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# How Do Renewable Energy, Economic Growth and Natural Resources Rent Affect Environmental Sustainability in a Globalized Economy? Evidence From Colombia Based on the Gradual Shift Causality Approach

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Undoubtedly, fossil fuel energy consumption causes global warming. The question at the core is whether or not we want to quit energy consumption? The obvious answer to this question is "no." Therefore, the necessity for innovation is curial to attain green energy and sustainable growth. This research specifically focused on Colombia, which represents the aforementioned threats to a large extent as the trajectory of economic expansion is characterized by significant $CO_2$ emissions in Colombia. In this regard, we examine the association between globalization, renewable energy, natural resources rent, economic growth, and $CO_2$ emissions from 1970 to 2017. The cointegration test confirmed a long association between the considered variables. This study employed the Fully Modified Ordinary Least Squares, Dynamic Ordinary Least Squares, and Autoregressive Distributed Lag estimators for the long-run analysis. The long-run empirical results uncovered growth-induced emissions in Colombia. The result illustrated that the path of development is unsustainable in Columbia. In contrast, globalization and renewable energy demonstrated a favorable contribution to environmental quality. The outcomes of the Gradual Shift Causality indicated that globalization, natural resource rent, and economic growth Granger cause $CO_2$ emissions. The findings highlight the need to enact well-coordinated measures to reduce environmental deterioration in Colombia. Colombia must aggressively promote the development of renewable energy and also foster a better viable environment for renewable energy investment to mitigate environmental damage caused by economic growth.

**Keywords: environmental sustainability, Colombia, globalization, renewable energy, $CO_2$ emissions, gradual shift causality test**

# 1 INTRODUCTION

The threat of environmental degradation attracted considerable attention from governments across the globe because it causes global warming, which interrupts the carbon cycle. This recent development in the literature has presented climate change as a difficult challenge. Climate change, mainly $CO_2$ emissions, induced by greenhouse gases (GHGs), poses unparalleled threats to human growth and survival, including severe weather, animal and plants species elimination, and food shortages (Adeshola et al., 2021; Awosusi et al., 2021; Rjoub et al., 2021). The burning of fossil fuels (coal and natural gas) for energy and transportation is the major human activity that contributes to carbon emissions. The implications of global warming and climate change include a wide range of possible physiological, physical, and ecological consequences such as severe weather events (including drought, heatwaves, storms, and floods), increase in sea levels, interruptions in water supplies, and stunted growth of plants; therefore, emissions reduction is vital for human welfare.

Prior studies have suggested that the major sources of emissions are energy use and growth (Tufail et al., 2021; Umar et al., 2021). Developing nations may not be amongst the largest emitters but they do contribute to this process (EIA, 2013). However, the level of emission can reduce to at least 0.4 billion tonnes by 2020 owing to the use of cleaner energy (WHO, 2015). In 2015, about 146 nations had instigated renewable energy strategies targeted at reducing $CO_2$ emissions. Global Renewable Energy Investments were more than $282.2 billion in 2019 (REN21, 2020). Interestingly, the global capacity of renewable energy has upsurged by 43% between 2017 and 2022 (IEA, 2017). This shows the dedication of nations to adopt renewable energy sources. For example, by 2050, Germany and Sweden are anticipated to become carbon-free economies. Currently, Norway and Iceland provide electricity using green energy (Nathaniel and Iheonu 2019; Adebayo et al., 2021; Kirikkaleli and Adebayo, 2021).

Colombia relies largely on hydropower (about 78.29% in 2017), which offers cost-effective and sustainable electricity. Colombia possesses tremendous potential for non-conventional energy sources, including biomass, wind, and solar. Moreover, numerous places in Colombia offer great wind generating capabilities in South America. In particular, the northern Colombian region is divided into winds of class 7 (above 10 m/s). Colombia is projected to be able to create 21,000 MW of wind power in the region of Guajira, sufficient to cover Colombia's demand for electricity twice (Bedoya and Osorio, 2002; Caspary, 2009) in the region of Guajira. Colombia has considerable potential in solar power which can account for average daily insulation of 4.5 kWh/m$^2$ (Gómez-Navarro and Ribó-Pérez, 2018). Finally, Colombia is predicted to have an existing annual power generating potential of more than 16,260 MWh (1398 TOE) from renewable energy sources (Cadena et al., 2008). To take advantage of this potential, investment in these energy sources is necessary but it requires sustainable energy policies and political desire to make this possible. Unfortunately, Colombia still uses fossil fuel in its energy mix, thereby promoting emissions and deteriorating the environment. The benefits of renewable energy sources are enormous. Such as stimulating environmental conservation and supporting sustainable growth (Adebayo and Kirikkaleli, 2021).

There has been extensive literature that examines the extent of the connection between renewable energy and environmental degradation both in developed and emerging nations (Jebli and Youssef, 2017; Sarkodie and Adams, 2018; Dong et al., 2020; Akinsola et al., 2021; Doğan et al., 2021; Erdoğan et al., 2021; Gyamfi et al., 2021; Mohsin et al., 2021; Sarkodie et al., 2021). Nevertheless, their outcomes vary. For example, Dong et al. (2020); Onifade et al. (2021), and Bekun et al. (2021) found that renewable energy does impact $CO_2$ emissions and Jebli and Youssef (2017) claimed that clean energy sources do not necessarily lower emission; however, some studies denied these assertions (Sarkodie and Adams, 2018; Doğan et al., 2021; Gyamfi et al., 2021; Mohsin et al., 2021). Moreover, this explicitly depends on the sort of renewable energy source(s) employed in the model.

However, globalization in the past 3 decades has helped nations to open up their economies through the elimination of economic and social obstacles and constraints (Wang et al., 2020). Globalization aids growth by facilitating foreign investments and international trade (Bilgili et al., 2020). The rising amount of trade resulting from globalization, has three environmental implications, particularly the scale, composition, and technique effect. The scale effect is related to the impact of foreign trade on the level of production. Globalization boosts economic activity in this setting by boosting demand for products and services globally (Kirikkaleli and Adebayo, 2020). More production and more pollution are caused by the increasing economic activities. The scale effect describes the impact of trade on production in different nations. In this context, poor nations with weak environmental laws are particularly specialized in the manufacturing of dirty products whereas industrialized nations with stringent environmental rules are specialized in areas of clean production (Ulucak et al., 2020). This supports the argument of the pollution haven hypothesis and justifies the reallocation of dirty industries to developing nations from developed nations.

Likewise, the hypothesis of factor endowment states that nations endowed in natural resources would emphasize more on exporting the resource-intensive commodities generated by dirty industries *via* globalization when the environmental control is too stringent. The technique effect explains the impact of globalization in enabling nations to acquire clean energy technologies that may transform their manufacturing operations, thereby encouraging energy efficiency and minimizing $CO_2$ emissions (Ulucak and Ozcan, 2020). The unwanted impacts of foreign trade can be avoided by introducing appropriate environmental regulations (Teng et al., 2021). Globalization, through technology transfer from developed nations, may assist countries to improve environmental quality and environmental management (Nathaniel et al., 2021; Usman et al., 2021). This is one of the many benefits of the roles of globalization towards decreasing environmental degradation. The empirical findings regarding the role of globalization in environmental pollution differ. For instance, many studies conclude that globalization increases environmental pollution (Nguyen and Le., 2020; Wang et al., 2020) but numerous studies also refute these claims (Ulucak and Ozcan, 2020; Usman et al., 2020; Teng et al., 2021).

The choice of study to focus on Colombia is based on her special attributes making the country hugely interesting for this study. Colombia is the fifth-largest emitter of carbon emissions in Latin American Countries. The Colombian government is committed to reducing GHGs up to 51% by 2030 compared with the 2014 level. Despite her potential and commitment to decrease non-conventional energy sources, the use of non-renewable energy sources continues to increase. The consequences of climate change place Colombia at great risk. Most of the citizens live in the elevated Andes, where there is already a shortage of water and earth instability, and on the shore, where the rise in sea level and the flood can have an impact on settlements and economic activities. In addition, the country is seeing a high incidence of severe climate emergencies. Colombia has a large number of natural resources, namely gold, natural gas, copper, iron ore, limestone, steel, petroleum, emeralds, and nickel. The country's GDP increased by 2.7% in the fourth quarter of 2018. In the same year, natural resource rent contributed 5.02 percent to Colombia's GDP. Lastly, Colombia is strongly connected with the rest of the globe and follows various trade agreements. Such as the United States-Colombia Free trade agreement, Canada-Colombia Free trade agreement, Colombia-European Free trade association agreement, Guatemala-El Salvador-Colombia-Honduras Free Trade agreements, and Pacific alliance Free trade agreement. On these grounds, concentrating on Colombia would make a substantial contribution to the environmental literature and will help to suggest policies for attaining a low-carbon economy and carbon neutrality.

To avoid over-generalization, this research adds to the environmental literature in different ways. First, the roles of globalization and renewable energy in $CO_2$ emissions are ascertained in Colombia by incorporating natural resources rent and economic growth as control variables using annual data covering the period between 1970 and 2018. The study employed the globalization index (KOF index) which includes different aspects of globalization, namely economic, social, and political aspects. The authors of this study are unaware of any prior study that evaluated the effect of renewable energy, economic growth, globalization, and natural resource rents on $CO_2$ emissions in Colombia. Second, this research also contributes methodologically by utilizing the Autoregressive Distributed Lag (ARDL) model. The ARDL is robust against misspecification bias and endogeneity issues. Also, the long and short effect of the determinant of $CO_2$ emission is uncovered. Third, unlike other studies, the Gradual Shift Causality approach was used to detect the causal connection between $CO_2$ emissions and its determinants in the presence of structural shifts. Four, this study utilizes the Dynamic Ordinary Least Squares (DOLS) and Fully Modified Ordinary Least Squares (FMOLS) methods to ensure the soundness of the estimation; thus, the study intends to report reliable outcomes and policy suggestions.

The following outline is followed in the rest of the study. **Section 2** gives insights into the relevant literature for this study, **Section 3** describes the method used, **Section 4** presents the outcomes of the study, while **Section 5** contains the concluding remarks.

## 2 LITERATURE REVIEW

Su et al. (2021) reported the economic growth and $CO_2$ emissions interaction in Brazil from 1990 to 2018. The outcome shows an inverted U-shaped interaction between $CO_2$ emissions and economic growth. Ahmad et al. (2021) studied the association between $CO_2$ emissions and economic growth in 26 OECD economies spanning between 1990 and 2014 and the outcomes of the empirical analysis reveal that there is a positive interaction between $CO_2$ emissions and economic growth. Akadiri and Adebayo (2021) explore the causal interaction between $CO_2$ emissions and economic growth in NICs, using MMQR covering the period between 1990 and 2018. Their empirical analysis indicates a one-directional causality from economic growth to $CO_2$ emissions. The research of Gao and Zhang (2021) probed the relations between $CO_2$ emissions and economic growth for 13 Asian economies spanning from 1980 to 2010. The finding discovers a one-directional causality from $CO_2$ emissions to economic growth. Using the ARDL, Ali et al. (2021) detected a positive relationship between economic growth and $CO_2$ emissions in Pakistan covering 1971–2014. Namahoro et al. (2021) investigated the asymmetric association between $CO_2$ emissions and economic growth in seven East African countries. The empirical analysis uncovered that economic growth has a positive linkage with $CO_2$ emissions at the regional level; however, across the country level, the association was volatile.

Ghazouani (2021) detected a one-directional causality from economic growth to $CO_2$ emissions covering the period from 1972 to 2016 in Tunisia. Hao et al. (2021) established a positive interconnection between $CO_2$ emissions and economic growth, and a one-way causality from economic growth to $CO_2$ emissions in G7 economies. Bekun et al. (2021) also found a similar outcome between $CO_2$ emissions and economic growth in newly industrialised nations for data ranging between 1971 and 2014. Using similar techniques, Zhang et al. (2021) detected a one-way causality from economic growth to $CO_2$ emissions in Malaysia. A study for Ghana by Minlah and Zhang (2021) uncovered a bidirectional causality connection between $CO_2$ emissions and economic growth. Using ARDL and VAR, Zubair et al. (2020) discovered that an increase in economic growth causes environmental degradation and no causal link between $CO_2$ emissions and economic growth exists in Nigeria. Zhang and Zhang (2020) also corroborated this finding in 30 Chinese provinces using the VECM approach from 2000 to 2017.

Liu et al. (2020) reported the interaction between $CO_2$ emissions and globalization utilizing the semi-parametric panel fixed effect approach covering the period between 1970 and 2015 for G-7 economies. Their empirical evidence revealed an inverted U-shaped link between $CO_2$ emissions and globalization. Using the ARDL method, Nguyen and Le (2020) found a positive interconnection between $CO_2$ emissions and globalization in Vietnam spanning between 1990 and 2016. Wang et al. (2020) explored the interconnection between $CO_2$ emissions and globalization in G-7 economies employing the CS-ARDL approach, a positive interaction was evident between $CO_2$ emissions and globalization from 1996 to 2017. They also validated these findings by using the AMG (Augmented Mean Group) and CCEMG (Common Correlated Effects Mean Group). Umar et al. (2020) found a negative relationship between $CO_2$ and globalization employing ARDL, FMOLS, DOLS, and CCR for China covering 1980 to 2017 but the causality evidence indicates a one-way causality from globalization to $CO_2$ emissions.

Mehmood and Tariq (2020) establish that there is an inverted U-formed interaction between $CO_2$ emissions and globalization in South Asian nations over the period from 1972 to 2013 and a bidirectional causal association between $CO_2$ and globalization. Akadiri et al. (2020) used the Toda-Yamamoto Granger causality to establish no causal interaction between $CO_2$ emissions and globalization in China. Ahmed and Le's (2021) investigation in six ASEAN countries found a negative interaction between $CO_2$ emissions and trade globalization and unidirectional causality from trade globalization to $CO_2$ emissions. Ulucak and Khan's (2020) empirical evidence for BRICS covering 1990 to 2015, establishes a negative interaction between $CO_2$ emissions and globalization. Teng et al. (2021) applied the pooled mean group to establish a negative interconnection between $CO_2$ emissions and globalization in 10 selected countries. Using the dataset spanning from 1971 to 2014, Usman et al. (2020) employed the FMOLS for the case of South Africa and the empirical outcome uncovers a negative interconnection between $CO_2$ emissions and globalization. Using the AMG and the CCEMG, Nathaniel et al. (2021) scrutinized the interconnection between $CO_2$ emissions and globalization in LACC (Latin America and Caribbean Countries) and suggests a positive connection between $CO_2$ emissions and globalization. Using the non-linear ARDL methods, Ahmed et al. (2021a) and Ahmed et al. (2021b) unfoled that asymmetric relationships between various forms of globalization and environmental deterioration exist in Japan and the United States, respectively.

Adebayo and Kirikkaleli (2021) employed the wavelets tools to investigate the effects of renewable energy on carbon emission in Japan applying the quarterly dataset covering the period from 1990Q1-2015Q4. Their outcome showed that renewable energy mitigates $CO_2$ emissions. Muhammad et al. (2021) employed the dynamic fixed effect, and GMM estimators to explore how renewable energy impacts $CO_2$ emissions in 176 nations and discovered that renewable energy adds to environmental quality. Whereas, the investigation of Dong et al. (2020) for 120 countries found that renewable had no significant influence on emissions. The finding of Dong et al. (2020) opposed the study of Sarkodie and Adams (2018) for South Africa. Mohsin et al. (2021) reported that the continuous usage of renewable energy will help to mitigate the environmental degradation generated due to economic expansion in 25 Asian nations. Gyamfi et al. (2021) scrutinized the effect of renewable energy on emissions in E7 nations and uncovers that the increase in renewable energy reduced emissions by 0.088%. Doğan et al. (2021) uncovered that renewable energy drives environmental sustainability in 28 OECD nations. This is different from the outcome of Jebli and Youssef (2017) for North Africa countries. Nevertheless, the outcome of Nathaniel and Iheonu (2019) for Africa corroborates those of Doğan et al. (2021) by confirming that renewable energy reduces emissions.

Finally, the effects of natural resource rents on emissions are relatively less discussed in the environmental literature. The association of natural resources rent and emissions was investigated in OECD countries by Ulucak and Ozcan (2020) using AMG estimators. They revealed that natural resource rents contribute to environmental degradation. In a provincial panel analysis done in China, Shen et al. (2021) established the positive effect of natural resource rents on environmental degradation within the period between 1995 and 2017. The study of Tufail et al. (2021) in developed nations covering the period between 1990 and 2018, discovered the harmful effect of natural resource rents on the environment. Tauseef et al. (2021) revealed that natural resources damaged the quality of the environment in Pakistan. Wang et al. (2020) used CS-ARDL to investigate the effect of natural resource rents on environmental quality in G7 nations for the period of 1996–2017. They revealed that the natural resources rents contribute to environmental pollution. The study of Baloch et al. (2019) established a mixed outcome regarding the effect of natural resources rents on emission in BRICS economies. However, the study of Khan et al. (2021) for the United States opposes these outcomes and concluded that the natural resources rents reduce environmental pollution.

Previous literature on causal aspects and long-run relationships between these variables illustrates varied outcomes. Also, no empirical work exists in Columbia. This serves as a motivation for the authors to probe into the impact of renewable energy, economic growth, globalization, and natural resources rents on $CO_2$ emissions for insightful policies recommendation. Hence, this research adds to the environmental literature by probing the association between globalization, renewable energy, and natural resources rent on $CO_2$ emissions in Colombia. To the best of the authors' knowledge, no prior studies have investigated these associations before. Finally, the causal associations of the variables were investigated using the Fourier Toda-Yamamoto causality (Gradual Shift Causality), because this is a recent technique that is capable of capturing structural shift during regression, which provides accurate outcomes, unlike the conventional causality tests.

## 3 DATA, MODEL, AND METHODS

### 3.1 Data

To establish the aim of this study, the considered variables are renewable energy consumed, economic growth, globalization, natural resources rent, and $CO_2$ emissions. The renewable

**TABLE 1 |** Description of the variable.

| Variables | Description | Sourced |
|---|---|---|
| $CO_2$ | Per capita $CO_2$ emissions | British Petroleum database |
| GDP | GDP per capita (constant 2010 US$) | World Bank Database indicators |
| RENE | Renewable energy consumption per capita kWh | British Petroleum database |
| GLO | Globalization index based on economic, political, and social | KOF Globalization Index |
| NRR | Total natural resources rents (% of GDP) | World Bank Database indicators |

**TABLE 2 |** Descriptive statistics.

| | $CO_2$ | GDP | RENE | NRR | GLO |
|---|---|---|---|---|---|
| Mean | 1.6117 | 4,933.960 | 2059.667 | 4.4783 | 49.2305 |
| Median | 1.6139 | 4,801.069 | 2,303.578 | 4.1088 | 47.3094 |
| Maximum | 2.0923 | 7,694.427 | 3,040.812 | 9.6011 | 63.6590 |
| Minimum | 1.2969 | 2,879.251 | 782.7370 | 1.1855 | 38.3786 |
| Std. Dev. | 0.1793 | 1,361.853 | 630.3637 | 1.9254 | 8.2218 |
| Skewness | 0.3142 | 0.6381 | −0.5965 | 0.5882 | 0.4965 |
| Kurtosis | 2.7660 | 2.4446 | 2.1440 | 2.9597 | 1.8246 |
| Jarque-Bera | 0.9180 | 3.9559 | 4.4025 | 2.8289 | 4.8341 |
| Probability | 0.6318 | 0.1383 | 0.1106 | 0.2430 | 0.0891 |
| Observations | 49 | 49 | 49 | 49 | 49 |

energy consumed and $CO_2$ emissions were collected from the British Petroleum database[1]. The globalization index was obtained from the Swiss Economic Institute[2] (Dreher 2006; Gygli et al., 2019). From the World Bank Database[3], we obtained the economic growth and natural resources rents. We acquired annual data from 1970 to 2018, and the data span purely depends upon data availability on globalization. For adequate information about the variables of concern, see **Table 1**. The descriptive statistics for each variable are summarized in **Table 2**. The range of each variable, mean, median, standard deviation, and information regarding normality of data are presented in **Table 1**. The range for $CO_2$ lies between 2.0923 and 1.2969 with 1.6117 as its mean value, while 1.6139 and 0.1793 are its median and standard deviation values, respectively.

Economic growth possesses the highest mean value (4,933.960) amongst all variables. Its median and standard deviation values are 4,801.069 and 1,361.853, respectively, and the values of economic growth are between 7,694.427 and 2,879.251. For renewable energy, the range is between 1.1855 and 9.6011, the average value is 4.4783, while its median and standard deviation value are 4.1088 and 1.9254, respectively. The average value for natural resources rents is 4.4783 with its median value of 4.1088, the standard deviation value of 1.9254, and the range is between 1.1855 and 9.6011. The average, median, and standard deviation values of globalization are 49.2305, 47.3094, and 8.2218, correspondingly and it ranges between 38.3786 and 63.6590. Based on the normality of the variable, the Kurtosis for these series is platykurtic since values of the Kurtosis are less than 3 while the series' skewness is moderately skewed since the values of the skewness are less than 1. However, the Jarque-Bera and its probability also confirm that the series is normally distributed around its mean in most cases.

## 3.2 Model Construction

The association between the dependent and independent variable is defined in **Eq. 1**:

$$CO_{2t} = f\,(GDP_t, RENE_t, NRR_t, GLO_t) \tag{1}$$

Where: $CO_2$, GDP, RENE, GLO, and NRR denote $CO_2$ emissions, economic growth, renewable energy, globalization, and natural resources rents, respectively. **Eq. 2** depicts the econometric model since parameters $\beta_{\mathrm{i}\,=\,4}$ were included in the model to denote the coefficients of our considered variables, and $\varepsilon_t$ is the disturbance term.

$$CO_{2t} = \beta_0 + \beta_1 GDP_t + \beta_2 RENE_t + \beta_3 NRR_t + \beta_4 GLO_t + \varepsilon_t \tag{2}$$

Subscript t in the model indicates the period of concern (1970–2018). To ensure homogeneity among the variable used, we take the natural logarithm of the function of the $CO_2$ emissions, and the modified form of **Eq. 2** is expressed as **Eq. 3**.

$$CO_{2t} = \beta_0 + \beta_1 InGDP_{t-1} + \beta_2 InRENE_{t-1} + \beta_3 InNRR_{t-1} + \beta_4 InGLO_{t-1} + \varepsilon_t \tag{3}$$

## 3.3 Theoretical Underpinning

Concerning the general tradeoff between economic growth and environmental quality in the energy economics literature, we envisioned a positive coefficient between $CO_2$ emissions and GDP, i.e., $(\beta_1 = \frac{\delta CO_2}{\delta GDP} > 0)$ (Ayobamiji and Kalmaz, 2020; Murshed et al., 2021; Ramzan et al., 2021; Umarbeyli et al., 2021). It is generally acknowledged that the high use of fossil fuels contributes to a variety of environmental issues (Magazzino et al., 2020; Oladipupo et al., 2021). To mitigate these environmental issues, the study of Ahmed et al. (2021) and Bekun et al. (2021) suggested that the usage of fossil fuel should be substituted with renewable energy sources. Even though renewable energy use in Colombia has risen in comparison to the past, its share of overall energy has declined. The big concern is whether renewable energy use has achieved an adequate amount to mitigate environmental pollution in Colombia. As a result, this research considers the

[1]https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html

[2]https://kof.ethz.ch/en/forecasts-and-indicators/indicators/kof-globalisation-index.html

[3]https://data.worldbank.org/country/colombia

potential effect of renewable energy use on $CO_2$ emissions, and we expect that there is a negative interaction between $CO_2$ emissions and renewable energy use, i.e., ($\beta_2 = \frac{\delta CO_2}{\delta RENE} < 0$). Furthermore, we incorporate natural resource rents into the model to examine the role of natural resources in $CO_2$ emissions. Nations around the globe are more concerned about improving the quality of the environment; however, they choose quantity over quality that leads to ineffective environmental regulations. Natural resource exploitation deepens economic expansion as well as worsens the quality of the environment. Therefore, it is projected that natural resources rents will have a detrimental effect on the quality of the environment, i.e., ($\beta_2 = \frac{\delta CO_2}{\delta NRR} > 0$). Another contributor to environmental degradation is globalization. There are two opposing perspectives on this subject in previous studies. First, as part of the globalization trend, corporations invest in nations with strict environmental policies. Second, multinational corporations that operate on a global scale pass renewable technologies to the host country. As a result, the effect of globalization on $CO_2$ emissions needs to be investigated, since there are several multinational corporations present in Colombia. However, this study anticipates that there is a negative interaction between $CO_2$ emissions and globalization, i.e., ($\beta_4 = \frac{\delta CO_2}{\delta GLO} < 0$).

## 3.4 Econometric Methodology

### 3.4.1 Unit Roots Tests

This study begins empirical analysis with the unit root tests. For the unit root test, this study employed Augmented Dickey-Fuller (ADF) and Phillips–Perron (PP) tests developed by Dickey and Fuller (1979) and Phillips and Perron (1988), respectively. The ADF and PP unit root tests are regarded as conventional unit root tests. The ADF and PP unit-roots are defined in **Eqs 4** and **5** as follows:

$$\Delta Y_t = \beta_1 Y_{t-1} + \sum_{i-1}^{n} b_1 \Delta Y_{t-1} + \epsilon_t \tag{4}$$

$$\Delta Y_t = \beta_0 + \beta_1 t + \beta_2 Y_{t-1} + \epsilon_t \tag{5}$$

where: $\Delta$, $Y$, $n$, and $t$ depict the first difference, variables used, time, lags, and errors term.

### 3.4.2 ARDL Approach

The ARDL bound test of Pesaran et al. (2001) was utilized to ascertain the long-run linkage after exploring the order of integration among the variables used. There are several cointegration techniques, but this study deployed the ARDL bound test because it is more advantageous compared to the other cointegration techniques due to the following reasons. The bound test is flexible and allows variables integrated at the order I (0) and 1 (1) to be utilized in the model. It generates reliable long-run results, and a small sample size can be estimated using the ARDL bound test compared to the conventional cointegration tests. The endogeneity problem is also addressed by this method (Kirikkaleli et al., 2021). The F-statistic proposed by Pesaran et al. (2001) was compared with critical bound values to check the cointegration. The null and alternative hypotheses of this method check that there is no cointegrating interconnection in the long run, and there is cointegration in the long run, respectively. The alternative hypothesis is accepted if the F-Stat is higher than the upper bound critical value at 1, 5, or 10%, respectively.

The ARDL model in this paper is depicted in **Eq. 6**.

$$\begin{aligned}\Delta CO_{2t} = \theta_0 &+ \sum_{l=1}^{p} \theta_1 \Delta CO_{2t-1} + \sum_{i=1}^{p} \theta_2 \Delta GDP_{t-1} + \sum_{i=1}^{p} \theta_3 RENE_{t-1} \\ &+ \sum_{i=1}^{p} \theta_4 \Delta NRR_{t-1} + \sum_{i=1}^{p} \theta_5 \Delta GLO_{t-1} + \pi_1 CO_{2t-1} \\ &+ \pi_2 GDP_{t-1} + \pi_3 RENE_{t-1} + \pi_4 NRR_{t-1} + \pi_5 GLO_{t-1} \\ &+ \epsilon_t\end{aligned} \tag{6}$$

In **Eq. 6**, the parameter's coefficients of the short-run dynamic are represented by $\theta_i (i = 1 \ldots 5)$, the long-run connection amongst variables is shown by $\pi_i$ $(i = 1 \ldots 5)$, lag lengths are illustrated by t. Integrating the ECM into the ARDL short-term parameter, which transforms **Eq. 6** into **Eq. 7**:

$$\begin{aligned}\Delta CO_{2t} = \theta_0 &+ \sum_{l=1}^{p} \theta_1 \Delta CO_{2t-1} + \sum_{i=1}^{p} \theta_2 \Delta GDP_{t-1} + \sum_{i=1}^{p} \theta_3 RENE_{t-1} \\ &+ \sum_{i=1}^{p} \theta_4 \Delta NRR_{t-1} + \sum_{i=1}^{p} \theta_5 \Delta GLO_{t-1} + \pi_1 CO_{2t-1} \\ &+ \pi_2 GDP_{t-1} + \pi_3 RENE_{t-1} + \pi_4 NRR_{t-1} + \pi_4 GLO_{t-1} \\ &+ \alpha ECT_{-1} + \epsilon_t\end{aligned} \tag{7}$$

Where: the speed of adjustment for this model is represented by $\alpha$ and the error correction term is indicated by $ECT_t$. The predictable symbol of this coefficient, as anticipated, is negative and significant. After identifying the cointegration association in **Eq. 6** the ARDL method was utilized to analyze the dynamic interaction between $CO_2$ emissions and its determinants.

We capture coefficients in the long run by employing the DOLS and FMOLS approaches initiated by Phillips and Hansen (1990) and Stock and Watson (1993), respectively. The DOLS and FMOLS allow asymptotic coherence by taking into account the effect of serial correlation. However, these estimators will be employed after cointegration is evident amongst these variables.

### 3.4.3 Gradual Shift Causality

Using Nazlioglu et al. (2016)'s Fourier Toda-Yamamoto causality, we consider the causal linkage between $CO_2$ emissions and its regressors (economic growth, renewable energy, and globalization). The Fourier Toda-Yamamoto causality is capable of capturing structural shift during regression, which provides accurate causality outcome, unlike the conventional causality test. Nazlioglu et al. (2016) used the VAR (p + d) to construct this model. The VAR (p + d) model is described as:

$$y_t = \alpha(t) + \beta_1 y_{t-1} + \ldots + \beta_{p+d\max} y_{t-(p+d\max)} + \varepsilon_t \tag{8}$$

**TABLE 3 |** Conventional unit-root outcomes.

| | ADF | | PP | |
|---|---|---|---|---|
| | I (0) | I (1) | I (0) | I (1) |
| $CO_2$ | −2.143 | −7.934* | −2.115 | −8.024* |
| GDP | −2.621 | −3.958** | −2.146 | −3.958** |
| RENE | −2.331 | 7.486* | −2.217 | 8.727* |
| NRR | −3.654** | −6.996* | −3.510** | −9.359* |
| GLO | −3.001 | −8.952* | −2.945 | −12.334* |

*Significance levels of 0.01 and 0.05 are indicated as * and **, respectively.*

**TABLE 4 |** ARDL approach to cointegration.

| Model specification | $CO_2 = f(GDP, RENE, NRR, GLO)$ |
|---|---|
| F-statistic | 7.928* |
| Lower and Upper Bound | 3.74 and 5.61 |
| Inference | (3, 0, 4, 2, 0) |
| Cointegration | Yes |

*Significance level of 0.01 is indicated as *.*

where: the VAR model intercept is α, while the matrices parameter is β, and the variables used ($CO_2$, EC, GLO, and URB) are portrayed by $y_t$. Fourier Toda-Yamamoto causality is defined by these subsequent equations. **Eq. 9** portrays the Fourier approximation that uncovers the structural shifts.

$$\sigma(t) = \sigma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \tag{9}$$

Where s and $\gamma_{1k}$ depict the number and size of frequency, respectively. The changes in frequency are measured by $\gamma_{2k}$, and $k$ denotes the approximation frequency. The Fourier Toda-Yamamoto causality is defined in **Eq. 10** when **Eq. 9** was substituted into **Eqs 8** and **10** was formed

$$y_t = \sigma_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \ldots + \beta_{p+d} y_{t-(p+d)} + \varepsilon_t \tag{10}$$

Employing the Wald statistic, the null hypothesis guarding this approach is ($H_0$: $\beta_1 = \beta_\Theta = 0$) against the alternate hypothesis ($H_0$: $\beta_1 \neq \beta_\Theta \neq 0$).

## 4 EMPIRICAL FINDINGS AND DISCUSSION

### 4.1 Findings

Proceeding to empirical estimates, given the period of investigation, it is essential to examine whether the series are stationary at the level [I (0)] or the first difference [I (1)]. Thus, we utilized the ADF and PP stationary test. The outcomes of the unit root tests were reported in **Table 3**. For the ADF, at the first difference, $CO_2$ emissions, renewable energy use, natural resources rent, and globalization are stationary. Furthermore, NRR was stationary at I (0). All series are integrated at I (1) and I (0). For the case of PP, the outcomes were also similar to the ADF unit root test's outcomes. Overall, there is a mixed order of integration, fulfilling the prerequisite to do the cointegration analysis. Our decision to use the ARDL bounds test is based on the mixed stationarity nature of the variable used and other benefits discussed in the previous section. **Table 4** shows the outcome of the ARDL bounds test, confirming the rejection of the null hypothesis at a 1% significance level, thus, showing that cointegration is evident among the study's considered variables.

**TABLE 5 |** ARDL estimators outcome.

| Variable | Long-run outcomes | |
|---|---|---|
| | Coefficients | T-statistics |
| GDP | 1.129* | 4.510 |
| RENE | −0.257* | −4.669 |
| NRR | 0.050 | 1.443 |
| GLO | −1.380* | −4.241 |
| Short-run outcomes | | |
| ΔGLO | −0.562** | −2.214 |
| ΔNRR | −0.009 | 0.404 |
| ECT(−1) | −0.368* | −6.690 |
| Diagnostic check | | |
| $\chi^2$ Normality | 0.664 (0.718) | |
| $\chi^2$ LM | 0.370 (0.694) | |
| $\chi^2$ Heteroscedasticity | 1.415 (0.208) | |
| $\chi^2$ Ramsey | 2.633 (0.089) | |

*Significance levels of 0.01 and 0.05 are indicated as * and **, respectively. Values reported in brackets denote p-values.*

Based on the above findings the long-run relationship can be captured, which is a key objective of our study. Then, we used the ARDL test, which is suitable for evaluating the long and short-term elasticities, provides unbiased estimates, and solves endogeneity issues. **Table 5** reports the ARDL estimation, suggesting that economic growth, natural resource rents, and globalization are significant influencing factors of environmental degradation. For more details, the coefficient of economic growth is positive revealing that an upsurge in economic growth by 1% leads to a 1.12% increase in $CO_2$ emissions, inferring that deterioration of the environment is mostly impacted by the expansion in economic growth. Conversely, there is a negative interaction between renewable energy and $CO_2$ emissions, thus, an increase in environmental quality by 0.25% can be instigated by a one percent surge in renewable energy, suggesting that renewable energy reduces $CO_2$ emissions instead of increasing.

Astonishingly, there is a positive interaction between natural resources rents and $CO_2$ emissions but this is insignificant. Finally, globalization exhibits an adverse effect on $CO_2$ emissions. A 1% rise in globalization will reduce environmental degradation by 1.38%, meaning that globalization in Colombia helps to achieve a sustainable environment since it reduces $CO_2$ emissions.

For the short-run associations, the association between natural resources rent and $CO_2$ emissions is positive and insignificant. Between globalization and $CO_2$ emissions, a negative association was reported, which is identical to the long-run relationship.

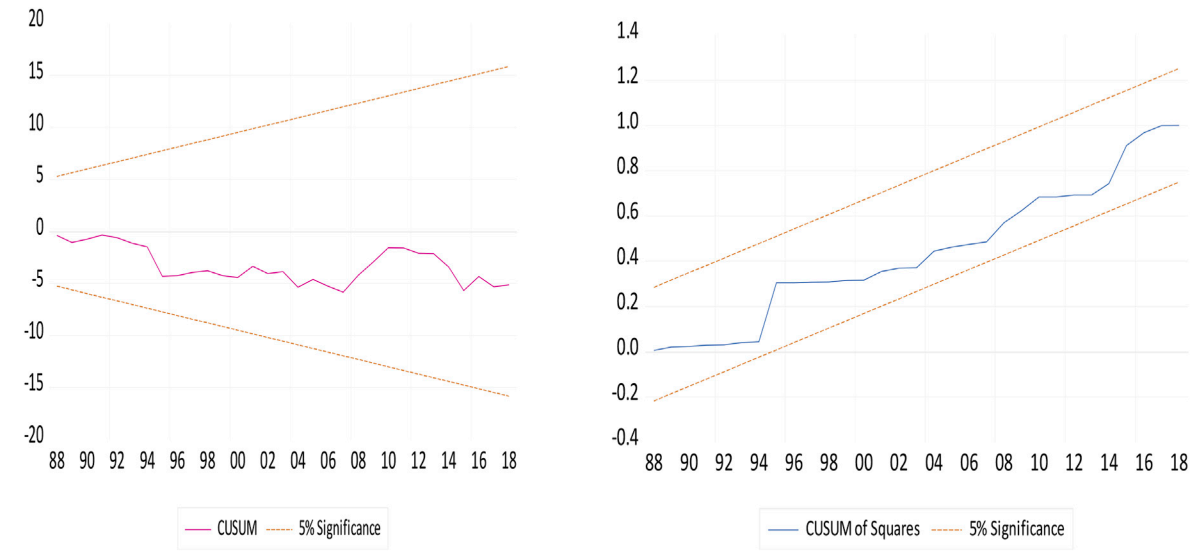


**FIGURE 1 |** Stability test.

**TABLE 6 |** Robustness estimator outcome.

| Variable | DOLS | | FMOLS | |
|---|---|---|---|---|
| | Coefficients | T-statistics | Coefficients | T-statistics |
| GDP | 2.061* | 5.222 | 1.812* | 7.134 |
| RENE | −0.326* | −3.510 | −0.270* | −3.423 |
| NRR | −0.012 | −0.231 | −0.019 | −0.516 |
| GLO | −2.501* | −4.614 | −2.181* | −6.223 |

*Significance level of 0.01 is indicated as *.*

**TABLE 7 |** Gradual shift causality test.

| Causal direction | No. of Fourier | Wald-stat | Prob. value |
|---|---|---|---|
| $CO_2$→ GDP | 4 | 5.686 | 0.577 |
| GDP → $CO_2$ | 4 | 14.942** | 0.037 |
| $CO_2$ → RENE | 4 | 10.364 | 0.169 |
| RENE → $CO_2$ | 4 | 6.956 | 0.433 |
| $CO_2$ → NRR | 3 | 5.628 | 0.584 |
| NRR → $CO_2$ | 3 | 21.583* | 0.003 |
| $CO_2$→ GLO | 1 | 6.070 | 0.532 |
| GLO → $CO_2$ | 1 | 22.794* | 0.002 |
| GDP→ RENE | 2 | 14.388** | 0.045 |
| RENE→ GDP | 2 | 4.347 | 0.740 |
| GDP→ NRR | 1 | 11.301 | 0.126 |
| NRR→ GDP | 1 | 1.176 | 0.992 |
| GDP→ GLO | 2 | 23.442* | 0.001 |
| GLO→ GDP | 2 | 2.469 | 0.929 |
| RENE→ NRR | 2 | 20.446* | 0.005 |
| NRR→ RENE | 2 | 4.802 | 0.684 |
| RENE→ GLO | 3 | 1.489 | 0.983 |
| GLO→ RENE | 3 | 15.410** | 0.031 |
| NRR→ GLO | 1 | 3.561 | 0.829 |
| GLO→ NRR | 1 | 14.883** | 0.038 |

*Significance levels of 0.01 and 0.05 are indicated by * and **, respectively.*

Since the ECM is 0.368 and negatively significant, this shows that in the case where there is a disequilibrium, the rate of convergence is 36.8% yearly. The model is considered satisfactory since the diagnostics test outcomes are desirable. The model has no downside as indicated by heteroscedasticity, serial correlation, Ramsey RESET test, and Normality test. Lastly, **Figure 1** shows that the model is stable at a 5% significance level. Therefore, this model is considered to be effective for policy recommendations. In the closing stage of the estimation of the long-run association, we try to check the accuracy and effectiveness of the outcome of the ARDL estimator by utilizing the FMOLS and DOLS estimators, which were depicted in **Table 6**. Also, the FMOLS and DOLS outcomes are similar to the ARDL estimator's results. Hence, we can conclude that our estimations are reliable for formulating policies.

After examining the long-run connection, it is critical to inspect the causal association to aid policy formulation. The causal interaction between the $CO_2$ emissions and its determinants was explored using the Gradual Shift Causality test (**Table 7**). As mentioned earlier, the advantage of this technique is that it incorporates structural shifts in estimation. The flow of causality is from economic growth to $CO_2$ emissions in Colombia. Likewise, there is a causal interaction flow from natural resources rents to $CO_2$ emissions within the period of analysis. Finally, the movement of causal interaction from globalization to $CO_2$ emissions is found. The outcome also shows that economic growth Granger causes renewable energy consumption and globalization. There is a one-directional causal association from renewable energy to natural resource rents. There is a one-directional causality from globalization to renewable energy usage. There is unidirectional causality from globalization to natural resource rents.

## 4.2 Discussion of Outcome

We proceed to the discussion of outcomes, it is evident that environmental deterioration is largely influenced by the expansion in economic growth in Colombia. This finding agrees with the study of Awosusi et al. (2021) for South Korea, Ayobamiji and Kalmaz (2020) for Nigeria, Awosusi et al. (2021) for MINT economies, Odugbesan et al. (2021) for Brazil. It also complies with the outcome of Ali et al. (2021) for Pakistan, Namahoro et al. (2021), Hao et al. (2021) for G7 economies, Ahmed et al. (2021c) for G7, Regmi and Rehman (2021) for Nepal, Rehman et al. (2021) for Pakistan but the study of Nathaniel and Iheonu (2019) contradict this study's outcome. The possible reason for this outcome is that Colombia like other developing nations prioritized the growth of her economy at the expense of environmental quality. The persistent economic growth over the last 10 years has continued to mount pressure on the energy demand. The major sector of the country (are mining, manufacturing, and agriculture) depend largely on conventional sources of energy that contributes to environmental degradation. The overwhelming reliance on the usage of fossil fuel in meeting the demands of the commercial and household sectors increases emissions. Furthermore, the development of the country's infrastructure also worsens the quality of the environment. The country's commitment to cut her GHGs flaring by 51% by 2030 requires a reduction in the usage of fossil fuels by adopting alternative sources of energy that will promote environmental sustainability.

The positive effect of renewable energy on environmental sustainability complies with the finding of Sarkodie and Adams (2018), Akadiri and Adebayo (2021), Mohsin et al. (2021), Gyamfi et al. (2021), Yuping et al. (2021), Rjoub and Adebayo (2021), and Doğan et al. (2021). The reasonable explanation of this effect is that Colombia is rich in energy particularly hydropower, which constitutes about 65% of the annual total energy consumption, thereby providing less costly electricity. According to the UN Industrial Development Organization and the International Centre on Small Hydro Power, in 2010, Colombia saw its highest growth for renewable energy generation and added 2,543 MW of additional capacity. Colombia had established even more ambitious renewable energy objectives throughout the previous decade. The government alone agreed in 2020 to construct 4,000 MW of new non-hydro renewable energy by 2030 which will represent nearly 24% of the country's estimated electrical capacity.

The positive impact of globalization on environmental sustainability contradicts the study of Nguyen and Le (2020) for Vietnam, Wang et al. (2020) for G-7 economies, Adebayo and Acheampong (2021) for Australia. Meanwhile, the finding agrees with the study of Umar et al. (2020) for China, Ahmed and Le (2021) for six ASEAN, Weimin et al. (2021) for 46 developing countries, Ulucak and Khan (2020) for BRICS, Teng et al. (2021) for 10 selected countries, He et al., 2021 for top 10 energy transition countries, Usman et al. (2020) for South Africa, and Nathaniel et al. (2021) for Latin America and Caribbean Countries. The process of globalization in Colombia began in 1990 with the liberation of trade that started by abolishing quantitative import limits, tariff reduction, and the simplification of international trade processes. This finding shows that developing relationships with the rest of the world have helped to drive environmental sustainability in Colombia. Also, Colombia is not an innovative giant with respect to technologies, thereby the transfers of cutting-edge energy-efficient technology, and investment from the rest of the world help to achieve a reduction in energy usage and increase resource efficiency. Furthermore, the ratification of the Paris agreement and being a member of the Kyoto protocol also shows that every aspect of globalization (whether social, economic, or political) contribute to the environmental quality of Colombia. Finding shows that natural resources rents have an insignificant effect on $CO_2$ emissions, which opposes the study of Ulucak and Ozcan (2020) for OECD nations, Tauseef et al. (2021) for Pakisan, Tufail et al. (2021) for developed nations, Khan et al. (2021) for the United States, Dagar et al. (2021) for the 38 OECD countries.

We continue with the causality outcome, the results reveal that economic growth, globalization, and natural resources rent Granger cause $CO_2$ emissions in Colombia, indicating the importance of globalization in driving environmental sustainability and the fact that economic growth adds to the degradation of the environment. Moreover, economic growth Granger causes renewable energy consumption and globalization. This outcome is anticipated because significant investment is needed for the development of renewable energy, and expansion of economic growth increases the energy demand while economic growth has shown to be a significant tool in promoting globalization. Besides, there is a one-way causal association from renewable energy use to natural resources rent, indicating that natural resource rent can be increased by increasing the use of renewable energy use. The causal association running from globalization to renewable energy use agrees with our argument regarding the role played by globalization in the development of renewable energy use through investment and transfers of energy-efficient technology. Finally, globalization Granger causes natural resources rent, showing that an increase in the globalization level will cause an upsurge in natural resources rents. This finding is expected since globalization allows the rest of the world to assess the country's natural resources (*via* international trade).

# 5 CONCLUSION AND POLICY PATH

This research explores the effect of globalization, renewable energy, natural resources rents, and economic growth on environmental sustainability in Colombia for the period from 1970 to 2018. The results of the cointegration tests demonstrate the long-run equilibrium connection amongst the variables of concern. The ARDL, FMOLS, and DOLS estimators are used for the long-run analysis. The long-run estimators' outcomes revealed a positive connection between economic growth and $CO_2$ emissions. In a nutshell, economic growth has an adverse impact on environmental quality. On the contrary, globalization and renewable energy use contribute to the reduction of $CO_2$ emissions. The Gradual Shift Causality test was used to capture the causal interconnection between $CO_2$ emissions and its determinants in the presence of structural shift. The causality test revealed that economic growth, globalization, and natural resources rent Granger cause $CO_2$ emissions. Similarly, economic growth Granger causes renewable energy use and globalization. Likewise, renewable energy use Granger causes natural resources rent (NRR). Also, globalization Granger causes renewable energy use. Lastly, globalization Granger causes natural resources rent.

The negative effect of globalization on $CO_2$ emissions calls for adopting measures to minimize customs duties and trade barriers and stimulate foreign investment. Conversely, policies should be established to discourage foreign investors from investing in dirty industries or technologies so that the beneficial impact of globalization on environmental quality could continue. Social interaction with the rest of the world should be expanded and local media outlets should be encouraged to promote environmental awareness.

Concerning the negative effect of economic expansion on environmental sustainability, the relevant solution and the only lasting response to this challenge is the adoption of renewable energy sources. Developing and adopting solid policies to manage the activities of the energy and industrial sector of Colombia would enhance the sustainable growth of the nation. Moving toward renewable energy is the best way to address energy security and environmental degradation issues, and its prominence has intensified in the post-COVID-19 world.

Households should be encouraged to use renewable energy technologies by allowing them to purchase these technologies at a subsidized rate. Thus, this would help to improve the acceptance of renewable technologies among households by highlighting the affordability factor. Consequently, this specific policy will cause a budgetary strain on the economy, which can be alleviated by tapping into the manufacturing or industrial sector. However, renewable energy technologies could be made readily accessible to the manufacturing or industrial sector at a higher rate compared to households. Additionally, based on the dirty industries, a differential pricing system may be implemented, which may deter corporations from continuing to use non-renewable energy. Furthermore, people-public-private partnerships should be encouraged to raise the awareness of the Colombian population regarding environmental sustainability and to encourage the use of renewable energy use or energy-efficient technologies.

Although the contribution of the study is significant to environmental literature, especially in Colombia. However, this research also has some limitations. These limitations are related to the use of only a few variables in the study. Future studies may include more variables and study their effect on different environmental indicators.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## AUTHOR CONTRIBUTIONS

All authors contributed equally. All authors have read and agreed to the published version of the manuscript.

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