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The contribution of economic development, renewable energy, technical advancements, and forestry to Uruguay's objective of becoming carbon neutral by 2030

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Abstract

Uruguay has set a target of becoming carbon neutral by the year 2030, and this study looks into the role that economic progress, renewable energy utilization, technological innovations, and forest extent could play in reaching the goal. The Dynamic Ordinary Least Squares (DOLS) technique was applied to examine time series data from 1990 to 2021. According to the outcomes of the DOLS estimation, a one-percentage-point boost in economic growth is associated with a 1.16% increase in CO_2 emissions. However, increasing the use of renewable energy by 1% is related to a reduction in CO_2 emissions of 0.73 percent over the long run, as indicated by the coefficient of renewable energy being negative and statistically significant. The calculated long-run coefficient of technological innovations is negative and statistically significant, suggesting that a 1% increase in technological innovation causes a 0.11% cut in CO_2 emissions. The long-run coefficient of forest area is notably negative and significant, which means that expanding forest area by 1% lessens CO_2 emissions by 0.56%. The empirical results show that as Uruguay's economy grows, so do its CO_2 emissions, but the country may get closer to its goal of carbon neutrality through the growing use of renewable energy, technological innovation, and sustainable forest management. The robustness of the outcomes was verified by utilizing the fully modified least squares (FMOLS) and canonical cointegrating regression (CCR) techniques. In order for Uruguay to reach its goal of carbon neutrality by 2030, this article offers policy ideas centered on a low-carbon economy, promoting renewable energy utilization, financing of technological innovations, and sustainable forest management.

Highlights

- Rapid emission reduction is essential to achieve Uruguay's goal of carbon neutrality by 2030.
- This research investigated the effects of potential emission reduction elements in Uruguay.
- Dynamic Ordinary Least Squares approach was employed by utilizing time series data.
- The results shed new light on renewable energy, technological innovations, and forests in Uruguay.
- This article offers policy suggestions to achieve net zero emissions.

Keywords Carbon neutrality, Renewable energy, Emission reduction, Technological innovation, Forests, Sustainability

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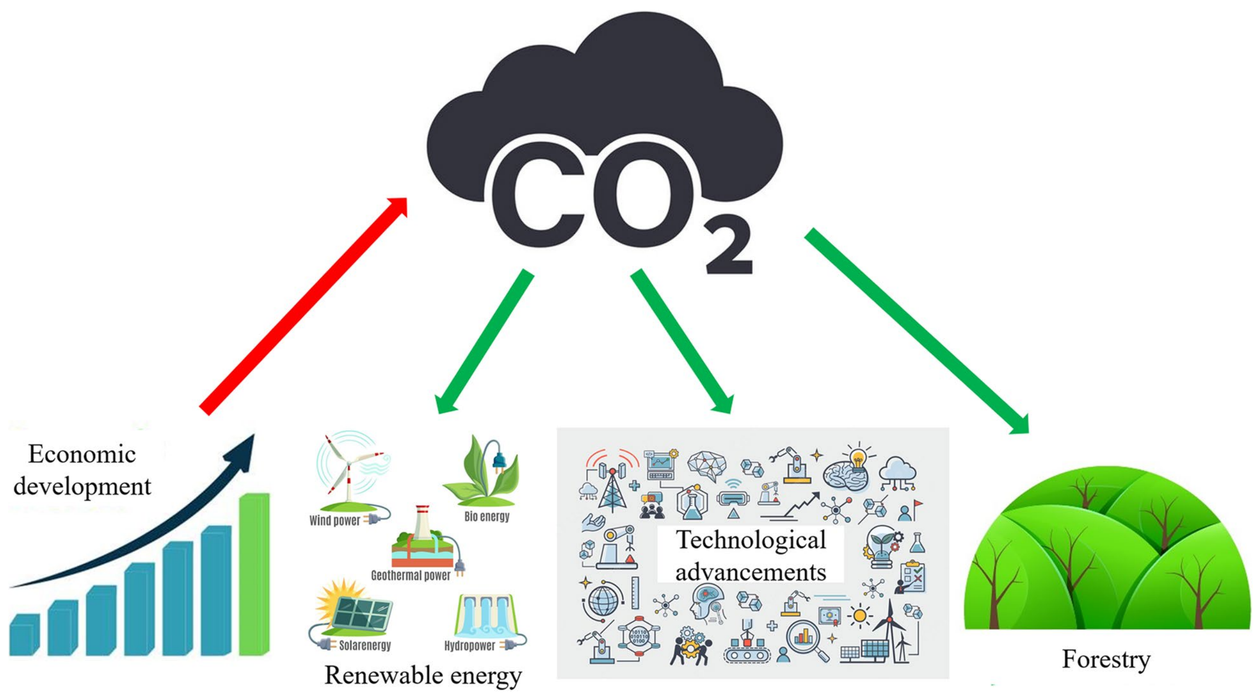
Graphical Abstract



1 Introduction

Human actions like burning fossil fuels and clearing forests contribute significantly to increasing atmospheric concentrations of GHGs, making climate change a pressing concern in the twenty-first century (Isfat and Raihan 2022). Consistently rising CO_2 emissions are predicted to have far-reaching implications for the global climate system, with disastrous effects for every sector of society (Ali et al. 2022; Islam et al. 2022; Raihan and Himu 2023). In order to build a sustainable, progressive, and successful society in which no one is left behind, the world must work toward the goal of a climate-neutral future (Raihan et al. 2022a). Therefore, current academic research has made it a priority to find ways to reduce CO_2 emissions as part of creating a green and sustainable future by considering a wide range of enabling factors, including renewable energy, technological innovation, enhancing forest area, and economic development (Raihan et al. 2022b). The United Nations has anticipated Sustainable Development Goals (SDGs) for 2030 that highlight the importance of inexpensive and clean energy, comprehensive and sustainable economic growth, technological innovation, and sustainable forest management in the fight against climate change (SDGs 7, 8, 9, 13, and 15).

The United Nations Framework Convention on Climate Change (UNFCCC) passed the Paris Pact, a joint environmental accord, to enhance the worldwide rejoinder to the risks posed by climate change within the perspective of sustainable development. After signing the Paris Agreement in 2016, Uruguay became part of a global effort to keep global warming far beneath 2 degrees Celsius, with the ultimate purpose of keeping it to 1.5 degrees Celsius. Being part of the Paris Agreement, Uruguay pledged to cut net emissions in half by 2025 from the gross emissions baseline in 2005. Recently, Uruguay is forecast to be carbon neutral by 2030, according to its Nationally Determined Contribution (NDC) to the Paris Agreement. Rapid emission reduction is essential to reach climate neutrality. By taking steps to mitigate climate change, Uruguay hopes to achieve multiple environmental goals at once, including better air quality, a circular economy, and biodiversity protection, as well as ensure sustainable growth and a just transition. Uruguay's authorities need a better understanding of the country's net-zero emission potential if they intend to find a compromise between sustainable growth and climate change mitigation.

The question of whether or not the benefits of economic growth outweigh the costs of environmental damage informs decisions about how best to promote environmental sustainability and development. Increases in economic growth allow for the replacement of older, more polluting technologies with newer, more environmentally friendly ones, thereby improving environmental quality (Raihan 2023a). There are a number of factors that can help decouple economic growth from environmental degradation, including shifts in production edifice, the espousal of cleaner industrial technology, stricter eco-friendly rules, and a heightened public awareness of environmental issues (Raihan et al. 2023a). Although Uruguay is a small country that contributes little to global emissions, but the country is working to decouple emissions from economic growth. As a result, a major issue is whether or not Uruguay's growing economy is consistent with its ambition to become carbon neutral.

The magnitude of renewable energy has been underscored by the growing unease regarding global climate change and environmental sustainability (Voumik et al. 2022a). Intercontinental economies tend to use more sustainable renewable energy resources as a consequence of the rapid depletion of fossil fuels and the focus of conventional economic development is shifted (Raihan et al. 2022c). Renewable energy's benefits include the cut-down of the usage of traditional energy supplies while protecting the world's economy for the long haul (Raihan et al. 2022d). Solar, wind, water (hydropower), biomass, and geothermal are the five primary sources of renewable energy. Wind, sun, and other renewable sources of energy are plentiful, clean, and safe alternatives to traditional power sources. Many people believe that renewable energy can solve the problems of energy security and pollution (Raihan et al. 2022e; Voumik et al. 2023). The objective of cutting global emissions by half by 2050 and of becoming carbon neutral in Uruguay by 2030 both rely heavily on the utilization of renewable energy resources. To accomplish carbon neutrality by 2030, Uruguay is altering its energy mix by boosting the segment of nonconventional renewable energy resources through public–private partnerships and new investments. Currently, the bulk of Uruguay's energy comes from renewable sources. By the end of 2020, 61% of this nation's energy mix consists of renewable sources, compared to the global average of 12%. In addition, Uruguay's Investment Promotion Law has been amended to provide tax advantages for projects that invest at least 5% of their capital in renewable energy. When Uruguay's energy industry reform is complete, greenhouse gas emissions are expected to be 20 to 40 times lower than the global average. To achieve carbon neutrality, Uruguay needs to maximize its usage of renewable energy, hence this is an important topic for study.

At this time, technological innovation is the single most important factor in reducing global climate change (Shahzadi et al. 2022). The consistent growth of direct environmental technology with the aim of reducing CO_2 emissions has been facilitated by the advancement of environmental legislation. The method of economic reform and optimization relies heavily on technological innovations (Chien et al. 2021). To lessen the carbon dioxide (CO_2) emissions caused by industrialization, the focus of conventional economic development is shifted from production to innovation. In addition, technological innovation is viewed as crucial to enhancing a nation's energy efficiency (Habiba et al. 2022). When applied to the economy, modern technologies allow for a certain level of production to be attained while requiring less energy overall (Udemba et al. 2022). Furthermore, technological innovation permits the economy to alter from using nonrenewable energy supplies to meeting energy needs to renewable energy sources. Technological innovations have reduced the need for fossil fuels and the resulting reduced emissions of carbon dioxide (Qayyum et al. 2021). Most of Uruguay's energy needs are now met by using renewable sources, and the country is in a prime position to take advantage of emerging technologies that will assist in fulfilling the emission reduction target. Uruguay's industrial structure may be modernized with the help of technological innovations, and this would be an excellent catalyst for the country's economic progress. To boost economic growth and reach carbon neutrality, studying the impact of technological innovations on emission reduction is essential from a hypothetical and pragmatic standpoint.

Forest regions are also under strain from the growing demands for shelter, food, agriculture, public transport, and other infrastructures. Urbanization, industrialization, mining, settlements, and agriculture have all caused a shrinkage of forest zone (Jaafar et al. 2020). Forest loss and other land use changes can significantly increase CO_2 emissions and are the second biggest contributor to climate change (Raihan et al. 2021a). Conversely, forests act as both carbon sinks and sources, significantly influencing the structure of the global climatic system (Koondhar et al. 2021). When trees capture CO_2 from the atmosphere and accumulate as biomass, carbon sequestration takes place (Raihan et al. 2021b). This aids in reducing the speed of climate change. Around 300 billion tons of CO_2 is captured annually by forests; however, deforestation and forest degradation are expected to cause an added three billion tons of CO_2 to escape into the atmosphere (Raihan et al. 2023b). As temperature is predicted to increase by 1.5 degrees Celsius across preindustrial stages between 2030 and 2052 under forecast global warming and climate change scenarios, the influence of forest regions in collecting atmospheric carbon has turned out to be progressively more important

(Shahzadi et al. 2022). Nearly 11.6% of Uruguay's land area is covered by forests (World Bank 2023), which are crucial to the nation's carbon balance. In order to achieve carbon neutrality in Uruguay, it is crucial to consider the forest's potential.

Obtaining a climate-neutral culture will prerequisite the collaborative exertions of several parties. This complexity is a challenge for the government, which must be instigated by defining who is liable for what and how at the federal, state, and local levels, along with commercial and public thespians and private citizens. There will also be an emphasis on developing novel methods of building collaboration across different levels of the government and civil society players. Given Uruguay's goal of carbon neutrality by 2030, it is essential to examine how policies, tools, and measures promote a low-emissions path. Before the target for climate neutrality can be established, the most crucial parameters must be explained in detail. Planning the approach to reach the objective of carbon neutrality by the end of the decade is a monumental challenge that requires strong and effective action from virtually every nation. There must be transparency and clarity regarding the relevant parameters of the objective. Even though research into the possibilities of emission reduction aspects using econometric methods has turned out to be a popular issue in current ages, Uruguay has conducted remarkably little research in this area. This study applied the dynamic ordinary least squares (DOLS) approach to investigate the dynamic effects of economic growth, renewable energy usage, technological innovations, and forest area on CO_2 emissions in Uruguay.

This study is significant because it offers information that may be applied in a number of ways to both the body of literature already in existence and the continuing policy discussions in Uruguay. To begin with, the novel findings from the in-depth econometric analysis of the connection between CO_2 emissions and emission reduction factors in the context of Uruguay fill a gap in the prior academic literature. A new approach used in this article is an scrutiny of how the adoption of renewable energy supplies, technological innovations, and sustainable forest management can affect Uruguay's carbon footprint. Second, this study illuminates the frequently neglected but critical role of patent applications in emission reduction. And third, the investigation utilized the most latest and thorough data accessible in recent 32 years (1990–2021). Multiple unit root tests, diagnostic tests, and cointegration models (including the DOLS, CCR, and FMOLS tests) were utilized to establish the validity of the findings. For Uruguay to reach its objective of carbon neutrality by 2030, the verdicts of this evaluation will give lawmakers additional complete and relevant indication for formulating fruitful strategies concerning low-carbon economy, boosting renewable energy consumption, supporting technological innovation, and sustainable forest management. Besides, the results of this study can be applied to the review and development of environmental policies to help get Uruguay ready for a 1.5 °C earth by sustaining strategy and action plans to minimize the effects of climate change and ensure sustainable development. The findings from this study may also be useful for other developing nations as they seek to fortify their own climate change adaptation and mitigation plans.

2 Literature review

Numerous studies have been performed over the past several years to determine how and to what degree renewable energy can cut down on carbon dioxide emissions. A number of economic analyses have concluded that expanding the usage of renewable energy sources would lead to lower levels of carbon dioxide emissions. Moreover, several empirical studies have demonstrated the link between expanding economies and rising CO_2 emissions. Multiple studies from different nations that considered a number of different aspects and used a number of different approaches were taken into account. By employing several econometric methods using time series data, Raihan and Tuspekova (2022a), Raihan and Tuspekova (2022b), and Raihan and Tuspekova (2022c) found that economic growth was positively related to CO_2 emissions, whereas the use of renewable energy was negatively related to CO_2 emissions in the context of Peru, Nepal, and Mexico.

Additionally, increasing R&D spending can improve economic production efficiency and resource consumption efficiency, hence the connection between technological innovation and emission reduction has been studied extensively in recent years. Many countries have successfully decreased their emission levels and enhanced their environmental performance by implementing new technologies and environmental protection measures. The favorable impact that technological innovation might have on carbon emission reduction has been the subject of a lot of prior research. Because patents safeguard business interests and intellectual property, they are favored by most academics as a proxy for technological innovation used in solving environmental issues. Green technology innovation is widely regarded as having positive effects on the environment. There are several empirical studies demonstrating that technological innovation helps lower carbon dioxide emissions. By employing several econometric methods using time series data, Chien et al. (2021), Raihan and Tuspekova (2022d), Raihan and Voumik (2022a), Raihan and Voumik (2022b), and Raihan and Tuspekova (2023a) found that economic expansion positively affected CO_2 emissions while the usage of renewable energy and technical innovation negatively affected CO_2 emissions in Pakistan, Kazakhstan, India, China, and Iceland. As it is already generally understood that technological innovations play a substantial role in reducing emissions while sustaining economic growth, a better understanding of the process of technological innovation is likely to increase our knowledge of mitigation possibilities.

Furthermore, the connection between forests and CO_2 emissions has recently been thoroughly studied. Parajuli et al. (2019) found a negative connection between forest areas and CO_2 emissions using country-specific panel data for 86 nations. By using time series data, Begum et al. (2020), Raihan and Tuspekova (2022e), and Raihan and Tuspekova (2022f) revealed a positive association between economic growth and CO_2 emissions and a negative relationship between forest area and CO_2 emissions in Malaysia, Kazakhstan, and Russia. Additionally, Waheed et al. (2018), and Koondhar et al. (2021), reported the negative impacts of renewable energy use and forested area on CO_2 emissions using time series data from Pakistan and China. A recent study by Shahzadi et al. (2022) revealed the reduction in GHG due to the utilization of renewable energy and increase in the forest area in developed and developing countries. By employing several econometric methods using time series data, Raihan (2023b), Raihan (2023c), Raihan and Tuspekova (2022g), Raihan and Tuspekova (2022h), Raihan and Tuspekova (2022i), Raihan and Tuspekova (2022j), and Raihan et al. (2023c), discovered that economic expansion positively affected CO_2 emissions, whereas the use of renewable energy and forest area negatively affected CO_2 emissions in the Philippines, Chile, Brazil, Turkey, India, Malaysia, and Thailand.

Moreover, by employing several econometric methods using time series data, Raihan et al. (2022f), Raihan et al. (2022g), and Raihan and Tuspekova (2023b) found that economic expansion positively influenced CO_2 emissions, while renewable energy, technological innovations, and forest area helped to cut CO_2 emissions in Bangladesh, Indonesia, and New Zealand. Despite this encouraging trend, the entire potential of renewable energy use, technological innovations, and forests are yet unclear, as well as the methods of knowledge acquisition. The majority of environmental studies have concentrated on the relationship between CO_2 emissions and its drivers, but few on the relationship between emission reduction mechanisms and CO_2 emissions, particularly in Uruguay. Therefore, the current study aims to address the gap in the literature by combining multiple econometric methodologies to investigate the potential of economic growth, renewable energy use, technical innovations, and forest area to help Uruguay reach its goal of carbon neutrality by 2030.

3 Methodology

3.1 Data

By applying the DOLS method of cointegration created by Stock and Watson (1993), this study offered an empirical examination of the effects of economic development, renewable energy utilization, technological innovations, and forest area on CO_2 emissions in Uruguay. This research's econometric evaluation made use of the most up-to-date time series data from Uruguay, which stretched from 1990 to 2021. The data were taken from the World Development Indicator (WDI) database (World Bank 2023). In this study, carbon dioxide emissions served as the dependent parameter, whilst economic expansion, renewable energy, technological progress, and forests served as the explanatory factors. Furthermore, it should be mentioned that technological innovation refers to the interest in finding new technology shown by a country's industrial and commercial entities, which may be quantified using a metric like the number of patents. Since patents are the formalized form of technology, patenting ventures can stand in for innovation in that field. An expansion in patent applications is a sign that businesses and individuals want to adopt cutting-edge innovations. As a result, the total number of patent applications has been used as a stand-in for technological progress (both domestic and foreign). In addition, a logarithmic transformation is applied to the variables to guarantee a normal distribution. Table 1 displays the variables, their logarithmic representations, the measurement technique, and the researchers that collected the data. Besides, Fig. 1 displays the yearly trends of the research variable.

3.2 Theoretical framework

This research utilized the framework of a Cobb–Douglas production function to analyze the hypothesis (Cobb and Douglas 1928). This research topic uses standard production economics to assess how GDP growth, renewable energy adoption, technological innovations, and forest area have affected CO_2 emissions in Uruguay. The cumulative output function can be derived as follows, assuming a constant rate of return and a standard Cobb–Douglas production function:

$$Y_t = f(K_t, L_t) \tag{1}$$

Table 1 Data sources, units of measure, and logarithms of the variables

Variables	Description	Logarithmic forms	Units	Sources
CO_2	CO_2 emissions	LCO2	Metric tons per capita	WDI
GDP	Economic growth	LGDP	GDP per capita (constant Peso Uruguayo)	WDI
RNE	Renewable energy use	LRNE	% of total final energy use	WDI
TI	Technological innovation	LTI	Number of patent applications	WDI
FA	Forest area	LFA	Square kilometers (sq. km)	WDI

where Y_t represents the GDP at time t; K_t represents capital at time t; and L_t represents effective labor at time t

There is a theoretical link between CO_2 emissions and financial success. Given the widespread belief that emissions of carbon dioxide (CO_2) are caused by human economic activity, we can express the CO_2 emission function as:

$$CO_{2t} = f(GDP_t) \tag{2}$$

where CO_{2t} indicates CO_2 emissions at time t

Moreover, hasty economic expansion is associated with increased energy ingesting in the manufacturing procedure, whereas snowballing the amount of renewable energy in the overall final energy usage aids to attain ecological sustainability by lowering carbon emissions from fossil fuel energy resources. Therefore, the idea of this research is to provide an estimate of how much renewable energy utilization affects carbon dioxide emissions. As a result, Eq. (2) may be rewritten as:

$$CO_{2t} = f(GDP_t; RNE_t) \tag{3}$$

where RNE_t represents renewable energy usage at time t

This study takes into account technological innovation in the model as a result of the discussion in the introduction and literature review segments, which show that technological innovations can have multiple effects on CO_2 emissions. Technological innovation is also important since it increases factor yield and guarantees energy efficiency, together with which promotes economic growth. In addition, forests moderate climate change by absorbing atmospheric carbon dioxide. In order to comprehend the association between CO_2 emissions, economic growth, renewable energy consumption, technological innovations, and forest area, the following economic functions were utilized in the current study:

$$CO_{2t} = f(GDP_t; RNE_t; TI_t; FA_t) \tag{4}$$

where TI_t represents the number of patent applications at time t; FA_t represents the forest area at time t

3.3 Econometric model

Equation (5) illustrates the empirical model:

$$CO_{2t} = \tau_0 + \tau_1 GDP_t + \tau_2 RNE_t + \tau_3 TI_t + \tau_4 FA_t \tag{5}$$

Equation (5) is further elaborated as the following econometric model:

$$CO_{2t} = \tau_0 + \tau_1 GDP_t + \tau_2 RNE_t + \tau_3 TI_t + \tau_4 FA_t + \varepsilon_t \tag{6}$$

where τ_0 and ε_t denote intercept and error term whereas τ_1, τ_2, and τ_3 represent the coefficients.

Furthermore, Eq. (7) demonstrates the logarithmic composition of Eq. (6):

$$LCO2_t = \tau_0 + \tau_1 LGDP_t + \tau_2 LRNE_t + \tau_3 LTI_t + \tau_4 LFA_t + \varepsilon_t \tag{7}$$

Figure 2 is a flowchart of the analytic methods used to investigate the impact of Uruguay's expanding economy, increasing reliance on renewable energy, rapid technological innovations, and enhanced forest area on the country's carbon footprint.

3.4 Data stationarity techniques

Applying a unit root test is indispensable for thwarting flawed regression. By differentiating the variables in the regression and by means of stationary methods to assess the equation of interest, this method ensures that the variables are, in fact, stationary (Raihan 2023d). Before investigating cointegration between variables, the empirical literature acknowledges the requirement to define the sequence of integration. As the power of unit root testing varies with sample dimension, numerous research recommended using multiple tests to determine the best sequence for series integration (Raihan 2023e). This investigation applied the Augmented Dickey-Fuller (ADF) test by Dickey and Fuller (1979), the Dickey-Fuller generalized least squares (DF-GLS) test by Elliott et al. (1992), and the Phillips-Perron (P-P) test by Phillips and Perron (1988) to identify the autoregressive unit root. To guarantee that no variables in this study outstripped the order of integration and to deliver more evidence for the superiority of the DOLS procedure over

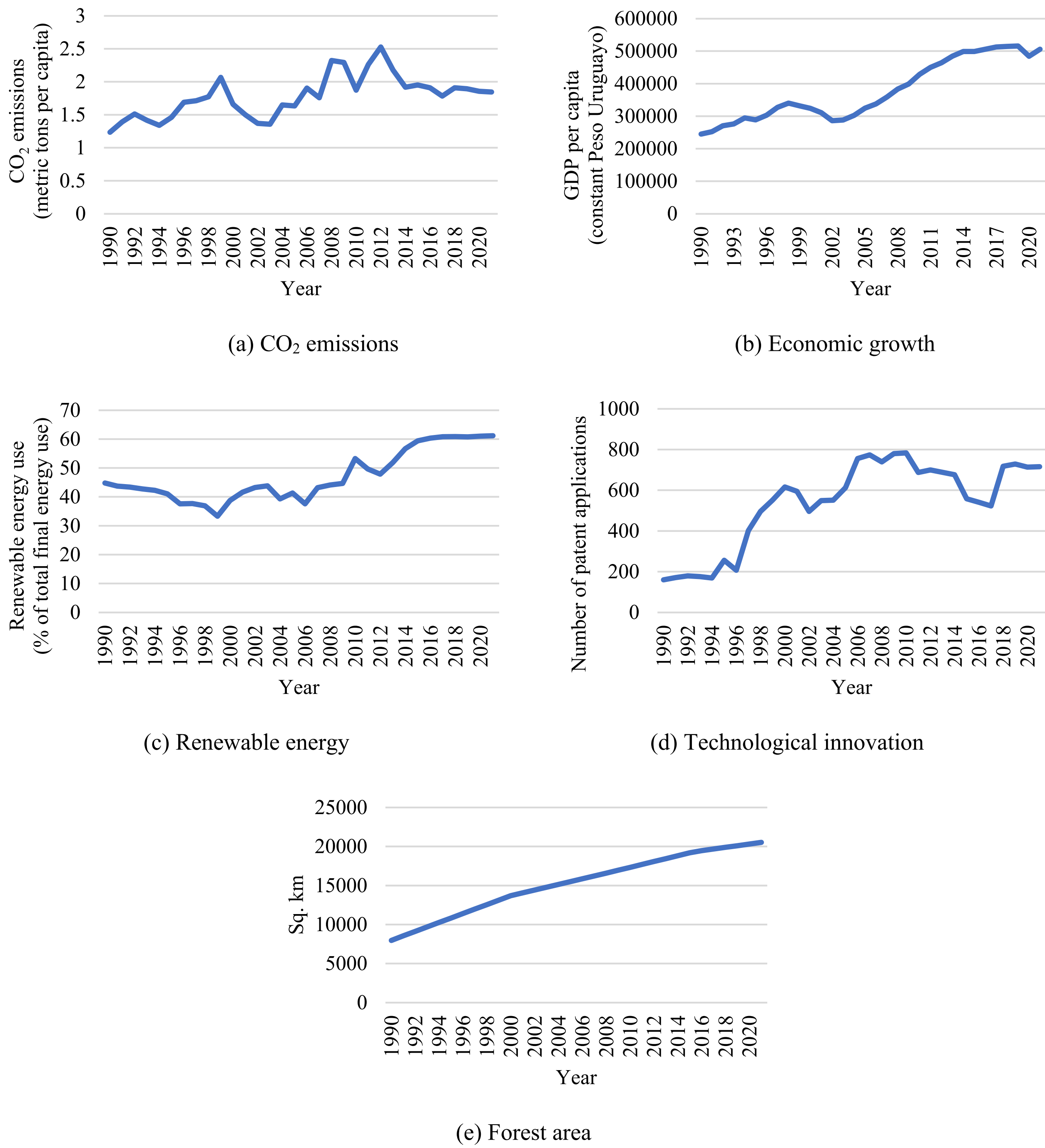


Fig. 1 Yearly trends of the study variables

conventional cointegration structures, the unit root tests were employed.

3.5 DOLS method of cointegration regression

This research investigated time series data with DOLS, an extended equation of ordinary least squares estimation. The DOLS cointegration test uses explanatory parameters along with leads and lags of their initial difference terms to regulate endogeneity and calculate standard deviations utilizing an error covariance matrix that is resistant to serial correlation (Raihan et al. 2022h). The orthogonalization of the error term

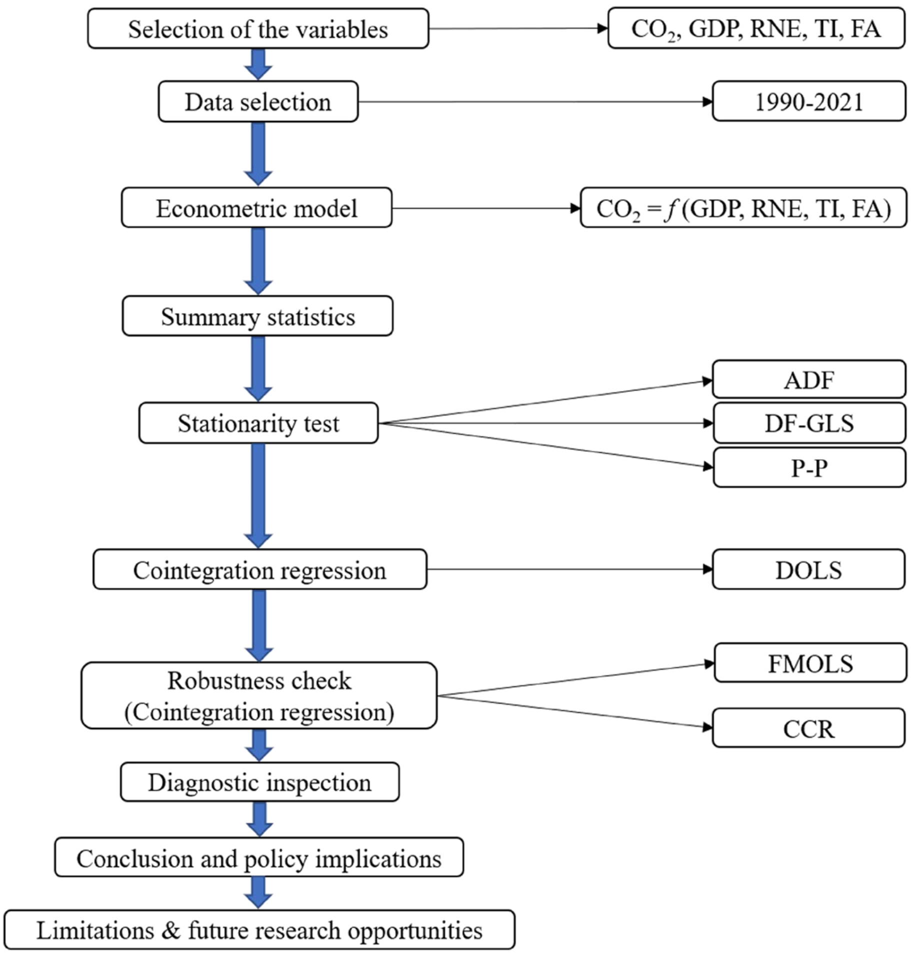


Fig. 2 Flow chart of the analysis

is shown by the insertion of the prominent and pulling phrases of the specific ones. Using the DOLS estimator's standard deviations as a test for statistical significance is a safe bet because they follow a normal asymptotic dissemination. The DOLS method is useful for integrating cointegrated outlines with factors that integrate in a different order, as it estimates the dependent parameter based on the explanatory variables in leads, lags, and levels (Raihan et al. 2022i). The principal advantage of DOLS estimation is the mixed order integration of individual variables in the cointegrated outline. While some of the other variables in the regression were I(1) variables with leads (p) and lags (-p) of the initial difference, others of the variables were I(0) variables with a constant term, similar to the estimate method used by DOLS. By summing the leads and lags among explanatory factors, this estimate removes issues with small sample bias, endogeneity, and autocorrelation (Raihan and Tuspekova 2022k). After demonstrating that the variables are cointegrated, the analysis proceeds to estimate the long-run coefficient using DOLS (using Eq. 8).

$$\Delta LCO2_t = \tau_0 + \tau_1 LCO2_{t-1} + \tau_2 LGDP_{t-1} + \tau_3 LRNE_{t-1} + \tau_4 LTI_{t-1} + \tau_5 LFA_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LCO2_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta LGDP_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta LRNE_{t-i} + \sum_{i=1}^{q} \gamma_4 \Delta LTI_{t-i} + \sum_{i=1}^{q} \gamma_5 \Delta LFA_{t-i} + \varepsilon_t \quad (8)$$

where Δ represents first difference operator while q represents optimum lag length

3.6 Robustness check

In order to safeguard the soundness of the DOLS calculations, this investigation applied the fully modified

OLS (FMOLS) and Canonical Cointegrating Regression (CCR) techniques. Hansen and Phillips (1990) created the FMOLS regression to put together the most accurate estimates of cointegration. The FMOLS method is a modification of least squares that allows for endogeneity in the independent variables and serial correlation effects due to cointegration. The FMOLS method aids with spurious regressions by employing conventional regression method (OLS) for nonstationary data. The CCR procedure, which entails transforming data with only the stationary module of a cointegrating model, was also pioneered by Park (1992). A cointegrating linkage from the cointegrating model will persist unchanged following such statistics handling. The CCR conversion eliminates the zero-frequency dependence of the error term on the regressors in a cointegrating model. The CCR approach produces estimators that are asymptotically efficient in addition to asymptotic chi-square tests that are free of any nuisance parameters. Asymptotic coherence can be established with the help of FMOLS and CCR practices by investigating the impact of serial correlation (Raihan et al. 2023d). Consequently, the FMOLS and CCR procedures were utilized to establish the long-term elasticity, as demonstrated by Eq. (8).

4 Results

4.1 Summary statistics

Table 2 displays the statistical assessments of many normality tests (kurtosis, skewness, probability, and Jarque–Bera) applied to the outcomes of the summary measures between variables. Uruguay's time series data for each variable spans the years 1990 through 2021 and feature 32 observations. Negative skewness values indicate that all of the parameters are normally distributed. This investigation also used kurtosis to determine whether or not the series they were studying deviated significantly from a normal distribution. All empirical series are shown to be platykurtic, with values below 3. All the parameters are normal, as shown by the tiny values of the Jarque–Bera probability.

4.2 Results of unit root tests

To certify that no variables had an order of integration higher than the others, this analysis used the unit root test to support the use of the DOLS technique rather than ordinary cointegration approaches. This research employed trend-and-constants-based ADF and DF-GLS and P-P methods to isolate the autoregressive unit root. The outcomes of the tests for locating the unit root are shown in Table 3. All three unit root tests showing that the series were not level-stationary, but did become stationary once the first difference was taken. Therefore, the unit root calculations suggest that the series share a first-difference order of integration. This means that there is no possibility of a deceptive regression analysis because all of the parameters integrated in the empirical investigations tend toward their true values.

4.3 DOLS outcomes

The DOLS estimation findings are shown in Table 4. When all other factors are controlled for, the projected long-run coefficient of LGDP is positive and statistically significant at the 1% level. This indicates that a 1% rise in economic growth would result in a 1.16% growth in CO_2 emissions. When looking at long-term effects, however, the appraised coefficient of renewable

Table 2 Summary statistics of the data series

Variables	LCO2	LGDP	LRNE	LTI	LFA
Mean	0.560896	12.81396	3.834555	6.177788	9.598449
Median	0.574929	12.73271	3.779174	6.356460	9.660244
Maximum	0.927168	13.15387	4.113591	6.664409	9.930129
Minimum	0.211198	12.40879	3.505511	5.078294	8.984694
Std. Dev	0.179202	0.247203	0.180944	0.539057	0.275509
Skewness	-0.010576	0.114009	0.335142	-0.142013	-0.698107
Kurtosis	2.339305	1.551985	1.927681	2.719167	2.399449
Jarque–Bera	0.582621	2.864986	2.132196	1.060850	2.800103
Probability	0.747284	0.238713	0.344350	0.290292	0.214370
Observations	32	32	32	32	32

Table 3 The findings of unit root tests

Logarithmic structure of the parameters		LCO2	LGDP	LRNE	LTI	LFA
ADF	Log levels	-2.5155	-0.9978	-0.4826	-2.0221	-2.0727
	Log first difference	-5.9482[a]	-3.4008[b]	-6.0921[a]	-6.0959[a]	-3.6272[b]
DF-GLS	Log levels	-1.7714	-0.2237	-0.5666	0.7675	0.1523
	Log first difference	-5.5366[a]	-3.4491[a]	-5.9908[a]	-6.2034[a]	-3.3832[b]
P-P	Log levels	-2.5157	-1.0528	-0.3808	-2.0221	-2.7455
	Log first difference	-6.0520[a]	-3.4008[b]	-6.0944[a]	-6.0608[a]	6.0888[a]

[a] and [b] indicate significance at the 1% and 5% levels

Table 4 The results of the DOLS: dependent variable LCO2

Variables	Coefficient	Standard error	t-Statistic	*P*-value
LGDP	1.159706[a]	0.141538	8.193604	0.0000
LRNE	-0.727575[a]	0.117371	-6.198958	0.0000
LTI	-0.112569[b]	0.067982	-1.655872	0.0193
LFA	-0.562382[b]	0.183904	-3.058019	0.0095
C	8.726718	0.980283	8.902241	0.1111
R^2	0.820154			
Adjusted R^2	0.793510			
Standard error of the estimate	0.000013			
F-statistic	342.7912			
Prob (F-statistic)	0.000000			
Root mean square error (RMSE)	0.018743			
Mean Absolute Error (MAE)	0.022681			

[a] and [b] indicate significance at the 1% and 5% levels

Table 5 The outcomes of FMOLS: dependent variable LCO2

Variables	Coefficient	Standard error	t-Statistic	*P*-value
LGDP	1.149489[a]	0.111512	10.30821	0.0000
LRNE	-0.651212[a]	0.117772	-5.529433	0.0000
LTI	-0.164881[b]	0.058139	-2.835966	0.0187
LFA	-0.524257[a]	0.173811	-3.015668	0.0057
C	7.660019	0.912672	8.392963	0.1305
R^2	0.787743			
Adjusted R^2	0.755088			

[a] and [b] indicate significance at the 1% and 5% levels

Table 6 The outcomes of CCR: dependent variable LCO2

Variables	Coefficient	Standard error	t-Statistic	*P*-value
LGDP	1.148588[a]	0.104608	10.97991	0.0000
LRNE	-0.659331[a]	0.131218	-5.024686	0.0000
LTI	-0.167143[b]	0.066945	-2.496731	0.0192
LFA	-0.509982[a]	0.180820	-2.820376	0.0091
C	7.771612	0.897567	8.658530	0.1056
R^2	0.788131			
Adjusted R^2	0.755536			

[a] and [b] indicate significance at the 1% and 5% levels

energy is negative and statistically significant at the 1% level, suggesting that boosting the use of renewable energy by 1% is linked to a decline in CO_2 emissions of 0.73 percent. In addition, at the 5% significance level, the calculated long-run coefficient of technological innovation is negative, meaning that for every 1% surge in technological innovations, CO_2 emissions decrease by 0.11%. Finally, the long-run coefficient of forest area is notably negative at a 1% level, which means that expanding forest area by 1% reduces CO_2 emissions by 0.56%. The empirical findings divulge that expanding economic expansion disparages Uruguay's environmental condition while increasing the use of renewable energy, technological innovation, and forest area all assist the country achieve sustainable development by reducing CO_2 emissions.

Moreover, it is worth mentioning that the theoretical and practical indications of the assessed coefficients are coherent. It appears that the computed regression model suits the data flawlessly, with R^2 and modified R^2 estimates of 0.8201 and 0.7935, respectively. This suggests that the changes in the explanatory parameters may justify approximately 80% of the variation in the dependent variable. In addition, the F-statistic shows that the DOLS framework is backed by the independent and the dependent parameters. The regression model is statistically significant with an F-statistic and a p-value of 0.0000. Furthermore, the DOLS modeling generated results that were an almost great fit to the statistics, as evidenced by the RMSE and MAE figures staying positive and near to zero.

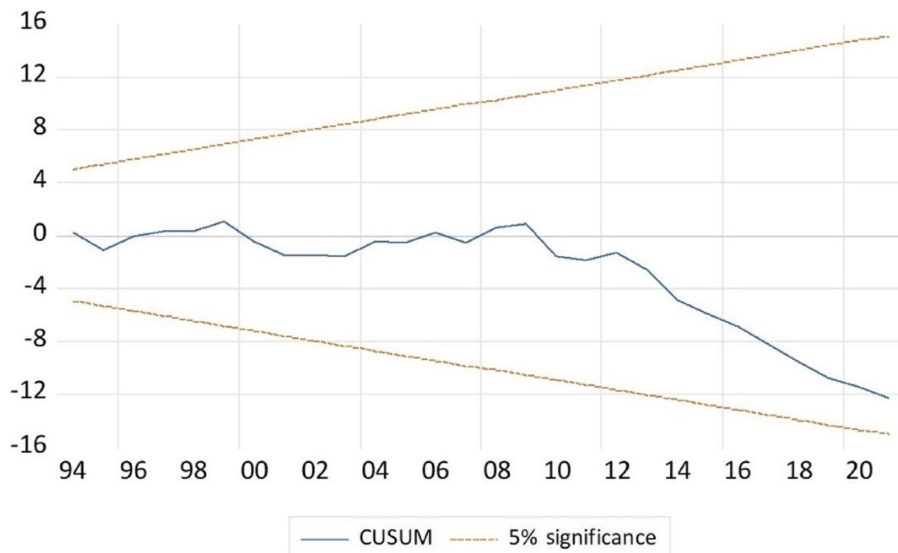
4.4 Robustness check

To ensure that DOLS estimation was consistent, this investigation applied the FMOLS and CCR techniques. Tables 5 and 6 display the model's estimated FMOLS and CCR values, respectively. The findings of the FMOLS and CCR estimations show how reliable the DOLS assessment is. The positive coefficient of economic growth at a 1% level of significance was validated by both the FMOLS and CCR evaluation results. Moreover, the negative coefficients of renewable energy and forest area were confirmed at the 1%

Table 7 The results of diagnostic tests

Diagnostic tests	Coefficient	*p*-value	Decision
Jarque–Bera test	3.268329	0.1951	Residuals are normally distributed
Breusch-Godfrey LM test	0.386061	0.6836	No serial correlation exits
Breusch-Pagan-Godfrey test	0.240004	0.8677	No heteroscedasticity exists

level of significance in both FMOLS and CCR estimate results. In addition, FMOLS and CCR assessment findings corroborate the negative link between technological progress and carbon dioxide emissions at the 5% significant level. Additionally, the goodness of fit is reflected in the assessed R^2 and modified R^2 estimates from FMOLS and CCR estimates. Thus, it can be concluded that CO_2 emissions rise as Uruguay's economy expands, while progress in renewable energy, technological innovations, and forest development could assist the country to become carbon neutral by 2030.



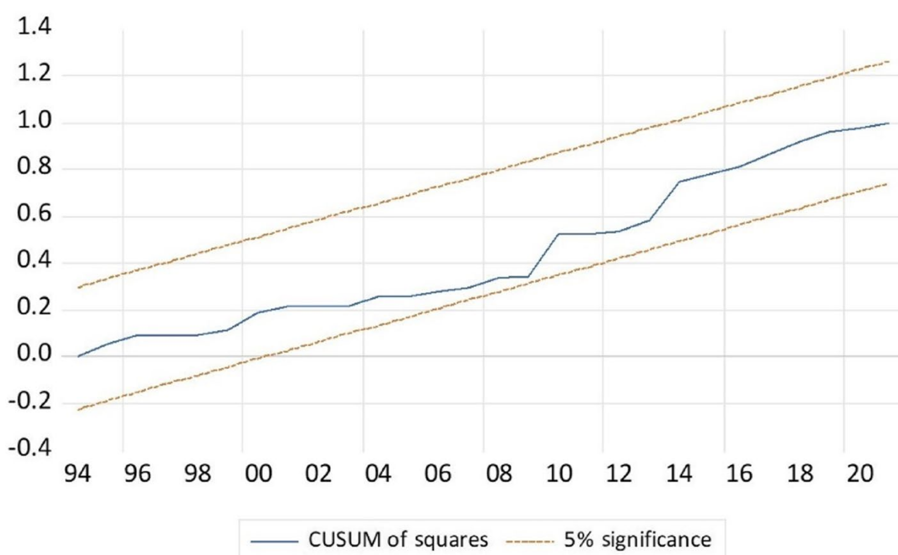


Fig. 3 The plots of CUSUM and CUSUMQ tests

4.5 Diagnostic inspection

This investigation ran tests for normality, heteroscedasticity, and serial correlation to make sure the cointegration assessment was accurate. The results of the diagnostic techniques are summarized in Table 7. The model does not exhibit any signs of autocorrelation or heteroscedasticity, and the data follow a normal distribution. Moreover, the CUSUM and CUSUMQ tests were used to examine the model's robustness to recursive changes. Figure 3 shows the CUSUM and CUSUMQ plots at the 5% level of significance. The lines in blue represent the residual values, while the lines in red represent the confidence intervals for those values. The estimated values of the examined residuals are consistent with the confidence intervals, indicating that the model is stable at the 5% level of significance.

5 Discussion

This research shows that Uruguay's economic expansion affects environmental deterioration over time. The positive correlation between GDP and CO_2 emissions in the case of Uruguay is validated by previous studies, for instance, Chien et al. (2021), Qayyum et al. (2021), and Udemba et al. (2022). Emissions have increased as industrialization has led to more energy use, infrastructural development, and economic capitalization, all of which have had a positive upshot on investments and business yield. When the economy expands, pollution levels tend to rise alongside it. It causes greater pollution, waste, and environmental deterioration as more communal needs are met through consumption and development activities (Voumik et al. 2022b). Therefore, economic activities appear appropriate for environmental development and protection as opposed to providing a peril to the long-term quality of the environment. As a result, the ability to attain carbon neutrality may be at risk unless the economy makes a massive transition to using low-carbon technology for producing goods and services. Consequently, in order to accomplish carbon neutrality in Uruguay, effective strategies and ways to lessen dependance on fossil fuel resource, energy intensity, as well as carbon emissions are required.

The present study revealed a negative alliance between renewable energy application and CO_2 emissions in Uruguay. The outcome demonstrates the possibility of reducing emissions by boosting the utilization of renewable energy sources in Uruguay. The result suggests that the application of renewable energy technologies is crucial for Uruguay to reach the target of carbon neutrality. The finding of this investigation is consistent along with the studies of Chien et al. (2021), Qayyum et al. (2021), Waheed et al. (2018), Koondhar et al. (2021), Habiba et al. (2022), Shahzadi et al. (2022), and Udemba et al. (2022). Utilizing renewable sources for energy generation is essential for both sustainable development and climate change mitigation in light of the impending threat of climate change. Besides to lowering carbon emissions, renewable energy delivers major economic benefits, such as increased energy availability, enhanced energy security, and the use of local renewable resources (Raihan et al. 2023e).

The Energy Efficiency Plan of Uruguay seeks to reduce energy consumption in all sectors, particularly the residential and transportation sectors, which will account for 75% of the country's total accumulated reduction by 2024 owing to the substantial amount of investments pushed by official initiatives. For instance, the revolution of the energy sphere was made feasible by a public–private venture that averaged 3% of the GDP each year and was accumulated over several years. Contained by the context of the "National Energy Policy 2005- 2030", Uruguay has made significant efforts to attain a clean energy mix, which corresponds to 83% of the industrial sector's total energy consumption and 93% of power generation. Even though significant progress has been made in this sector in recent years, there are still several prospects for action. As an outcome, the energy sector's total emissions per GDP are extraordinarily low; the energy sector's emission intensity is one-third of the global average. In addition, there is even significant reduction capacity, particularly in the transport sphere, which the country is eager to undertake if the resources to do so become available. Uruguay will continue to develop renewable energy technologies while retaining the current low intensity of emissions in the energy industry, to reach its goal of carbon neutrality by 2030.

This study also investigated how technological progress can help Uruguay reach carbon neutrality. The empirical result suggests that a rise in patent applications may result in lesser quantities of CO_2 emissions. This suggests that the adoption of green technologies in Uruguay's industrial sector may contribute to the country's efforts to improve environmental quality by achieving its target of carbon neutrality. The findings of the present study concur with those of other researchers who discovered that technological innovations contribute to environmental sustainability, for instance, Chien et al. (2021), Qayyum et al. (2021), Habiba et al. (2022), Shahzadi et al. (2022), and Udemba et al. (2022). With the help of green technologies and the green economy, Uruguay aspires to accomplish carbon neutrality by 2030. The deliberation over the starring role that patent applications might play in mitigating climate change is escalating as the world enters an era where environmental sustainability is more crucial than ever (Raihan 2023f). Green technology patents guarantee that the environment will always be preserved for future generations even as they are used to advance the field.

The outcomes indicate that the utilization of renewable energy supplies becomes increasingly important when CO_2 emissions increase with economic growth. Further results suggest that a strong economy may stimulate the development of innovative renewable energy sources. Due to the resources made accessible by a thriving economy, renewable energy infrastructure and technological research and development can expand. Technological breakthroughs are facilitating the shift away from fossil fuels and toward renewable energy in order to fulfill rising energy stresses and upsurge energy efficiency. When a country's GDP increases, it has more discretionary revenue to invest in R&D and the adoption of innovative machinery. As a consequence of decreased reserve usage and merchandise by-products, technological innovations bring about a reduced amount of waste and pollution. For example, if more capital is sponsored in research and development, it is anticipated that environmental quality will improve. This study also demonstrates that the use of renewable energy is a immediate consequence of economic growth and technological innovations. New technology will facilitate the mass adoption of renewable energy as the economy grows. In contrast, because of the government's broad renewable energy promotion plan, the renewable energy industry is now a significant economic sector that significantly contributes to the nation's socioeconomic and long-term development. The extension of renewable energy has enhanced the condition of life of people and the globe as a whole in numerous ways, including the creation of jobs, the reduction of prices, and the reduction of pollution. For Uruguay to achieve carbon neutrality, the economy must persist to expand, as this will give the finances crucial to research and build renewable energy technology and infrastructure.

According to this study, forest ecosystems improve Uruguay's ecology because they catch CO_2 from the atmosphere and store it in the soil and vegetation of the woods. Based on the empirical results, increasing forest carbon sinks via increasing forest reserves slows down ecological damage over time. The study's findings, which demonstrate a negative link between forest acreage and CO2 emissions, are corroborated by Waheed et al. (2018), Parajuli et al. (2019), Begum et al. (2020), Koondhar et al. (2021), and Shahzadi et al. (2022). Since forests are the second-largest source of CO_2 emissions in the world, forest degradation has been seen as a contributing factor to environmental destruction (Raihan et al. 2018). Therefore, minimizing deforestation may be the simplest method for reducing CO_2 emissions.

However, Uruguay is a country in which there is no net deforestation; this is highly exceptional among emerging nations. In fact, the overall area covered by natural forests has expanded over the previous three decades and is presently 752 000 hectares. Approximately one-third of the surface area of these forests has experienced an increase in carbon stores due to expansion and secondary growth. This is in response to laws prohibiting the logging of native forests and to tax exclusion inducements offered to listed regions with indigenous forests, amounting to around $5 million each year. By 2030, it is anticipated that yearly CO_2 reductions in Uruguay from native forests using domestic resources will be approximately 1300 Gg and might reach 2500 Gg with further execution strategies. In addition, between 1990 and 2010, Uruguay planted 689,000 effective hectares with trees, representing a 430% increase in the overall area planted throughout the time. Carbon sequestration levels in tree plantations and expanding indigenous forests decided that Uruguay acted as a net CO_2 sink at the turn of this century. From 2010 to 2030, Uruguay aims to contribute, using local reserves, a further growth of the overall tree plantation area of approximately 300,000 hectares, which will represent total yearly CO_2 reductions of 11,200 Gg in 2030. The State also helped to reduction of the economy's emissions by providing tax incentives for ventures in low-carbon production capabilities, specifically to encourage afforestation. Half of the plantation expenditures in the sector were financed for over fifteen years.

In addition, Uruguay will be able to participate within the Reducing Emissions from Deforestation and forest Degradation (REDD+) framework by eliminating carbon and averting emissions that might be anticipated at an additional 2100 Gg of CO_2 in 2030. The cumulative figure for forest removals helped by local resources is 4,125,000 Gg of CO_2 in 2030, which may reach 15,800 Gg if extra implementation resources were made available. Moreover, the soils beneath degraded grasslands and eroding croplands in Uruguay have a high potential for carbon sequestration. Regarding damaged grasslands, it is anticipated that by 2030, 600 Gg will be removed using domestic resources and 3,300 Gg will be removed using additional methods of implementation. Regarding carbon in farmland soils, Uruguay has established extensive no-till agriculture and newly enacted obligatory conservation measures that decrease soil erosion and support an expansion in soil biomass source. The expected net effect of these actions is approximately 100 Gg CO_2 collected by 2030. Through carbon sequestration in soils, Uruguay would remove 700 Gg CO_2 annually in 2030 using local resources and a total of 3,400 Gg CO_2 with extra implementation means.

Undoubtedly, the most cost-effective tactic for terminating ecological deterioration and reducing climate change is to increase forest carbon sequestration

(Raihan et al. 2019). A foremost topic in the current climate research society is the significance of restoring, preserving, and conserving forests as a means of diminishing climate change. Additionally, forestry-based mitigation tactics (afforestation, forest protection, and natural regeneration) may provide a number of purposes, comprising carbon sequestration, ecosystem regrowth, biodiversity preservation, and the production of commodities and services for society (Raihan and Said 2022). By cutting CO_2 emissions and boosting forest biomass, which in turn increases the country's carbon sink, Uruguay's forestry segment has a major power to mitigate forestry-based global climate change. To put it briefly, improving forest areas would be an effective approach to reducing carbon emissions and support Uruguay's effort to reach carbon neutrality by 2030.

6 Conclusion and policy implications

This research looks into how carbon neutrality in Uruguay can be accomplished by factors like economic development, renewable energy adoption, technological innovations, and forest area. The DOLS technique was applied on time series data that extended from 1990 to 2021. In this research, the ADF, DF-GLS, and P-P unit root tests were applied to verify the order of integration of the series. According to the results of the DOLS estimation, a one-percentage-point growth in economic development is associated with a 1.16% increase in CO_2 emissions. However, increasing the use of renewable energy by 1% is related to a reduction in CO_2 emissions of 0.73 percent over the long run, as indicated by the coefficient of renewable energy use being negative and statistically significant. The calculated long-run coefficient of technological innovations is negative and statistically significant, suggesting that a 1% upsurge in technological innovations results in a 0.11% decline in CO_2 emissions. The long-run coefficient of forest area is notably negative and significant, which means that expanding forest area by 1% reduces CO_2 emissions by 0.56%. Estimates hold up well when compared with both the FMOLS and CCR methods. This research provides fresh insight into how the implementation of renewable energy resources, cutting-edge technological innovations, and sustainable forest management in Uruguay have contributed to the country's progress toward carbon neutrality. Recommendations for policy were made in this article to promote sustainable development through the introduction of robust regulatory policy tools targeted at achieving carbon neutrality by 2030.

It will take new methods and procedures to get to net zero emissions, which is not an easy aim to achieve. An all-out effort, substantial investment, and careful planning are needed to make the leap to a climate-neutral civilization. In order to keep the political debate on the future's direction going strong, it is crucial to keep gathering facts and best practices. To reach carbon neutrality, all emissions must be reduced, and the many causes and potential remedies must be taken into account. For this reason, it's possible that a variety of sector-specific policies and initiatives will need to be implemented simultaneously in order to move forward. To reach carbon neutrality, the strategy must be adaptable and leave room for novel, creative ideas. Government actors, industrial partners, non-governmental organizations, and local municipalities must all work together and actively participate in the development and systematic reevaluation of a viable strategy for a climate-neutral Uruguay by 2030. To achieve a fair transition to a circular, competitive, climate-neutral future, the public must be involved in its development. Many local governments, businesses, and non-profits, as well as national organizations, have taken action to address climate change. Uruguay's emissions are predicted to decrease as a result of these measures. Since government effort alone won't be enough to combat climate change, it's crucial to back such projects.

This study suggests that Uruguay's administration aid markets by constructing a solid lawmaking structure that creates lasting significance for carbon neutrality and consistently encourages groundbreaking technologies that result in a less carbon concentrated economy. Uruguay's administration is considering expanding its application of carbon capture and storage systems with the goal of becoming carbon neutral. Legislators should also support and kindle renewable energy industries and innovations. These actions will aid the transition to a low-carbon economy by converting more conventional energy sources that generate a lot of emissions. In order to achieve the goals of a future without fossil fuels, in which all energy production comes from renewable origin by 2030, the authority might make and implement efficient policies to support venture in new renewable energy equipment. As a corollary, new technologies will need to be built through research and patent applications in order to reach the carbon neutrality goal. The creation of energy-saving technology is a portion of this endeavor and will likely play a major part in any upcoming steadiness strategy. Hybrid vehicles are one example of how modern technology can reduce energy use without compromising performance. In order to promote the development of low-carbon technology, the government may provide subsidy for firms performing technological innovation research on energy conservation and emission reduction. Uruguay's government is considering increasing its cooperation with academic institutions in an effort to promote technological innovations, especially in the field of green technology.

Green technology, such as renewable energy resources; management, recycling and waste technologies; energy storage; and GHG disposal, can all contribute to a more sustainable way of life. Innovative green technology utilization in the industry may have positive effects on all three of these fronts. In addition, the authorities should foster the exploitation of patents and the development of novel energy sources and environmental protection measures.

Additionally, this study's findings recommend Uruguay's politicians to design proper ecological and climate-resilient plans, with an emphasis on reducing carbon emissions through forest growth. Uruguay's forest policy may include the goal of attaining sustainable development, with sustainable forest management in particular aiding in preserving the quality of the environment and the socioeconomic benefits from forests. Consequently, a sound forest management approach and effective strategy implementation might be taken into account. The government of Uruguay may raise investments while enacting rigorous forest regulations as an effort to reduce carbon emissions by increasing forest biomass out of the preservation and protection of forests. The authority may also create commercial forest plantation portions to attract involvement from the business sector in sustainable forest management. By implementing a variety of forestry-based mitigation strategies, Uruguay may be better able to combat climate change and meet its goal of carbon neutrality by 2030. Because of better and more economical methods of managing forests, such as reforestation, afforestation, agroforestry, forest conservation, urban forestry, and greater natural regeneration, forests will continue to serve as carbon sinks. Last but not least, effective forest policy development might aid Uruguay in increasing its nationwide carbon sink, assuring nationwide green development, and sustainable forest management, which would result in carbon neutrality by 2030.

Although our approach has significant weaknesses, which may be addressed in future studies, our current study did produce substantial empirical findings in the case of Uruguay. The inaccessibility of data outside the study period severely restricts the usefulness of the econometric methods we employed. This research, however, looks at the interplay between Uruguay's expanding economy, renewable energy sources, technological progress, forest area, and CO_2 emissions. However, recycling items; decreasing water and electricity utilization; shift to organic food; etc. are all potential factors in lowering emissions that could be investigated in future research. Degradation of the environment due to GHG emissions was also measured using CO_2 in this study. Consumption-based carbon emissions, along with other emission dimensions such as sulfur dioxide, nitrous oxide, methane, and other transient climate difficulties, could be used as alternatives for ecological deterioration in more studies. CO_2 emissions are not the main contributor to environmental degradation, but they are used as a surrogate for contamination in this analysis. Water and soil contamination are two forms of environmental pollution that could be studied in greater depth in future studies.

Abbreviations

ADF	Augmented Dickey-Fuller
CCR	Canonical Cointegrating Regression
CO_2	Carbon dioxide
CUSUM	Cumulative sum of recursive residuals
CUSUMQ	Cumulative sum of squares of recursive residuals
DF-GLS	Dickey-Fuller generalized least squares
DOLS	Dynamic Ordinary Least Squares
FA	Forest area
FMOLS	Fully modified ordinary least squares
GDP	Gross domestic product
GHGs	Greenhouse gases
MAE	Mean absolute error
NDC	Nationally Determined Contribution
OLS	Ordinary Least Squares
P-P	Phillips-Perron
REDD	Reducing Emissions from Deforestation and forest Degradation
RMSE	Root mean square error
RNE	Renewable energy use
TI	Technological innovations
UNFCCC	United Nations Framework Convention on Climate Change
WDI	World Development Indicator

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Authors' contributions
AR contributed to the study's conceptualization, methodology development, data collection, data curation, data analysis, writing, and visualization. The author read and approved the final manuscript.

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References

Ali AZ, Rahman MS, Raihan A (2022) Soil carbon sequestration in Agroforestry systems as a mitigation strategy of climate change: a case study from Dinajpur, Bangladesh. Adv Environ Eng Res 3(4):1–15. https://doi.org/10.21926/aeer.2204056

Begum RA, Raihan A, Said MNM (2020) Dynamic impacts of economic growth and forested area on carbon dioxide emissions in Malaysia. Sustainability 12(22):9375. https://doi.org/10.3390/su12229375

Chien F, Ajaz T, Andlib Z, Chau KY, Ahmad P, Sharif A (2021) The role of technology innovation, renewable energy and globalization in reducing environmental degradation in Pakistan: a step towards sustainable environment. Renew Energy 177:308–317. https://doi.org/10.1016/j.renene.2021.05.101

Cobb CW, Douglas PH (1928) A theory of production'. Am Econ Rev 18:139–165

Dickey DA, Fuller WA (1979) Distribution of the estimators for autoregressive time series with a unit root. J Am Stat Assoc 74:427–431. https://doi.org/10.1080/01621459.1979.10482531

Elliott G, Rothenberg TJ, Stock JH (1992) Efficient tests for an autoregressive unit root. National Bureau of Economic Research, 1050 Massachusetts Avenue Cambridge, MA 02138, USA.

Habiba U, Xinbang C, Anwar A (2022) Do green technology innovations, financial development, and renewable energy use help to curb carbon emissions? Renew Energy 193:1082–1093. https://doi.org/10.1016/j.renene.2022.05.084

Hansen BE, Phillips PC (1990) Estimation and inference in models of cointegration: a simulation study. Adv Econ 8:225–248

Isfat M, Raihan A (2022) Current practices, challenges, and future directions of climate change adaptation in Bangladesh. Int J Res Publication Rev 3(5):3429–3437

Islam MM, Chowdhury MAM, Begum RA, Amir AA (2022) A bibliometric analysis on the research trends of climate change effects on economic vulnerability. Environ Sci Pollut Res 29:59300–59315. https://doi.org/10.1007/s11356-022-20028-0

Jaafar WSWM, Maulud KNA, Kamarulzaman AMM, Raihan A, Sah SM, Ahmad A, Saad SNM, Azmi ATM, Syukri NKAJ, Khan WR (2020) The influence of forest degradation on land surface temperature – a case study of Perak and Kedah. Malaysia Forests 11(6):670. https://doi.org/10.3390/f11060670

Koondhar MA, Shahbaz M, Ozturk I, Randhawa AA, Kong R (2021) Revisiting the relationship between carbon emission, renewable energy consumption, forestry, and agricultural financial development for China. Environ Sci Pollut Res 28:45459–45473. https://doi.org/10.1007/s11356-021-13606-1

Parajuli R, Joshi O, Maraseni T (2019) Incorporating forests, agriculture, and energy consumption in the framework of the environmental Kuznets curve: a dynamic panel data approach. Sustainability 11(9):2688. https://doi.org/10.3390/su11092688

Park JY (1992) Canonical cointegrating regressions. Econometrica 60:119–143. https://doi.org/10.2307/2951679

Phillips PC, Perron P (1988) Testing for a unit root in time series regression. Biometrika 75(2):335–346

Qayyum M, Ali M, Nizamani MM, Li S, Yu Y, Jahanger A (2021) Nexus between financial development, renewable energy consumption, technological innovations and CO_2 emissions: the case of India. Energies 14(15):4505. https://doi.org/10.3390/en14154505

Raihan A, Said MNM (2022) Cost-benefit analysis of climate change mitigation measures in the forestry sector of Peninsular Malaysia. Earth Syst Environ 6(2):405–419. https://doi.org/10.1007/s41748-021-00241-6

Raihan A, Tuspekova A (2022g) Dynamic impacts of economic growth, energy use, urbanization, tourism, agricultural value-added, and forested area on carbon dioxide emissions in Brazil. J Environ Stud Sci 12(4):794–814. https://doi.org/10.1007/s13412-022-00782-w

Raihan A, Tuspekova A (2022h) Dynamic impacts of economic growth, renewable energy use, urbanization, industrialization, tourism, agriculture, and forests on carbon emissions in Turkey. Carbon Res 1(1):20. https://doi.org/10.1007/s44246-022-00019-z

Raihan A, Tuspekova A (2022i) Nexus between emission reduction factors and anthropogenic carbon emissions in India. Anthropocene Science 1(2):295–310. https://doi.org/10.1007/s44177-022-00028-y

Raihan A, Begum RA, Said MNM, Abdullah SMS (2019) A Review of emission reduction potential and cost savings through forest carbon sequestration. Asian J Water Environ Pollut 16(3):1–7. https://doi.org/10.3233/AJW190027

Raihan A, Begum RA, Said MNM, Pereira JJ (2021b) Assessment of carbon stock in forest biomass and emission reduction potential in Malaysia. Forests 12(10):1294. https://doi.org/10.3390/f12101294

Raihan A, Begum RA, Said MNM, Pereira JJ (2022a) Dynamic impacts of energy use, agricultural land expansion, and deforestation on CO_2 emissions in Malaysia. Environ Ecol Stat 29(3):477–507. https://doi.org/10.1007/s10651-022-00532-9

Raihan A, Begum RA, Said MNM, Pereira JJ (2022b) Relationship between economic growth, renewable energy use, technological innovation, and carbon emission towards achieving Malaysia's Paris agreement. Environ Syst Decisions 42(4):586–607. https://doi.org/10.1007/s10669-022-09848-0

Raihan A, Farhana S, Muhtasim DA, Hasan MAU, Paul A, Faruk O (2022c) The nexus between carbon emission, energy use, and health expenditure: empirical evidence from Bangladesh. Carbon Res 1(1):30. https://doi.org/10.1007/s44246-022-00030-4

Raihan A, Muhtasim DA, Pavel MI, Faruk O, Rahman M (2022h) Dynamic impacts of economic growth, renewable energy use, urbanization, and tourism on carbon dioxide emissions in Argentina. Environ Proc 9(2):38. https://doi.org/10.1007/s40710-022-00590-y

Raihan A, Muhtasim DA, Farhana S, Rahman M, Hasan MAU, Paul A, Faruk O (2023) Dynamic linkages between environmental factors and carbon emissions in Thailand. Environ Proc 10(1):5. https://doi.org/10.1007/s40710-023-00618-x

Raihan A, Tuspekova A (2022a) The nexus between economic growth, renewable energy use, agricultural land expansion, and carbon emissions: new insights from Peru. Energy Nexus 6:100067. https://doi.org/10.1016/j.nexus.2022.100067

Raihan A, Tuspekova A (2022b) Nexus between economic growth, energy use, agricultural productivity, and carbon dioxide emissions: new evidence from Nepal. Energy Nexus 7:100113. https://doi.org/10.1016/j.nexus.2022.100113

Raihan A, Tuspekova A (2022c) Towards sustainability: dynamic nexus between carbon emission and its determining factors in Mexico. Energy Nexus 8:100148. https://doi.org/10.1016/j.nexus.2022.100148

Raihan A, Tuspekova A (2022d) Role of economic growth, renewable energy, and technological innovation to achieve environmental sustainability in Kazakhstan. Curr Res Environ Sustain 4:100165. https://doi.org/10.1016/j.crsust.2022.100165

Raihan A, Tuspekova A (2022e) Dynamic impacts of economic growth, energy use, urbanization, agricultural productivity, and forested area on carbon emissions: New insights from Kazakhstan. World Dev Sustain 1:100019. https://doi.org/10.1016/j.wds.2022.100019

Raihan A, Tuspekova A (2022f) Nexus between energy use, industrialization, forest area, and carbon dioxide emissions: New insights from Russia. J Environ Sci Econ 1(4):1–11. https://doi.org/10.56556/jescae.v1i4.269

Raihan A, Tuspekova A (2022j) Toward a sustainable environment: nexus between economic growth, renewable energy use, forested area, and carbon emissions in Malaysia. Resource Conserv Recycl Adv 15:200096. https://doi.org/10.1016/j.rcradv.2022.200096

Raihan A, Tuspekova A (2022k) The nexus between economic growth, energy use, urbanization, tourism, and carbon dioxide emissions: new insights from Singapore. Sustain Analytic Model 2:100009. https://doi.org/10.1016/j.samod.2022.100009

Raihan A, Tuspekova A (2023a) The role of renewable energy and technological innovations toward achieving Iceland's goal of carbon neutrality by 2040. J Technol Innov Energy 2(1):22–37. https://doi.org/10.56556/jtie.v2i1.421

Raihan A, Tuspekova A (2023b) Towards net zero emissions by 2050: the role of renewable energy, technological innovations, and forests in New Zealand. J Environ Sci Econ 2(1):1–16. https://doi.org/10.56556/jescae.v2i1.422

Raihan A, Voumik LC (2022a) Carbon emission dynamics in India due to financial development, renewable energy utilization, technological innovation, economic growth, and urbanization. J Environ Sci Econ 1(4):36–50. https://doi.org/10.56556/jescae.v1i4.412

Raihan A, Voumik LC (2022b) Carbon emission reduction potential of renewable energy, remittance, and technological innovation: empirical evidence from China. J Technol Innov Energy 1(4):25–36. https://doi.org/10.56556/jtie.v1i4.398

Raihan A, Begum RA, Said MNM, Abdullah SMS (2018) Climate change mitigation options in the forestry sector of Malaysia. J Kejuruteraan SI 1(6):89–98. https://doi.org/10.17576/jkukm-2018-si1(6)-11
Raihan A, Begum RA, Said MNM (2021a) A meta-analysis of the economic value of forest carbon stock. Geografia Malaysian J Soc Space 17(4):321–338. https://doi.org/10.17576/geo-2021-1704-22
Raihan A, Muhtasim DA, Farhana S, Hasan MAU, Pavel MI, Faruk O, Rahman M, Mahmood A (2022d) Nexus between economic growth, energy use, urbanization, agricultural productivity, and carbon dioxide emissions: new insights from Bangladesh. Energy Nexus 8:100144. https://doi.org/10.1016/j.nexus.2022.100144
Raihan A, Muhtasim DA, Farhana S, Hasan MAU, Paul A, Faruk O (2022e) Toward environmental sustainability: Nexus between tourism, economic growth, energy use and carbon emissions in Singapore. Glob Sustain Res 1(2):53–65. https://doi.org/10.56556/gssr.v1i2.408
Raihan A, Muhtasim DA, Farhana S, Pavel MI, Faruk O, Rahman M, Mahmood A (2022f) Nexus between carbon emissions, economic growth, renewable energy use, urbanization, industrialization, technological innovation, and forest area towards achieving environmental sustainability in Bangladesh. Energy Climate Change 3:100080. https://doi.org/10.1016/j.egycc.2022.100080
Raihan A, Muhtasim DA, Pavel MI, Faruk O, Rahman M (2022g) An econometric analysis of the potential emission reduction components in Indonesia. Clean Prod Lett 3:100008. https://doi.org/10.1016/j.clpl.2022.100008
Raihan A, Muhtasim DA, Khan MNA, Pavel MI, Faruk O (2022i) Nexus between carbon emissions, economic growth, renewable energy use, and technological innovation towards achieving environmental sustainability in Bangladesh. Clean Energy Syst 3:100032. https://doi.org/10.1016/j.cles.2022.100032
Raihan A, Ibrahim S, Muhtasim DA (2023a) Dynamic impacts of economic growth, energy use, tourism, and agricultural productivity on carbon dioxide emissions in Egypt. World Dev Sustain 2: 100059. https://doi.org/10.1016/j.wds.2023.100059
Raihan A, Muhtasim DA, Farhana S, Hasan MAU, Pavel MI, Faruk O, Rahman M, Mahmood A (2023b) An econometric analysis of Greenhouse gas emissions from different agricultural factors in Bangladesh. Energy Nexus 9:100179. https://doi.org/10.1016/j.nexus.2023.100179
Raihan A, Pavel MI, Muhtasim DA, Farhana S, Faruk O, Paul A (2023d) The role of renewable energy use, technological innovation, and forest cover toward green development: evidence from Indonesia. Innov Green Dev 2:100035. https://doi.org/10.1016/j.igd.2023.100035
Raihan A (2023a) An econometric evaluation of the effects of economic growth, energy use, and agricultural value added on carbon dioxide emissions in Vietnam. Asia Pacific J Region Sci 7(1). https://doi.org/10.1007/s41685-023-00278-7
Raihan A (2023b) The dynamic nexus between economic growth, renewable energy use, urbanization, industrialization, tourism, agricultural productivity, forest area, and carbon dioxide emissions in the Philippines. Energy Nexus 9:100180. https://doi.org/10.1016/j.nexus.2023.100180
Raihan A (2023c) Toward sustainable and green development in Chile: dynamic influences of carbon emission reduction variables. Innov Green Dev 2:100038. https://doi.org/10.1016/j.igd.2023.100038
Raihan A (2023d) Nexus between economic growth, natural resources rents, trade globalization, financial development, and carbon emissions toward environmental sustainability in Uruguay. Elect J Educ Soc Econ Technol 4(2):55–65. https://doi.org/10.33122/ejeset.v4i2.102
Raihan A (2023e) Exploring environmental Kuznets curve and pollution Haven hypothesis in Bangladesh: the impact of foreign direct investment. J Environ Sci and Econ 2(1):25–36. https://doi.org/10.56556/jescae.v2i1.451
Raihan A, Himu HA (2023) Global impact of COVID-19 on the sustainability of livestock production. Glob Sustain Res 2(2):1–11. https://doi.org/10.56556/gssr.v2i2.447
Raihan A, Voumik LC, Yusma N, Ridzuan AR (2023e) The nexus between international tourist arrivals and energy use towards sustainable tourism in Malaysia. Front Environ Sci 11:575. https://doi.org/10.3389/fenvs.2023.1131782
Raihan A (2023f) Nexus between Greenhouse gas emissions and its determinants: the role of renewable energy and technological innovations towards green development in South Korea. Innov Green Dev 2:100066. https://doi.org/10.1016/j.igd.2023.100066
Shahzadi I, Yaseen MR, Khan MTI, Makhdum MSA, Ali Q (2022) The nexus between research and development, renewable energy and environmental quality: Evidence from developed and developing countries. Renewable Energy 190:1089–1099. https://doi.org/10.1016/j.renene.2021.10.050
Stock JH, Watson MW (1993) A simple estimator of cointegrating vectors in higher order integrated systems. Econometrica 61(4):783–820
Udemba EN, Emir F, Khan NU, Hussain S (2022) Policy inference from technological innovation, renewable energy, and financial development for sustainable development goals (SDGs): insight from asymmetric and bootstrap Granger causality approaches. Environ Sci Pollut Res 29(39):59104–59117. https://doi.org/10.1007/s11356-022-19730-w
Voumik LC, Mimi MB, Raihan A (2023) Nexus between urbanization, industrialization, natural resources rent, and anthropogenic carbon emissions in South Asia: CS-ARDL approach. Anthropoc Sci. https://doi.org/10.1007/s44177-023-00047-3
Voumik LC, Islam MJ, Raihan A (2022a) Electricity production sources and CO_2 emission in OECD countries: static and dynamic panel analysis. Global Sustain Res 1(2):12–21. https://doi.org/10.56556/gssr.v1i2.327
Voumik LC, Nafi SM, Kuri BC, Raihan A (2022b) How tourism affects women's employment in asian countries: an application of generalized method of moments and quantile regression. J Soc Sci Manag Stud 1(4):57–72. https://doi.org/10.56556/jssms.v1i4.335
Waheed R, Chang D, Sarwar S, Chen W (2018) Forest, agriculture, renewable energy, and CO_2 emission. J Clean Prod 172:4231–4238. https://doi.org/10.1016/j.jclepro.2017.10.287
World Bank (2023) World Development Indicators (WDI); Data series by The World Bank Group; The World Bank: Washington, DC, USA. Retrieved from https://databank.worldbank.org/source/world-development-indicators

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