Furthermore, Eq. (4) can be expended as the econometric model in the following form:

$$\begin{aligned} CO_{2t} = {} & \tau_0 + \tau_1 GDP_t + \tau_2 FFE_t + \tau_3 RNE_t \\ & + \tau_4 URB_t + \tau_5 TR_t + \tau_6 AVA_t + \tau_7 FA_t + \varepsilon_t \end{aligned} \tag{4}$$

where τ_0 and ε_t stand for intercept and error term, respectively. In addition, τ_1, τ_2, τ_3, τ_4, τ_5, τ_6, and τ_7 denote the coefficients.

Moreover, the logarithmic arrangement of Eq. (4) can be as follows:

$$\begin{aligned} LCO2_t = {} & \tau_0 + \tau_1 LGDP_t + \tau_2 LFFE_t + \tau_3 LRNE_t \\ & + \tau_4 LURB_t + \tau_5 LTR_t + \tau_6 LAVA_t + \tau_7 LFA_t + \varepsilon_t \end{aligned} \tag{5}$$

where $LCO2_t$ is the logarithmic form of CO_2 emissions at time t, $LGDP_t$ is the logarithmic form of economic growth at time t, $LFFE_t$ is the logarithmic form of fossil fuel energy use at time t, $LRNE_t$ is the logarithmic form of renewable energy use at time t, $LURB_t$ is the logarithmic form of urbanization at time t, LTR_t is the logarithmic form of tourism at time t, $LAVA_t$ is the logarithmic form of agricultural value-added at time t, and LFA_t is the logarithmic form of the forested area at time t.

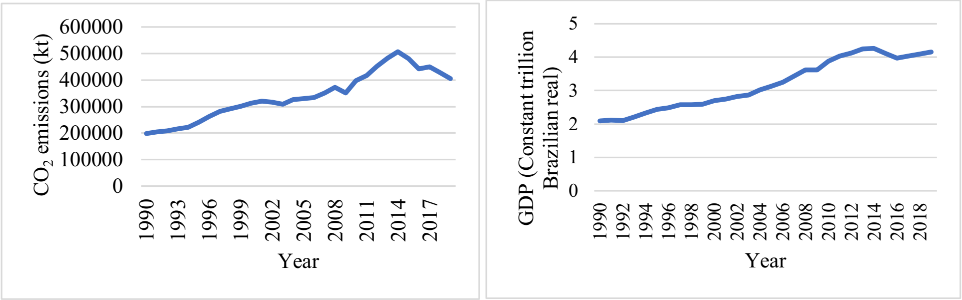
Flow chart of the analysis

The flow chart of the analytical techniques employed in the study to explore the dynamic impacts of economic growth, fossil fuel energy use, renewable energy use, urbanization, tourism, agricultural value-added, and forested area, on CO_2 emissions in Brazil, is depicted in Fig. 2.

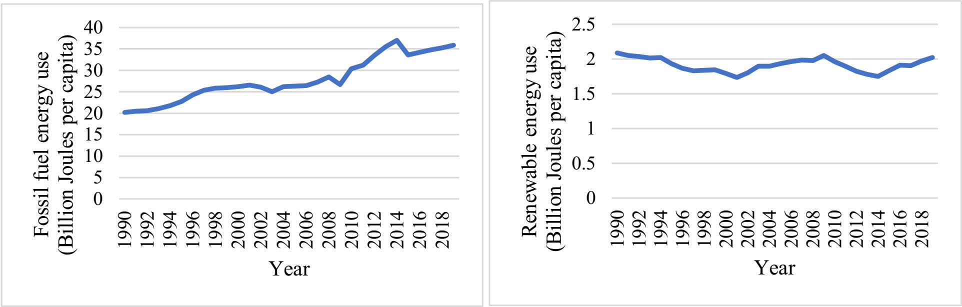
DOLS cointegration regression

The present study employed DOLS, an extended equation of ordinary least squares estimation to analyze the time series data. To regulate endogeneity and calculate standard deviations using a covariance matrix of errors that is resistant to serial correlation, the DOLS cointegration test incorporates explanatory variables as well as leads and lags of their initial difference terms. The fact that the leads and lags of the distinct terms are included demonstrates that the error term is orthogonalized. Because the standard deviations of the DOLS estimator have a normal asymptotic distribution, they provide a reliable test for the statistical significance of the variables. When a mixed order of integration occurs, the DOLS approach is effective at allowing individual variables in the cointegrated outline to be integrated by estimating the dependent variable on explanatory variables in levels, leads, and lags. The DOLS estimation's main advantage is the presence of mixed order integration of individual variables in the cointegrated outline. For example, in DOLS estimation, one of the $I(1)$ variables was regressed against other variables, some of which were $I(1)$ variables with leads (p) and lags ($-p$) of the first difference, while others were $I(0)$ variables with a constant term (Begum et al. 2020). As a result of aggregating the leads and lags among explanatory variables, this estimate solves small sample bias, endogeneity, and autocorrelation issues. However, after confirming cointegration among the variables, the study proceeds with

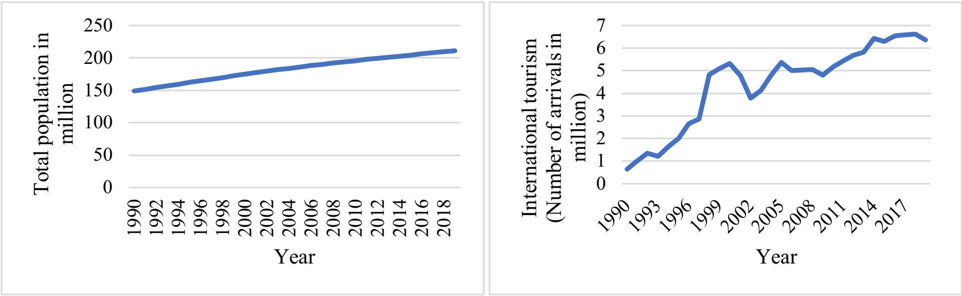
Fig. 1 Annual trends of the study variables in Brazil. **a** CO_2 emissions. **b** Economic growth. **c** Fossil fuel energy use. **d** Renewable energy use. **e** Urbanization. **f** Tourism. **g** Agricultural value-added. **h** Forested area. Source: World Bank (2022)



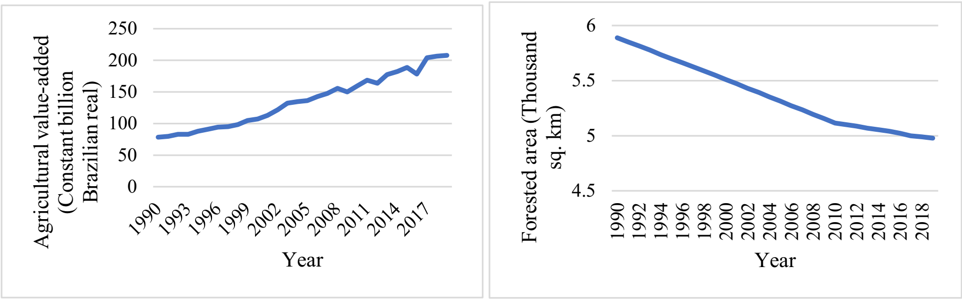
(a) CO_2 emissions (b) Economic growth



(c) Fossil fuel energy use (d) Renewable energy use



(e) Urbanization (f) Tourism



(g) Agricultural value-added (h) Forested area

the DOLS estimation of the long-run coefficient by using Eq. (6).

where Δ is the first difference operator and q is the optimum lag length in Eq. (6).

$$\begin{aligned}\ni^{\cdots}\mathrm{LCO2}_t = {} & \tau_0 + \tau_1\mathrm{LCO2}_{t-1} + \tau_2\mathrm{LGDP}_{t-1} + \tau_3\mathrm{LFFE}_{t-1} + \tau_4\mathrm{LRNE}_{t-1} + \tau_5\mathrm{LURB}_{t-1} + \tau_6\mathrm{LTR}_{t-1} + \tau_7\mathrm{LAVA}_{t-1} \\ & + \tau_8\mathrm{LFA}_{t-1} + \sum_{i=1}^{q}\gamma_1\ni^{\cdots}\mathrm{LCO2}_{t-\mathrm{i}} + \sum_{i=1}^{q}\gamma_2\ni^{\cdots}\mathrm{LGDP}_{t-\mathrm{i}} + \sum_{i=1}^{q}\gamma_3\ni^{\cdots}\mathrm{LFFE}_{t-\mathrm{i}} + \sum_{i=1}^{q}\gamma_4\ni^{\cdots}\mathrm{LRNE}_{t-\mathrm{i}} \\ & + \sum_{i=1}^{q}\gamma_5\ni^{\cdots}\mathrm{LURB}_{t-\mathrm{i}} + \sum_{i=1}^{q}\gamma_6\ni^{\cdots}\mathrm{LTR}_{t-\mathrm{i}} + \sum_{i=1}^{q}\gamma_7\ni^{\cdots}\mathrm{LAVA}_{t-\mathrm{i}} + \sum_{i=1}^{q}\gamma_8\ni^{\cdots}\mathrm{LFA}_{t-\mathrm{i}} + \varepsilon_t\end{aligned} \tag{6}$$

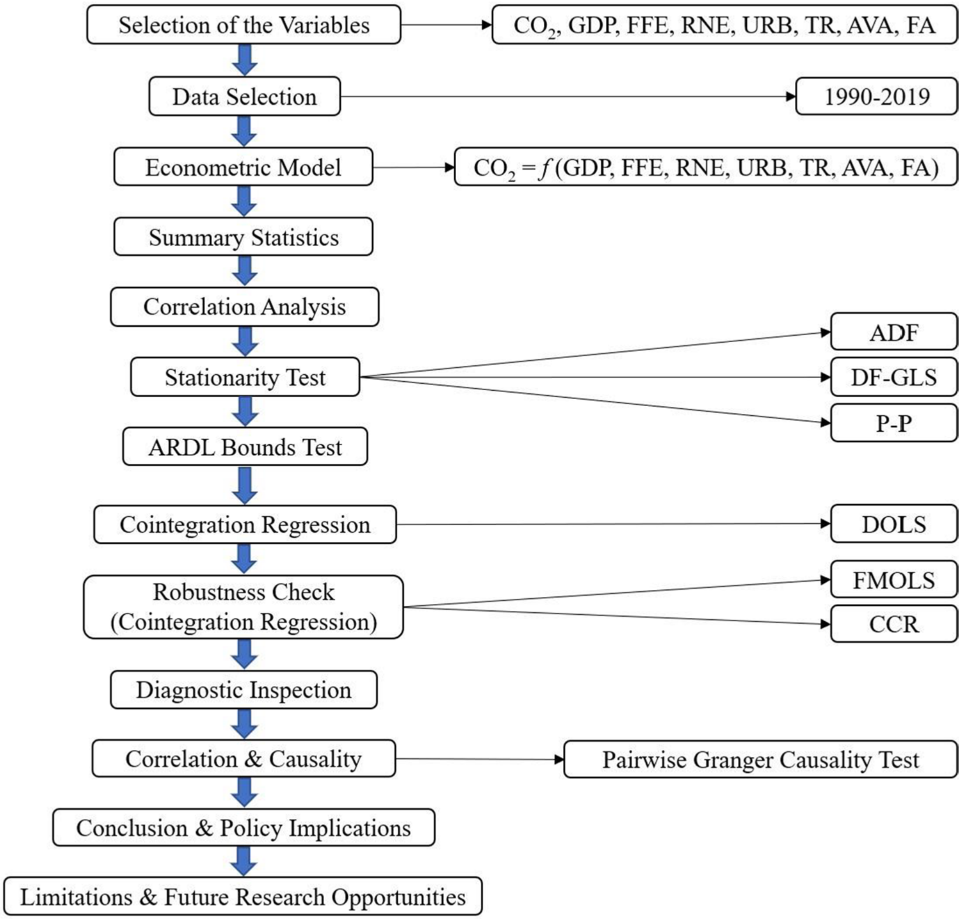


Fig. 2 Flow chart of the analytical techniques employed in the study

Pairwise Granger causality test

The present research intends to capture the causal effects between the variables. Therefore, we utilize the pairwise Granger causality test proposed by Granger (1969) to examine if there is a causal association between the variables. Granger causality is a statistical concept of causation based on a prediction that has several advantages over other time series research approaches and is therefore used in this study. If a time series Y can help predict the future of another time series X, then Y "Granger-causes" X. The time series of these two variables have data length T, denoting their values at time t by X_t and Y_t $(t=1,2,\ldots,T)$, respectively. However, X_t and Y_t can be modeled by a bivariate autoregressive model:

$$X_t = \sum_{l=1}^{p} \left(a_{11,l}X_{t-1} + a_{12,l}Y_{t-1}\right) + \varepsilon_t \tag{7}$$

$$Y_t = \sum_{l=1}^{p} \left(a_{21,l}X_{t-1} + a_{22,l}Y_{t-1}\right) + \xi_t \tag{8}$$

where p is the model order, $a_{ij,1}$ $(i,j=1,2)$ are coefficients of the model, and ε_t and ξ_t represent residuals. Ordinary least squares can estimate the coefficients, and the Granger causality between X and Y can be detected by F tests.

Empirical findings

Summary statistics

The outcomes of the summary measures amid variables are shown in Table 2 with the statistical values of different normality tests (skewness, probability, kurtosis, and Jarque–Bera) used. Each variable includes 30 observations of time series data from 1990 to 2019 for Brazil. The skewness values close to zero imply that all the variables adhere to normality. Furthermore, the research employed kurtosis to evaluate if the series is light-tailed or heavy-tailed relative to normal distribution. The empirical findings indicate that all the series are platykurtic as their values are less than 3. In addition, the smaller values of the Jarque–Bera probability reveal that all the parameters are normal.

Table 2 Summary statistics of the variables

Variables	LCO2	LGDP	LFFE	LRNE	LURB	LTR	LAVA	LFA
Mean	12.709	28.762	24.037	21.368	19.020	15.318	25.587	15.494
Median	12.703	28.754	23.996	21.365	19.036	15.429	25.632	15.489
Maximum	13.136	29.081	24.337	21.459	19.168	15.706	26.060	15.588
Minimum	12.197	28.369	23.728	21.274	18.820	14.504	25.085	15.421
Std. Dev	0.2834	0.2550	0.1891	0.0504	0.1054	0.3285	0.3160	0.0549
Skewness	− 0.2499	− 0.1337	0.1152	− 0.0088	− 0.3648	− 0.7729	− 0.1215	0.2240
Kurtosis	2.0418	1.5968	1.9873	2.0523	1.9214	2.5281	1.6790	1.6599
Jarque–Bera	1.4598	2.5505	1.3484	1.1230	2.0839	2.2654	2.2550	2.4946
Probability	0.4820	0.2794	0.5096	0.5704	0.3528	0.1954	0.3238	0.2871
Sum	381.26	862.86	721.12	641.04	570.59	459.54	767.62	464.82
Sum Sq. Dev	2.3302	1.7410	1.0370	0.0738	0.3221	3.1299	2.8960	0.0876
Observations	30	30	30	30	30	30	30	30

DOLS outcomes

The outcomes of the DOLS estimated by using Eq. (6) are presented in Table 3. When other variables are held constant, the predicted long-run coefficient of LGDP is positive and significant at a 1% level, implying that a 1% rise in economic growth will result in a 0.54% increase in CO_2 emissions. This finding reveals that economic growth triggers environmental degradation in the long run. Moreover, the estimated long-run coefficient of LFFE is positive and significant at a 5% level, which reveals that an increasing 1% of fossil fuel energy use is linked with a rising of 0.20% CO_2 emissions in Brazil. Furthermore, the estimated coefficient of renewable energy use is negative and significant at a 1% level, indicating that increased use of renewable energy by 1% is associated with reducing CO_2 emission by 1.04% in the long run. This reveals the emission reduction potential of expanding the use of renewable energy in Brazil. However, the estimated long-run coefficient of LURB is positive and significant at a 10% level, implying that a 1% rise in urbanization results in a 0.33% increase in CO_2 emissions. This indicates that urbanization is also responsible for environmental degradation in Brazil which is responsible for higher energy consumption, deforestation, and land use change. In addition, the estimated long-run coefficient of LTR is positive and significant at the 1% level, which specifies that an increase in tourism activities by 1% is associated with a 0.06% increase in CO_2 emissions in the long run. The outcome reveals that while boosting the economic growth in Brazil, tourism development deteriorates the environmental quality by increasing the consumption of fossil fuels. Nevertheless, the estimated coefficient of agricultural value-added

Table 3 The outcomes of DOLS: dependent variable LCO2

Variables	Coefficient	Standard error	*t* statistic	*p* value
LGDP	0.538672***	0.148264	3.633184	0.0015
LFFE	0.199299**	0.083424	2.388992	0.0259
LRNE	− 1.041053***	0.200849	− 5.183262	0.0000
LURB	0.326114*	0.691986	0.471273	0.0642
LTR	0.059361***	0.013701	4.332602	0.0003
LAVA	0.074497**	0.060261	1.236240	0.0294
LFA	− 1.563837***	2.033105	− 0.769186	0.0045
C	42.28742	53.58662	0.789141	0.4385
R^2	0.997246			
Adjusted R^2	0.996369			
Standard error of the estimate	0.017080			
Long-run variance	0.000543			
Mean of the dependent variable	12.72637			
F-statistic	558.4065			
Prob (*F*-statistic)	0.000000			
Root mean square error (RMSE)	0.006816			

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

is positive and significant at a 5% level, implying that a 1% increase in agricultural value-added results in a 0.07% rise in CO_2 emissions. This reveals that an increasing trend of agricultural value-added degrades the environmental quality due to the excessive use of fossil fuels for machinery, fertilizers and pesticides for increasing agricultural productivity, pump for irrigation water, and many more. Finally, the estimated long-run coefficient of forested area is negative and significant at a 1% level, which indicates that a 1% reduction of the forested area due to deforestation and forest degradation has an impact of escalating 1.56% of CO_2 emissions in Brazil. This suggests that increasing forested area mitigates CO_2 emissions as the forest ecosystems absorb the atmospheric CO_2 and store it in tree biomass. The result demonstrates that forest ecosystems can be utilized as a tool to keep the environment clean by avoiding deforestation and increasing forest biomass through forest protection and conservation in Brazil.

Moreover, it is noteworthy that the signs of the estimated coefficients are consistent from both a theoretical and a practical standpoint. The present study also used a variety of diagnostic tests to assess the goodness of fit of the estimated model. First, the R^2 and adjusted R^2 values are 0.9972 and 0.9964, respectively, indicating that the calculated regression model fits very well. This means that the independent factors can account for 99% of the variation in the dependent variable's change. Second, the F-statistic indicates that the dependent and independent variables support the calculated DOLS regression. The F-statistic has a p value of 0.0000, indicating that the model's linear relationship is statistically significant. Third, for multiple periods, the root mean square error (RMSE) provides an accurate estimate of model predictions. The RMSE value is 0.0068 (near 0) and non-negative, indicating that the DOLS model's results were a near-perfect fit to the data.

Results of pairwise Granger causality test

The relationship between the variables indicates that there is the existence of Granger causality, which the F-statistic determines. The summary of pairwise Granger causality is presented in Table 4, including the causality direction between the variables, such as unidirectional causality from left to right ($\rightarrow$), unidirectional causality from right to left ($\leftarrow$), bidirectional causality ($\leftrightarrow$) when both variables cause each other, and no causality ($\neq$). The pairwise Granger causality test results indicate that LGDP and LCO2; LFFE and LCO2; LURB and LCO2; LTR and LCO2; LAVA and LCO2; LRNE and LGDP; LTR and LGDP; LFA and LGDP; LAVA and LGDP; LURB and LFFE; and LTR and LFFE show unidirectional causality due to statistical significance leading to the rejection of the null hypothesis. This clearly indicates that economic growth, fossil fuel energy use, urbanization, tourism, and agricultural value-added cause CO_2 emissions; tourism, forested areas, and agricultural value-added cause economic growth while economic growth causes renewable energy use; fossil fuel energy use causes urbanization; and tourism causes fossil fuel energy use in Brazil. Furthermore, the pairwise Granger causality test shows bidirectional causality between LFFE and LGDP; LURB and LGDP; and LTR and LURB which implies that fossil fuel energy use causes economic growth and vice versa; urbanization causes economic growth and vice versa; and tourism causes urbanization and vice versa. Figure 3 illustrates the causal linkage between the examined variables.

Discussion

The present study investigates the relationship between economic growth and environmental pollution in the case of Brazil. The examined result of economic growth shows a positive and significant effect on CO_2 emissions in the long run. According to the findings, increased economic expansion is linked to a decrease in the mitigation of CO_2 emissions in Brazil. The result of this study is supported by Alam et al. (2016), Zambrano-Monserrate et al. (2016), Danish et al. (2019), Jebli and Youssef (2019), Adebayo et al. (2021a), and Adebayo et al. (2021b) who found a positive connection between GDP and CO_2 emissions in Brazil. However, rising economic growth is associated with more societal demands being satisfied through consumption and development activities, leading to increased pollution, waste, and environmental deterioration (Raihan and Tuspekova 2022d). Thus, economic activities appear acceptable for environmental protection and development rather than constituting a danger to long-term environmental quality (Raihan and Tuspekova 2022e). Our finding suggests that Brazil is an energy-dependent country, and its economic growth is critical for supplying the resources required for long-term development. Expanding renewable energy will thus not only boost Brazil's economic growth and mitigate environmental degradation but also provide an opportunity for the country to take a leadership position in the worldwide system and improve its competitiveness with more developed countries. However, the federal government of Brazil launched the Green Growth National Program on 25 October 2021, which is coordinated by the ministries of the environment and economy and aims to link economic growth with sustainable development toward a green and low-carbon economy. The Brazilian Green Growth National Program aims to link economic growth to sustainable development; improve natural capital management to incentivize productivity, innovation, and competitiveness; create green jobs; promote forest conservation and biodiversity; reduce GHG

Table 4 The results of the pairwise Granger causality test

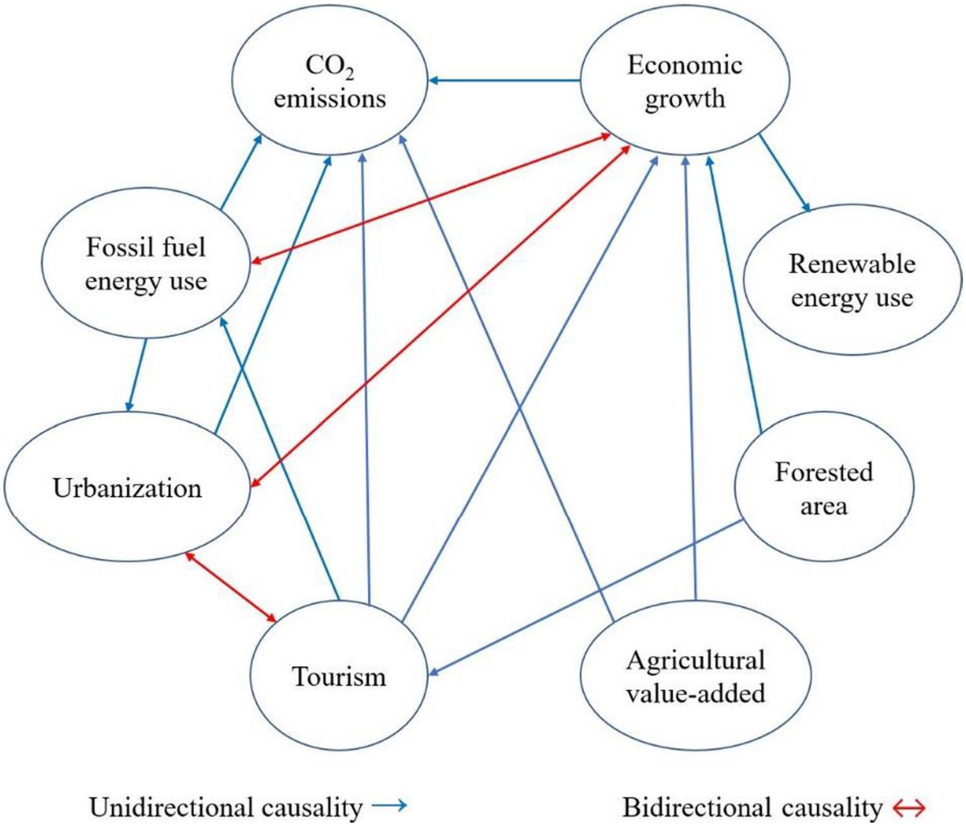
Null hypothesis	*F*-statistic	Decision on *N*-hypothesis	Causality direction
LGDP does not Granger cause LCO2	3.7366**	Reject	LGDP → LCO2
LCO2 does not Granger cause LGDP	3.5515	Accept	
LFFE does not Granger cause LCO2	2.1677*	Reject	LFFE → LCO2
LCO2 does not Granger cause LFFE	0.1008	Accept	
LRNE does not Granger cause LCO2	1.9754	Accept	LRNE ≠ LCO2
LCO2 does not Granger cause LRNE	0.6235	Accept	
LURB does not Granger cause LCO2	3.3661*	Reject	LURB → LCO2
LCO2 does not Granger cause LURB	0.2873	Accept	
LTR does not Granger cause LCO2	3.2344*	Reject	LTR → LCO2
LCO2 does not Granger cause LTR	0.1476	Accept	
LFA does not Granger cause LCO2	0.4522	Accept	LFA ≠ LCO2
LCO2 does not Granger cause LFA	1.5346	Accept	
LAVA does not Granger cause LCO2	2.8392*	Reject	LAVA → LCO2
LCO2 does not Granger cause LAVA	0.9348	Accept	
LFFE does not Granger cause LGDP	3.9304**	Reject	LFFE ↔ LGDP
LGDP does not Granger cause LFFE	2.5987*	Reject	
LRNE does not Granger cause LGDP	0.1416	Accept	LRNE ← LGDP
LGDP does not Granger cause LRNE	3.2348*	Reject	
LURB does not Granger cause LGDP	5.2937**	Reject	LURB ↔ LGDP
LGDP does not Granger cause LURB	7.4887***	Reject	
LTR does not Granger cause LGDP	2.9817*	Reject	LTR → LGDP
LGDP does not Granger cause LTR	0.2479	Accept	
LFA does not Granger cause LGDP	4.5386**	Reject	LFA → LGDP
LGDP does not Granger cause LFA	1.3709	Accept	
LAVA does not Granger cause LGDP	1.8249*	Reject	LAVA → LGDP
LGDP does not Granger cause LAVA	0.0236	Accept	
LRNE does not Granger cause LFFE	0.2833	Accept	LRNE ≠ LFFE
LFFE does not Granger cause LRNE	0.2039	Accept	
LURB does not Granger cause LFFE	1.2039	Accept	LURB ← LFFE
LFFE does not Granger cause LURB	7.6074***	Reject	
LTR does not Granger cause LFFE	2.3541*	Reject	LTR → LFFE
LFFE does not Granger cause LTR	0.6445	Accept	
LFA does not Granger cause LFFE	0.4476	Accept	LFA ≠ LFFE
LFFE does not Granger cause LFA	0.8397	Accept	
LAVA does not Granger cause LFFE	1.6398	Accept	LAVA ≠ LFFE
LFFE does not Granger cause LAVA	0.9384	Accept	
LURB does not Granger cause LRNE	2.2608	Accept	LURB ≠ LRNE
LRNE does not Granger cause LURB	1.4292	Accept	
LTR does not Granger cause LRNE	0.1042	Accept	LTR ≠ LRNE
LRNE does not Granger cause LTR	0.7637	Accept	
LFA does not Granger cause LRNE	0.6547	Accept	LFA ≠ LRNE
LRNE does not Granger cause LFA	0.7543	Accept	
LAVA does not Granger cause LRNE	0.2467	Accept	LAVA ≠ LRNE
LRNE does not Granger cause LAVA	0.4376	Accept	
LTR does not Granger cause LURB	4.12586**	Reject	LTR ↔ LURB
LURB does not Granger cause LTR	5.3449***	Reject	
LFA does not Granger cause LURB	1.3847	Accept	LFA ≠ LURB
LURB does not Granger cause LFA	1.8765	Accept	
LAVA does not Granger cause LURB	0.3243	Accept	LAVA ≠ LURB
LURB does not Granger cause LAVA	2.1233	Accept	

Table 4 (continued)

Null hypothesis	*F*-statistic	Decision on *N*-hypothesis	Causality direction
LFA does not Granger cause LTR	3.0758*	Reject	LFA → LTR
LTR does not Granger cause LFA	0.6531	Accept	
LAVA does not Granger cause LTR	1.7652	Accept	LAVA ≠ LTR
LTR does not Granger cause LAVA	1.4225	Accept	
LAVA does not Granger cause LFA	1.5337	Accept	LAVA ≠ LFA
LFA does not Granger cause LAVA	1.2329	Accept	

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Fig. 3 Granger causality between the examined variables



emissions in order to transition to a low-carbon economy; increase green finance; and increase green research and development.

This study examines the interconnection between energy use and environmental pollution in Brazil. The results of this study emphasize the negative repercussions of fossil fuel consumption as well as the benefits of renewable energy use, with a particular focus on carbon emissions. The examined results of fossil fuel energy consumption point to a positive and significant impact on CO_2 emissions in the long run. The finding indicates that increasing fossil fuel energy consumption degrades Brazil's environmental quality. The scrutinized study result is aligned with the other studies on Brazil by Alam et al. (2016), Zambrano-Monserrate et al. (2016), Adebayo et al. (2021a), and Amarante et al. (2021). This study confirms that Brazil's principal energy source depends on fossil fuels, which are directly responsible for environmental damage. Brazil is an oil and natural gas producing country; thus, the national energy plan that promotes fossil fuel–based economic development is understandable. As a result, industrial and residential activities have a significant negative impact on the environment. Another concern is that fossil fuels are non-renewable energy sources, which means that overexploitation will result in their depletion, and economic development scenarios reliant on fossil fuels would fail. Thus, the most important policy is to establish a sophisticated renewable energy infrastructure that eventually replaces fossil fuels. Brazil has been developing renewable energy technologies for the last few decades, although fossil fuel–based energy output has remained unchanged.

We investigate the potential of renewable energy use to mitigation of CO_2 emissions in Brazil. According to our empirical result, renewable energy usage appears to have a critical role in lowering CO_2 emissions in Brazil. The estimates demonstrate that renewable energy consumption has a negative and significant impact on CO_2 emissions, implying that increasing renewable energy sources in the total energy mix can help Brazil reduce CO_2 emissions. Our finding is consistent with Danish et al. (2019), Jebli and Youssef (2019), Khattak et al. (2020), Adebayo et al. (2021b), and Amarante et al. (2021) who suggest that renewable energy leads to a reduction of CO_2 emissions in Brazil. With climate change looming, employing renewable energy sources for energy production is critical to ensuring sustainable development and mitigating climate change. Renewable energy delivers significant economic advantages in addition to decreasing carbon emissions, such as increased energy availability, improved energy security, and the use of local renewable resources. As a result of rising global environmental awareness, it is critical to shift Brazil's energy balance to renewables in order to enable the use of sustainable energy sources and the development of an environmentally sustainable ecosystem.

Brazil is regarded as the world's first biofuel economy, a biofuel sector leader, and a policy model for other nations. Following the 1970s oil shocks, the Brazilian government has constantly promoted sugarcane ethanol as a renewable energy source (Pao and Fu 2013). Brazil produces the world's second and fourth greatest amounts of ethanol and biodiesel, respectively, and both have been gradually increasing. Between 1975 and 2015, the country maintained a significant sugarcane-derived ethanol program, with 370 industrial units and 950,000 jobs, saving the consumption of 380 billion liters of gasoline (Lima et al. 2020). Moreover, two nuclear reactors produce around 3% of Brazil's electricity. To address the needs of the country's fast-growing economy, the Brazilian government has proposed building two additional nuclear facilities after 2020. Furthermore, in March 2022, Brazil's total installed solar power was anticipated to be around 14 GW, delivering approximately 2.48% of the country's electricity demand, up from 0.7% in 2018. Brazil ranked 14th in the world in terms of installed solar power in 2020 (7.8 GW). Brazil has been promoting renewable energy sources since 2002 when the Programme of Incentives for Alternative Electricity Sources (PROINFA) was established, a program that has significantly increased the use of renewable energy sources in electricity production, particularly wind energy. Furthermore, the Brazilian government has held specific energy auctions for renewable technologies (solar and wind), thus eliminating competition from conventional sources of energy. Solar energy has been developing rapidly recently as a result of a series of public policies encouraging the spread of distributed power.

The scrutinized results of urbanization reveal a positive impact to worsen Brazil's environmental quality in the long run. This demonstrates that the rapid growth of the urban population due to migration to cities from the countryside is threatening environmental sustainability in Brazil. The examined finding by the present study is consistent with the other studies on Brazil, for example, Adebayo et al. (2021a). Our finding suggests that Brazil's urbanization contributed to an increase in energy demand driven by fossil fuel resources, resulting in increased CO_2 emissions. When the roots of CO_2 emissions come from three networks, such as electrical appliance consumption, residential and commercial building development, and transportation, it is not surprising that CO_2 emissions react so dramatically. According to Pata (2018), increased urbanization increases energy demand, which increases GHG emissions and worsens the environment in metropolitan areas. Furthermore, because the urban region is one of the most electricity-intensive areas of the economy, a spike in the demand for electrical appliances (ventilation, appliances, lighting, cooling, and so on) contributed to increasing CO_2 emissions. Adebayo et al. (2021a) reported that urbanization influences economic growth positively which ultimately contributes to CO_2 emissions in Brazil. Hence, Brazil's urban development has become unsustainable.

This research uncovers a significantly positive link between tourism and CO_2 emissions in Brazil, suggesting that increasing tourism activities lead to deterioration in air quality by augmenting environmental degradation in Brazil. Our finding indicates that the rising number of international arrivals of tourists in Brazil increases energy consumption while adversely affecting climate change. Tsai et al. (2014) found that hotels with better service levels emit more CO_2 per guest on average. However, tourism is one of the primary causes of declining environmental health, resulting in CO_2 emissions from not just the transportation sector, but also the generation of power and heat (Ng et al. 2015). Deforestation is one of the most important global environmental consequences of mass tourism development. Moreover, tourism has a biophysical and socio-cultural impact on the environment. Tourism, for example, pollutes the atmosphere by emitting smoke, sulfur dioxide, nitrogen oxides, and other dangerous chemicals. Tourist activities have the potential to harm the natural environment and reduce its appeal. The addition of waste can convert a beautiful location into a dump. Furthermore, tourism contributes greatly to noise pollution, which includes both physical noise and vehicular traffic. In addition, airlines, hotel stays, and motorized water activities are all contributing to the rise in carbon emissions (Raza et al. 2021). As a result, sustainable tourism must be developed in order to mitigate tourism's negative effects on the society, environment, climate, and economy. However, tourism is undeniably crucial for Brazil's economic development, and it should be appropriately supported and developed. Brazil's interest in long-term tourism development is critical since the country is swiftly learning the importance of striking a balance between development and the environment, amid concerns that tourism is putting the country's fragile ecosystem under strain.

Moreover, this research uncovers a significantly positive link between agricultural value-added and CO_2 emissions in Brazil, suggesting that increasing agricultural value-added raises CO_2 emissions in the long run. Furthermore, due to the growth in agricultural value-added, the current study's findings could be explained by the excessive use of fossil fuels for irrigation, fertilizers, and pesticides to increase agricultural productivity. Brazil's agricultural strategy has not been increasingly concerned with long-term development. Ensuring food security with increased agricultural productivity by increasing agricultural value-added has increased deforestation to create more agricultural land, while fossil fuels and chemical fertilizers are being used to increase agricultural production. Brazil has demonstrated that agricultural and environmental challenges are mutually exclusive. The IPCC (2014) reported that achieving the goal of reducing GHG emissions from the agriculture sector would not only result in a cleaner environment but will also provide new sources of income as more farming operations may be carried out. Carbon release may be stored by agricultural operations when proper management and technology are used, resulting in a reduction in carbon footprint. Various international organizations have recently established climate-smart agriculture (CSA) approach to aid in the transformation of agri-food systems to green and climate-resilient methods. The CSA is dedicated to accomplishing internationally agreed-upon goals, such as the SDGs.

Our investigation reveals that forested area has a negative impact on CO_2 emissions in Brazil. Thus, it confirms that reducing the forested area through deforestation increases CO_2 emissions and contributes to global climate change. Instead, forest ecosystems mitigate CO_2 emissions from Brazil's environment as the forests absorb the atmospheric CO_2 and store it in tree biomass. Our empirical finding indicates that enhancing forest carbon sink by increasing forested area mitigates environmental degradation in the long run. As the second-biggest source of anthropogenic CO_2 emissions into the atmosphere, forest loss has been considered a driver of environmental deterioration (IPCC 2014). Hence, controlling deforestation could be the simplest way to reduce CO_2 emissions. According to Raihan et al. (2019), the most cost-effective method to prevent environmental degradation and ameliorate global climate change is to increase forest carbon sequestration. However, between 2005 and 2013, Brazil managed to reduce deforestation rates by 70%, resulting in an estimated reduction of 3.2 Gt of CO_2 emissions (Zambrano-Monserrate et al. 2016). Reversing forest losses via restoration, enhancement, and conservation is a crucial aim for climate change mitigation, and it is a hot topic in today's climate debate. Implementing cost-effective mitigation strategies in the forestry sector to prevent deforestation and forest degradation can reduce global carbon emissions and avert climate change at the lowest cost (Raihan et al. 2018). Furthermore, forestry-based mitigation strategies (forest protection, afforestation, natural regeneration) would serve a multifunctional purpose, including carbon sequestration, biodiversity conservation, ecosystem enhancement, and community outputs of goods and services (Raihan and Said 2021). The Brazilian forestry sector has a huge potential to mitigate global climate change by reducing CO_2 emissions and increasing forest biomass while also increasing the country's carbon sink through the widespread implementation of forestry-based mitigation measures. As a result, improving forested land can be a useful measure for reducing Brazil's carbon emissions.

Conclusion and policy implications

Conclusion

The present study empirically investigates the dynamic impacts of economic growth, fossil fuel energy use, renewable energy use, urbanization, tourism, agricultural value-added, and forested area on CO_2 emissions in Brazil by utilizing time series data from 1990 to 2019. The DOLS outcomes reveal that economic growth, fossil fuel energy use, urbanization, tourism, and agricultural value-added cause environmental degradation by increasing CO_2 emissions in Brazil while increasing renewable energy and forested areas help to mitigate CO_2 emissions in Brazil. In addition, the pairwise Granger causality test is utilized to capture the causal linkage between the variables. This research contributes to the existing literature by shedding light on the determinants of environmental degradation in Brazil. This article put forward policy recommendations toward environmental sustainability through the mitigation of CO_2 emissions by establishing strong regulatory policy instruments to reduce environmental degradation.

Policy implications

Our research suggests that the policymakers in Brazil prepare an environmental policy that reduces CO_2 emissions without jeopardizing economic growth. In Brazil, the greatest strategic choice for combating climate change is a low-carbon economy. To avoid pollution at the source, the "pollute first, then treat" strategy might be altered, and the economic development mode at the expense of the environment could be transformed. In this regard, we recommend the government assist markets by building a robust legislative framework that generates long-term value for emission reductions and continually promotes innovative technologies that lead to an economy that is less carbon-intensive. In addition, the Brazilian government can set up some regulations, such as a high carbon tax, carbon capture, carbon storage, and emission trading schemes to reduce CO_2 emissions from fossil fuel use in power generation and industry. To achieve the effect of decoupling at the regional level, significant changes are required in a centralized state policy, patterns of behavior, and the pace of scientific and technological progress. Brazil might shift its focus from extensive to intensive growth and alter its economic development pattern by focusing not only on economic output but also on improving the green economy. In addition, fostering the economic transition to renewables is critical for reducing the environmental pressures caused by economic development. Renewable energy companies and technology could also be encouraged and promoted by policymakers. By displacing CO_2-intensive conventional energy sources, these measures would assist the economy in increasing the percentage of renewable energy consumption in overall energy consumption. In addition, institutional alignment is required to encourage renewable energy consumption across economic activities and assure long-term economic growth.

Brazil's long-term prosperity could be enhanced by developing and implementing effective regulations to control the country's industrial sector practices. To optimize the energy usage structure, the current study recommends that more clean energy or renewable energy be used. Brazil's energy usage structure is still dependent on traditional high-carbon energy sources like oil, natural gas, and coal. An increase in renewable energy usage would have a long-term impact on CO_2 emissions and industrialization. Renewable energy is abundant in Brazil, but promotion is hindered by higher costs. Brazil may develop policies to reduce the cost of renewable energy and discourage the use of fossil fuels in industries, businesses, and households. Regulatory policies may be established to promote renewable energy and mitigation of CO_2 emissions. The authorities would also promote energy-efficient home appliances and more affordable renewable energy sources for the household sector. The government could devise and implement effective policies to promote investment in new renewable energy technologies, thereby increasing renewable energy consumption. For example, the government may invest in renewable energy projects through public–private partnerships. In addition, Brazil may be able to create technical assistance networks with other countries while also proactively growing its renewable resources. Furthermore, local governments and non-governmental organizations (NGOs) may work to raise environmental consciousness among people of all ages by sharing information on green energy technology and energy efficiency. This can be accomplished through school and university-based training and instructional programs. In addition, performance labeling, commercials, conferences, seminars, and public awareness initiatives can all be beneficial. The government might use the media to promote its green lifestyle concept and campaign for low-carbon lifestyles and consumption habits. Since Brazil is still a developing economy, if cleaner energy is more expensive, the public will prefer cheaper energy, even if it results in higher carbon emissions. Tax incentives, financial subsidies, and government procurements are all examples of fiscal measures that the government might use to encourage people to switch to cleaner energy.

Furthermore, policymakers could create regulations to design and offer environmental urban and smart development technologies, as people cannot live in hazardous and contaminated regions. It becomes vital for the Brazilian government to focus efforts on the designing, improvement, and promotion of green and sustainable urbanization which would lead to the improvement and maintenance of economic progress without any ecological mortification. In addition, the ongoing development of the health conditions of urban people and the effective design of comprehensive land use and suitable infrastructure with efficient consumption of energy through technology innovation might be accomplished. Urbanization deteriorates the ecosystem, which raises the need for urban development planning via energy efficiency improvements, deploying innovative technology, and supporting sustainable lifestyles. Therefore, policymakers may encourage sustainable, green urbanization to limit the likelihood of environmental damages, thereby enhancing the influence of renewables on subsequent urbanization, including the usage of electric vehicles, solar lights, and ethanol for cars. Utilizing renewable energy and energy efficiency appliances and office equipment can reduce energy consumption and CO_2 emissions in the metropolitan area. Thus, sustainable urbanization and the popularization of renewable energy could be fostered by the government of Brazil. The government may work hand in hand with NGOs and educational institutions to improve public awareness of renewable energy and a clean environment in metropolitan areas. In addition, green vegetation in the form of tree planting is another strategy to reduce CO_2 emissions and cool the urban environment due to its potential to absorb around 1000 kg of CO_2 per tree. The present study suggests that government needs to invest more in public amenities and green technologies to enhance emission reduction in the urban region. Financial institutions must play a role by (i) assisting building developers in the construction of green buildings, allowing such buildings to be widely available in the market; and (ii) assisting private citizens in renovating their homes and changing the existing building envelope to meet green criteria. However, attention is needed to maintain a balance between rural and urban people to avoid drift to urban centers and overpressure on urban infrastructures. Therefore, the government may encourage people to forsake megacities, such as São Paulo and Rio de Janeiro, and select middle-sized and small cities (MSCs). In addition, the government might stimulate the location of industries and generation of employment in rural equivalents. Such methods can promote the cities' general economic growth, relieve the burden on megacities, and improve the vitality of MSCs. Finally, policymakers may also offer methods such as carbon taxes, emissions trading systems, and carbon capture and storage for diverse urban activities in Brazil.

The study's findings on environmental degradation as a result of tourism development highlight the need for a novel approach and concentrate on green tourism that promotes long-term sustainability. Adequate and proper legislation would support tourism activities in terms of economic development while also encouraging energy conservation and environmental protection. Providing subsidized green public transportation, tax incentives, or rebates for taxpayers who provide high-energy efficiency tourism-related facilities is one example. The government might also set an example by installing energy efficiency measures into buildings and facilities at the most-visited tourist attractions, which would provide them with each opportunity to save money on energy. Hotels and restaurants should not consume more energy than is required, and the energy may be obtained from environmentally acceptable sources. The Brazilian government may establish a structure that holds locals, tourists, and other stakeholders accountable for their actions in relation to the natural environment of the country's tourist hotspots. By encouraging all tourist stakeholders to go green and embrace sustainability in their operations, visitors would not only have a better overall experience but would also be better educated. Aside from information brochures and flyers, public service announcements with clear infographics could be distributed to the general public as frequently as possible, along with updates on the authorities' efforts and progress on going green, encouraging them to be aware of the importance of energy conservation, environmental sustainability, and mitigation of CO_2 emissions and to embrace green practices even while on vacation. Furthermore, technological innovation in transportation must be bolstered, such as the use of energy-efficient airplanes, high-speed trains, and electric vehicles. CO_2 emissions can be reduced by renovating public transportation as a result of increased tourism, as well as investing in energy efficiency and waste management. Additionally, to protect the environment in commonly visited tourist destinations, the government may impose and enforce environmental levies. Moreover, the government might make it simpler for businesses to employ green and low-carbon technologies, as well as alternative energy sources, for transportation, logistics, accommodation, and other tourism-related operations, lowering CO_2 emissions and minimizing natural resource overexploitation. Other options include investing in adequate equipment to monitor and regulate the use, installing energy-saving lighting, environmentally friendly air conditioning, minimizing water use, and heating with efficient boilers. Brazil might strengthen its existing environmental policies and shine a light on other developing countries where tourism is causing environmental degradation. Governments in the South American region ought to join hands and work together to implement effective actions for sustainable tourism, which might include ecotourism, educational tourism, recreational and adventure tourism, and cultural tourism.

This study suggests the policymakers of Brazil design effective policies for the mitigation of CO_2 emissions while increasing agricultural productivity. Increased efforts are needed for sustainable agricultural productivity by introducing modern agro-based technology including high-yield and disease-resistant crop varieties, as well as persuading farmers to reject old farming practices in favor of more advanced agrarian approaches. Moreover, agricultural value-added components may be improved at a greater level with the help of contemporary agricultural technology and the availability of good seeds and other agricultural inputs. Sustainable agriculture may minimize emissions and increase carbon sequestration by establishing organic and low-carbon agriculture systems. To accomplish long-term agricultural value-added, the government might encourage more efficient energy infrastructure and support the switch to cleaner, more efficient energy sources in agriculture. The government could support the use of renewable energy, particularly clean renewable energy like wind, solar, and biofuel because it boosts agricultural value-added while also helping to battle global warming and climate change. Subsidies for renewable energy use in agriculture would help the industry become more competitive in worldwide markets while emitting less pollution. For a carbon–neutral environment, irrigation methods can be switched from non-renewable to renewable energy sources. Other important agricultural changes include encouraging farming people to use solar tube wells for irrigation, organic farming, tunnel farming, changing traditional tillage to no-till, and reducing fertilizer use to decrease environmental impact. These contemporary agriculture technologies can help large farms cut personnel, improve productivity, and cut emissions. Excessive use of fertilizers and pesticides must be avoided, and green production must take precedence for the sake of sustainable agriculture and pollution reduction. The agriculture industry may have a significant positive impact on the environment by using an organic framework. Furthermore, boosting agricultural investment in Brazil through improved international collaboration would aid in the reduction of emissions from Brazil's agriculture sector while increasing agricultural value-added.

Furthermore, the findings of our analysis suggest that Brazilian policymakers undertake effective environmental and climate-resilient policies, with a particular focus on reducing CO_2 emissions through the expansion of forested areas. The interest of attaining sustainable development through sustainable forest management, which helps to maintain environmental quality as well as social and economic advantages from forests, could be considered in Brazilian forestry policy. Therefore, appropriate planning of forest management and ambitious policy implementation could be taken into consideration. In partnership with state governments, a special focus on greening Brazil might be given through strengthening forest conservation via reforestation and restoration of degraded forest regions. The Brazilian government might boost financial investment by enacting strong forest regulations to reduce CO_2 emissions by avoiding deforestation and increasing forest biomass through forest protection and conservation. Furthermore, the government may raise public awareness about the consequences of deforestation and the significance of preserving forests to increase forest biomass. Furthermore, by establishing private forest plantation areas, the government may stimulate private investment in forest development. Brazil may also engage with foreign organizations to generate investments in GHG emission reduction projects through reducing emissions from deforestation and forest degradation (REDD +) and clean development mechanism (CDM). Brazil can also improve its climate change mitigation potential by implementing a large number of forestry-based mitigation initiatives. For example, afforestation, reforestation, forest conservation, sustainable forest management, enhanced natural regeneration, agroforestry, urban forestry, and wood-based bioenergy are anticipated to be more efficient and cost-effective ways to reduce CO_2 emissions by increasing the forest carbon sink. Finally, actual forestry policy enforcement might assist Brazil in becoming an emission-free country by enhancing the national carbon sink while ensuring national green growth and sustainable forest management.

Limitations and future research opportunities

Though the present study has produced substantial empirical outcomes in the case of Brazil, the analysis has several limitations that might be addressed in future research. The unavailability of data on renewable energy consumption, tourism, and forest area outside its study period limited the analytical capacity of the econometric methodologies applied. This study has explored the dynamic interaction of economic growth, fossil fuel energy use, renewable energy use, urbanization, tourism, agricultural value-added, and forested area on CO_2 emissions in Brazil utilizing current time series data. Further research might be undertaken for other developing countries while utilizing different econometric modeling or the usage of micro-disaggregated data. Moreover, future research can account for other growth determinants that have not been addressed in this study, such as trade openness, financial development, foreign direct investments, industrialization, institutional quality, globalization, and technological innovation. However, this study utilized CO_2 as an indicator of environmental degradation. Further studies could be conducted by utilizing consumption-based carbon emissions as a proxy for environmental degradation, or other measures of environmental emissions such as nitrous oxide (N_2O) and sulfur dioxide (SO_2), methane (CH_4), carbon monoxide (CO), ground-level ozone (O_3), hydrogen sulfide (H_2S), and other short-lived climate forces (SLCF) to improve the overall environmental quality in Brazil. Nevertheless, CO_2 emission is utilized as a representation of environmental degradation in the present study, which is not the only cause of environmental pollution. More environmental pollution indicators, such as water pollution and land pollution, could be included in future research for the case of Brazil to investigate this interconnection. Furthermore, future research can compare country-specific results to overall panel outcomes utilizing advanced econometric approaches, in addition to panel estimations. These could provide useful comparisons with the findings of this study, shedding light on the relevant literature.

Appendix 1

Correlation between the variables

The results of the correlation analysis revealed that all the variables are correlated to one another. LCO2, LGDP, LFFE, LURB, LTR, and LAVA indicate a strong and positive correlation with each other which implies that when the value of one variable rises, the value of the other tends to rise as well and vice versa. Nevertheless, LRNE and LFA show a negative correlation with LCO2, LGDP, LFFE, LURB, LTR, and LAVA which reveals that when the values of the LRNE and LFA rise, the values of LCO2, LGDP, LFFE, LURB, LTR, and LAVA tend to drop and vice versa. Furthermore, LRNE and LFA show a positive correlation with each other which indicates that when the value of renewable energy use rises, the value of the forested area tends to rise as well and vice versa (Table 5).

Table 5 The results of the correlation analysis

	LCO2	LGDP	LFFE	LRNE	LURB	LTR	LAVA	LFA
LCO2	1.0000	0.9764	0.9787	−0.5166	0.9763	0.8791	0.9626	−0.9723
LGDP	0.9764	1.0000	0.9508	−0.3418	0.9807	0.8477	0.9793	−0.9908
LFFE	0.9787	0.9508	1.0000	−0.5084	0.9506	0.8560	0.9437	−0.9465
LRNE	−0.5166	−0.3418	−0.5084	1.0000	−0.3747	−0.3847	−0.3092	0.3235
LURB	0.9763	0.9807	0.9506	−0.3747	1.0000	0.8856	0.9913	−0.9960
LTR	0.8791	0.8477	0.8560	−0.3847	0.8856	1.0000	0.8696	−0.8767
LAVA	0.9626	0.9793	0.9437	−0.3092	0.9913	0.8696	1.0000	−0.9936
LFA	−0.9723	−0.9908	−0.9465	0.3235	−0.9960	−0.8767	0.8696	1.0000

Stationarity techniques for data

Avoiding spurious regression necessitates the use of a unit root test. It checks that variables in regression are stationary by differencing them and using stationary processes to estimate the equation of interest. The empirical literature acknowledges the need to define the sequence of integration before looking into cointegration among variables. According to some studies, it is critical to use more than one unit root test to evaluate the integration order of the series since unit root tests have different potency depending on the sample size. To detect the autoregressive unit root, we used the Augmented Dickey-Fuller (ADF) test proposed by Dickey and Fuller (1979), the Dickey-Fuller generalized least squares (DF-GLS) test proposed by Elliott et al. (1992), and the Phillips-Perron (P-P) test proposed by Phillips and Perron (1988). The unit root test was used in this study to ensure that no variable exceeded the order of integration and to support the use of the DOLS technique over traditional cointegration methods. The findings demonstrate that all of the variables were non-stationary at the level but became stationary at the first difference in all three unit root tests. Thus, the unit root results imply that the variables have a common order of integration at first difference. As a result, all of the variables included in the empirical studies are mean-reverting, eliminating the potential of a misleading regression analysis (Table 6).

ARDL bounds test for cointegration

We applied the ARDL bounds test proposed by Pesaran et al. (2001) to capture the cointegration among the series. The ARDL bounds test for cointegration valuation has many advantages over the other one-time integer methods. Firstly, it can be utilized when series have a mixed order of integration as the ARDL bounds test does not have obligatory assumptions, and all variables must be incorporated in the same order in the analysis. Secondly, it is significantly more reliable, particularly for a small sample size. Thirdly, it offers an accurate estimation of the long-term model. Therefore, the ARDL bounds testing approach can be used irrespective of whether the fundamental returning system is in sequence to a part in the $I(2)$, and the cointegration order happens at $I(0)$ or $I(1)$. The ARDL bounds test is depicted in Eq. (6).

The *F*-distribution is followed by the ARDL bounds test, and its critical values were proposed by Pesaran and Timmermann (2005). The estimating technique starts with Eq. (6) and employs OLS to allow the *F*-test to evaluate the joint significance of the lagged variables' coefficients. The goal of this technique is to see if there is any chance of a long-term association between the variables. The null hypothesis (H_0) reveals no cointegrating relationships among the regressors in this case. As in Pesaran et al. (2001), the *F*-statistics can be compared to the critical values of the upper and lower bounds. The null hypothesis is

Table 6 The results of unit root tests

Logarithmic form of the variables	ADF		DF-GLS		P-P	
	Log levels	Log first difference	Log levels	Log first difference	Log levels	Log first difference
LCO2	−1.2017	−4.5228***	0.1051	−4.5023***	−1.1965	−4.5207***
LGDP	−1.3563	−3.6808**	−0.2790	−3.6436***	−1.2383	−3.6591**
LFFE	−0.6460	−5.9122***	0.2486	−6.0108***	−0.6460	−5.9087***
LRNE	−2.1994	−3.7610***	−1.5949	−3.6256***	−2.1994	−2.7771***
LURB	−0.2578	−3.1681**	−0.2303	−2.1456***	−1.47751	−5.0969***
LTR	−0.8629	−3.2453**	−0.5011	−3.9216***	−1.2186	−3.9876***
LAVA	−0.6701	−8.0429***	0.2933	−7.5651***	−0.6504	−9.0337***
LFA	−0.7856	−1.9708*	−0.8565	−1.9818*	−0.7856	−2.4682*

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 7 Findings from cointegration with ARDL bounds testing

F-bounds test		Null hypothesis: no levels of relationship		
Test statistic	Value	Significance	*I*(0)	*I*(1)
Value of *F*-statistic	5.476452	At 10%	1.92	2.89
K	7	At 5%	2.17	3.21
		At 2.5%	2.43	3.51
		At 1%	2.73	3.90

rejected if the *F*-statistics are higher than the upper critical value, indicating the existence of a long-run association between the variables. The null hypothesis, on the other hand, is accepted if the *F*-statistics are smaller than the lower critical value. The test is inconclusive if the *F*-statistics are observed within the lower and higher critical values. This study used an appropriate lag duration to calculate the *F*-statistic, which was based on the lowest values of Akaike's Information Criterion (AIC). The results of the ARDL bounds test are presented in such a way that if the estimated value of the *F*-test is greater than the values of both limits, the existence of a long-run relationship between the parameters is confirmed (lower and upper bound). The findings reveal that the estimated *F*-statistic value (5.476452) is higher than 10%, 5%, 2.5%, and 1% of the crucial upper limit in the order zero and one which rejects the null hypothesis by indicating that a long-run relationship exists among the respective variables (Table 7).

FMOLS and CCR cointegration regression to check the robustness of DOLS estimation

We utilized the fully modified OLS (FMOLS) and canonical cointegrating regression (CCR) to verify the robustness of DOLS outcomes. The FMOLS regression was developed by Hansen and Phillips (1990) to incorporate the best cointegrating regression estimates. The FMOLS approach modifies least squares to account for the serial correlation effects and endogeneity in the independent variables that result from cointegrating. The FMOLS approach uses typical regression techniques (OLS) for nonstationary (unit root) data to help with false regressions. Furthermore, Park (1992) introduced the CCR method, which entails data transformation using only the stationary component of a cointegrating model. After such data transformation, a cointegrating link provided by the cointegrating model will stay unaffected. In a cointegrating model, the CCR transformation makes the error term uncorrelated with regressors at zero frequency. As a result, the CCR approach produces asymptotically efficient estimators as well as nuisance parameter-free asymptotic chi-square tests (Raihan and Tuspekova 2022f). By analyzing the influence of serial correlation, asymptotic coherence can be obtained using FMOLS and CCR approaches. Therefore, long-term elasticity is assessed using the FMOLS and CCR estimators, as shown in Eq. (6).

The outcomes of FMOLS and CCR provide evidence of the robustness of the DOLS estimation. The FMOLS and CCR results confirmed the coefficients of economic growth, fossil fuel energy use, urbanization, tourism, and agricultural value-added are positive and significant. In addition, the results further validated the significant inverse relationship between renewable energy use and forested area with CO_2 emissions. Hence, it can be stated that economic growth, fossil fuel energy use, urbanization, tourism, and agricultural value-added cause environmental degradation by increasing CO_2 emissions in Brazil while increasing renewable energy use and forested areas help to mitigate CO_2 emissions in Brazil. The results of the FMOLS and CCR are duly in line with the findings from DOLS outcomes. The R^2 and adjusted R^2 values from FMOLS and CCR estimation reflect the model's goodness of fit, demonstrating that the independent variables can account for 99% of the variation in the dependent variable's change (Tables 8 and 9).

Table 8 The results of FMOLS: dependent variable LCO2

Variables	Coefficient	Standard error	*t* statistic	*p* value
LGDP	0.516077***	0.077469	6.661736	0.0000
LFFE	0.212958***	0.033604	6.337285	0.0000
LRNE	– 1.022964***	0.062168	– 16.45494	0.0000
LURB	0.282900**	0.326405	0.866714	0.0396
LTR	0.055228***	0.010159	5.436361	0.0000
LAVA	0.065897**	0.046323	1.422547	0.0169
LFA	– 1.619991***	0.919093	– 1.762598	0.0095
C	42.55410	23.02354	1.848286	0.1787
R^2	0.996887			
Adjusted R^2	0.995849			
Standard error of the estimate	0.017475			

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Table 9 The results of CCR: dependent variable LCO2

Variables	Coefficient	Standard error	*t* statistic	*p* value
LGDP	0.492853***	0.106082	4.645972	0.0001
LFFE	0.220694***	0.042132	5.238142	0.0000
LRNE	– 1.028072***	0.074915	– 13.72310	0.0000
LURB	0.333991**	0.364660	0.915896	0.0371
LTR	0.052774***	0.012304	4.289060	0.0003
LAVA	0.057091**	0.064563	0.884270	0.0386
LFA	– 1.858594***	1.236155	– 1.503528	0.0076
C	48.07720	30.22738	1.590518	0.1267
R^2	0.996870			
Adjusted R^2	0.995827			
Standard error of the estimate	0.017521			

***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

Diagnostic inspection

We performed normality, heteroscedasticity, and serial correlation analysis to verify the intensity of the cointegration valuation. The model indicates normality and nonexistence of autocorrelation and heteroscedasticity. In addition, we employed the cumulative sum of recursive residuals (CUSUM) and cumulative sum of squares of recursive residuals (CUSUMQ) test to check the stability of the model. The CUSUM and CUSUMQ plots at a 5% significance level are presented in the following figure (Fig. 4). The values of the residuals are represented by blue lines, while the confidence levels are represented by red lines. At a 5% significance level, the calculated results show that the studied residuals' values remain within the lines of confidence, which confirms the model's stability (Table 10, Fig. 4).

Table 10 The results of diagnostic tests

Diagnostic tests	Coefficient	*p* value	Decision
Jarque–Bera test	2.084606	0.3526	Residuals are normally distributed
Lagrange Multiplier test	1.274041	0.1634	No serial correlation exits
Breusch-Pagan-Godfrey test	1.882076	0.1215	No heteroscedasticity exists

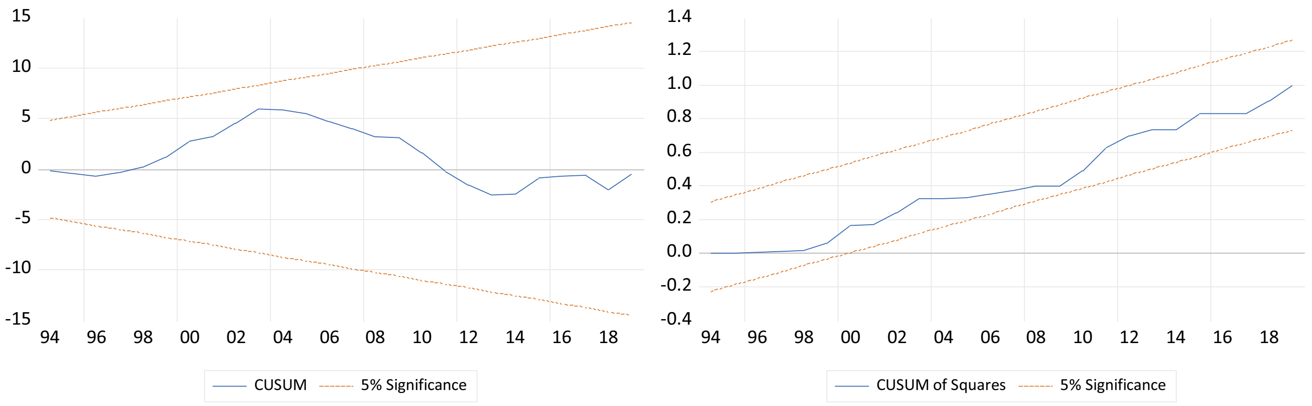


Fig. 4 The plots of CUSUM and CUSUM of squares (critical bounds at 5% significance level)

Data availability All data generated or analyzed during this study are available here: https://databank.worldbank.org/source/world-development-indicators.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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