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RESEARCH ARTICLE

Influences of foreign direct investment and carbon emission on economic growth in Vietnam

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Abstract
Over the course of the previous three decades, Vietnam has seen a phase of economic growth, resulting in the influx of foreign direct investment (FDI). However, it is essential to note that there was an extensive rise in carbon dioxide (CO_2) emissions throughout this period. The objective of this research is to analyze the impact of FDI and CO_2 emissions on Vietnam's economic growth, utilizing time series data from 1990 to 2021. The stationarity of the data was assessed using unit root tests, while an autoregressive distributed lag (ARDL) procedure was utilized to examine the long- and short-run associations between the components. Based on the research outcomes, it is seen that a marginal rise of one percent in both FDI and CO_2 emissions is associated with a corresponding long-term gain of 1.36 percent and 1.11 percent in gross domestic product (GDP). Furthermore, in the short term, these increments yield an increase of 0.61 percent and 0.29 percent in GDP. The conclusions of this study will provide valuable insights for policymakers in crafting policies that effectively promote sustainable development. Specifically, these policies would aim to strike a balance between capital growth derived from foreign investments and economic expansion, while concurrently mitigating carbon emissions.

Keywords: Economic growth; FDI; Environmental degradation; CO_2 emissions; Sustainable development

Introduction

Over the last few years, Vietnam's economy has witnessed a rapid expansion. The country experienced a notable rise in its GDP per capita, which escalated from 1562 US dollars in 2010 to 3561 US dollars in 2020. The government has set an ambitious objective of achieving a GDP per capita of 7500 US dollars by the year 2030. FDI shows a crucial function in both the early stages of an economy's development and its later stages of industrialization, modernization, and the establishment of a knowledge-based economy (Quoc & Thi, 2018; Raihan, 2023a). The aforementioned statement can be attributed to the observation that FDI shows a crucial function in fostering economic expansion through the augmentation of overall investment capital (Raihan & Voumik, 2022a). Vietnam, a nation situated in Southeast Asia, is currently through a process of economic transition characterized by industrialization and modernization (Raihan, 2023b). Vietnam's economic growth has been greatly influenced by the substantial influx of foreign capital, a trend that has been observed since the enactment of the Law on Foreign Investment in 1978. The allocation of these money has resulted in the promotion of exports and the improvement of human resources and technology. The attraction of FDI shows a pivotal function in the advancement of Vietnam's economic and social infrastructure (Nguyen et al., 2022).

The significant increase in FDI flowing into Vietnam since 1988 has been commonly perceived as indicative of the state's successful shift from a command economy to a market-oriented system, as noted by Cung (2020). The implementation of capital and FDI inflows into Vietnam has had a substantial increase over the years. From 1988, when it stood at US$0.32 billion, to about US$16.2 billion in 2023. This growth can be attributed to the introduction of the Doi Moi reform program in 1986. Since then, FDI inflows into Vietnam have displayed an average annual growth rate of 15.4 percent (Nguyen et al., 2022). Vietnam has had significant advantages as a result of foreign direct investment throughout this time frame. These measures encompass enhancing Vietnam's capital and production capacity, strengthening export endeavors, generating employment opportunities, and facilitating the transfer of both tangible and intangible assets, such as technology and international knowledge. FDI is often considered a significant determinant in the economic advancement of emerging nations, exemplified by the case of Vietnam. The correlation between FDI and economic growth has been a subject of significant scholarly attention within the realm of international development studies. In the context of volatile global capital flows, FDI has emerged as a dependable avenue for promoting accelerated growth in underdeveloped nations. The promotion of foreign direct investment is crucial for the mobilization and sustainable utilization of capital. However, it is imperative to adopt a cautious approach in formulating regulations that take into consideration the unique characteristics of each stage of development. Hence, it is imperative to analyze the influence of FDI on the economic enhancement of Vietnam.

The rapid economic growth experienced by Vietnam in recent decades has resulted in some notable impacts on the local ecosystem. Vietnam is presently grappling with notable environmental challenges, with global warming emerging as the most pressing concern, despite the country's notable economic achievements (Begum et al., 2020; Raihan et al., 2023a). Vietnam persistently exhibits a concerning lack of awareness on the importance of protecting a sustainable ecosystem. According to Raihan et al. (2022a), there has been an approximately sixfold rise in the total quantity of CO_2 emissions over the course of the past three decades. The rate of CO_2 emissions in Vietnam is experiencing a significant and concerning upward trend. The majority of CO_2 emissions are generated by coal-fired electricity bases (Raihan et al., 2022b; Voumik et al., 2022; Sultana et al., 2023a). It is projected that by the year 2020, the energy industry in Vietnam will produce an estimated annual carbon dioxide emission of 224 million tons, whereas other significant industries are expected to create roughly 10 million tons.

Vietnam has made a commitment to achieve carbon neutrality by the year 2050. In the pursuit of sustainable development, it is imperative to achieve a harmonious equilibrium between fostering GDP growth and sustaining the inflow of FDI to ensure the maintenance of stable levels of carbon emissions. Vietnam, akin to numerous other nations, endeavors to attain sustainable economic growth and development that upholds environmental integrity and avoids burdening future generations with any adverse consequences. To achieve this goal, it is imperative to protect the integrity of the ecosystem (Raihan, 2023c; Raihan, 2023d; Raihan, 2023e; Raihan, 2023f; Raihan, 2023g; Raihan, 2024a). The research undertaken on the relationship between CO_2 emissions and economic growth has incorporated multiple studies examining the influence of economic progress on CO_2 emissions (Raihan & Tuspekova, 2022a; Raihan et al., 2022c). However, there is a scarcity of study about the impacts of CO_2 emissions on the progress of economic development. This article makes a scholarly contribution by analyzing the influence of environmental degradation, specifically carbon dioxide emissions, on the economic growth of Vietnam.

The total volume of FDI in Vietnam exhibited a consistent annual growth pattern. Furthermore, there was a pointed simultaneous expansion in both the pace of economic expansion and the emission rate. One pertinent inquiry regarding the social milieu is to the potential correlation between the surge in FDI and CO_2 emissions in Vietnam, and the concomitant rise in economic advancement. In view of this, a research study was undertaken in Vietnam spanning the years 1990 to 2021, with the aim of examining the immediate and enduring impacts of FDI and CO_2 emissions on GDP. The stationarity and stability of the variables were verified through the implementation of three unit root tests. Additionally, the ARDL technique was employed to establish the associations between these variables and their long- and short-term causal dynamics. The findings of this research will specify constructive visions for legislators in crafting policies that effectively promote sustainable development. Specifically, these insights would help policymakers strike a delicate equilibrium between capital growth derived from foreign investments, economic expansion, and the imperative to mitigate carbon emissions.

Literature Review

Due to the rising concern about global warming and climate change (Raihan & Said, 2022; Raihan & Himu, 2023; Raihan & Bijoy, 2023; Raihan, 2023h),a considerable body of literature has been dedicated to exploring the liaison between CO_2 emissions and GDP (Raihan, 2023i; Raihan et al., 2023b). According to Bello et al. (2018), there exists a U-shaped inverted relationship between CO_2 emissions and economic prosperity. However, it is seen that the positive alliance between economic evolution and CO_2 emissions tends to decrease once the economy achieves a particular level of development. This assertion can be adequately evaluated since a rise in income levels is often associated with an improvement in the standard of living, which in turn tends to result in an increased requirement for ecological excellence (Raihan, 2023j).

The interconnections between nations in relation to economic endeavor and commerce have prompted scholarly investigations into possibilities concerning the liaison between pollution, economic outgrowth, and trade integration. Grossman and Krugger (1995) conducted the primary inquiry into the relationship between the Carbon Index and its impact on economic progress. The authors posited that the mitigation of trade obstacles and the amplification of economic endeavors will have an impact on the environment. This study additionally presents empirical evidence to evaluate the comparative magnitude of these three consequences through the implementation of trade liberalization in Mexico. In their study, Naranpanawa (2011) employed the ARDL method and Johansen cointegration procedure to examine the enduring association between economic development and the trading environment. The ends of this analysis suggest that there exists a transient association between business and CO_2 emissions. In a study conducted by Keho (2015), the ARDL model was employed to examine the enduring consequences of the ecological bearing resulting from universal trade in 11 nations within the Economic Community of West African States (ECOWAS) during the retro spanning from 1970 to 2010. The findings of this investigation led to the determination that global commerce is a significant contributor to environmental deterioration. In their study, Rahman and Kashem (2017) employed Toda and Yamamoto's causal model to examine the interrelationships among carbon emissions, energy consumption, and economic evolution in Bangladesh from the 1970s to the 2010s. The bulk of these research demonstrate a sustained relationship and a significant connection among the parameters. Furthermore, empirical research has demonstrated a significant positive association between the growth of GDP and the concurrent rise in CO_2 levels across the examined timeframe. Esso and Keho (2016) have demonstrated the existence of causal and enduring associations between energy use, CO_2 emissions, and economic advancement in diverse African states.

Alvarez-Herranz et al., (2017) utilized the Kuznets curve framework to assess the relationship between GDP and CO_2 emissions in a sample of 16 associate states of the Organization for Economic Cooperation and Development (OECD) throughout the retro from 1995 to 2016. The investigation outcomes imply that the presence of institutional misalliances during the energy development procedure negatively impacts ecological sustainability within economies. The study substantiated the Kuznets curve hypothesis and demonstrated that the proliferation of economic progress and the adoption of renewable power sources resulted in a reduction of environmental pollution across 17 OECD countries throughout the retro straddling from 1990 to 2012. In a research conducted by Sarkodie (2018), a sample of developing nations was utilized to examine the relationship between FDI and energy intensity. The findings of the study revealed a significant decrease in energy concentration as FDI levels grew. The aforementioned decline can be ascribed to the utilization of contemporary technology in conjunction with FDI, representing a significant advancement from the antiquated conventional technologies employed in other nations. This transition has resulted in a reduction of environmentally harmful emissions.

Several studies have investigated the correlation capital flows, between FDI, and ecological degradation in different countries or commercial regions. Frankel and Romer (2017) have conducted a study in which they found evidence suggesting that financial development and deregulation have the potential to attract FDI, drive economic growth, and thus enhance the dynamics of environmental performance. Shahbaz (2014) employed the ARDL framework to investigate the long-term relationships between renewables, FDI, natural resource trade, CO_2 emission, and GDP in the United Arab Emirates (UAE) during the period spanning from 1975 to 2011. The authors assert that there exists a correlation between these factors over a period of time. It has been determined that the process of trade integration and the influx of FDI are associated with a reduction in greenhouse gas (GHG) emissions. The phenomenon of economic expansion yields positive effects on energy use.

In their study, Hakimi and Hamdi (2016) examined the relationship between FDI inflows, trade openness, environmental attribute, and GDP in Tunisia and Morocco. They employed the Vector Error Correction Model (VECM) and cointegration techniques to analyze the data. This study posited that trade liberalization has resulted in mutual economic benefits for both economies, often leading to consequential impacts on CO_2 emissions. The research acted by Michieka et al. (2013) investigated the impact of energy exhaustion, trade, and monetary progress on the economic progression of China. The results suggest that the influence of economic and commercial development on pollution is significant, and it also has enduring consequences for CO_2 levels.

Corresponding to research accomplished by Ren et al. (2014), the substantial trade surplus and the influx of FDI are identified as the primary considerations providing to the significant rise in CO_2 emissions in China. In their study, Michieka et al. (2013) examined a sample including around 20 developing nations and saw a significant reduction in energy intensity in conjunction with the rise in foreign direct investment. The aforementioned fall can be ascribed to the adoption of contemporary technology in conjunction with foreign direct investment, representing a significant departure from the antiquated old technologies employed in other nations. This transition has resulted in a reduction of environmentally harmful emissions (Raihan, 2023k).

Soytas and Sari (2007) employed a VECM to assess the correlation between energy intake and the production divisions in Turkey. The conclusions of the analysis exhibit a significant and positive correlation between the parameters included in the model. Furthermore, the parameters inside the model exhibit a causal relationship. In 2009, the authors undertook an additional analysis utilizing the linear regression method to assess the correlation between economic expansion, energy consumption, and CO_2 emissions. The research findings also indicate the occurrence of a co-integration relationship midst the parameter parameters. Furthermore, the research also revealed a lack of enduring correlation between CO_2 emissions and the advancement of economic progress. Hence, the investigation arrived at the determination that it is feasible to mitigate CO_2 emissions without impeding the pace of economic advancement. The findings of Öztürk and Acaravcı's (2010) study exhibited analogous outcomes when employing the ARDL model and examining causality using authentic data from Turkey. The factors employed by the author encompassed energy, employment ratio, and emissions. The findings indicate a reversal of the Kunetz curve.

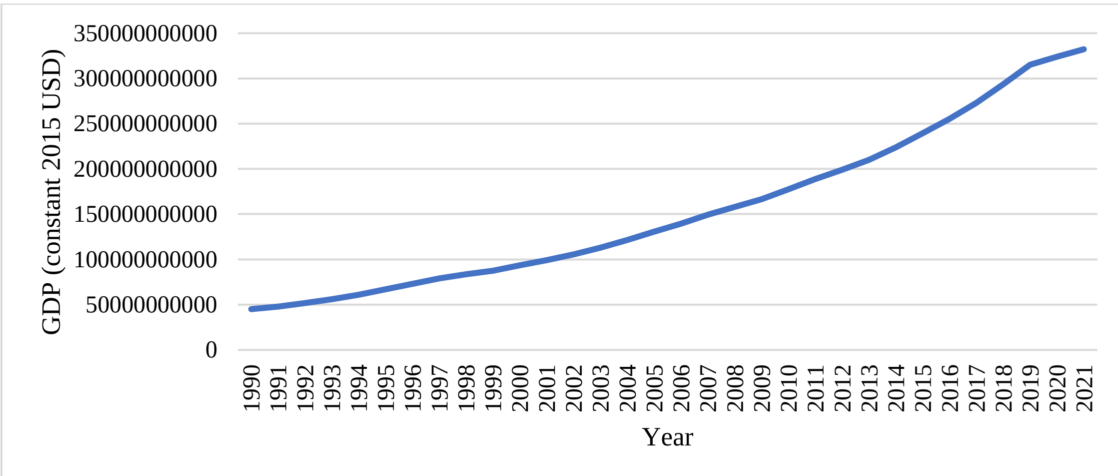
According to the findings of Begum et al. (2015), the empirical analysis conducted using the ARDL approach demonstrated a negative link between emissions and GDP in Malaysia between 1970 and 1980. Nevertheless, between 1980 and 2009, there was a prominent surge in per capita CO_2 emissions, which subsequently resulted in a corresponding rise in per capita GDP. The research findings indicate that the EKD hypothesis was shown to be invalid in Malaysia within the specified study duration. The conclusions of the study also indicate a significant and positive association between energy intake, GDP, and carbon emissions. The study additionally demonstrates that over an extended period, economic expansion can exert a detrimental influence on CO_2 emissions. Hence, the adoption of advanced technological gear and equipment that have little emissions (Raihan, 2023l), along with the utilization of alternative energy sources, will effectively mitigate emissions without compromising economic progress (Raihan, 2023m).

Numerous empirical studies have investigated the association between FDI, economic growth, economic integration, and CO_2 emissions. Nevertheless, there exist variations in research findings across different countries with respect to the short-term and long-term impacts, the presence of cointegration relationships, and the positive and negative effects observed in the interplay between various components. In light of the divergent outcomes observed across nations, the author intends to undertake an empirical investigation aimed at assessing the interrelationship between the rate of GDP growth, CO_2 emissions, and FDI in Vietnam. The empirical findings have the potential to assist policymakers in striking a compromise between the reduction of CO_2 emissions, the augmentation of FDI attractiveness, and the attainment of economic growth in forthcoming periods.

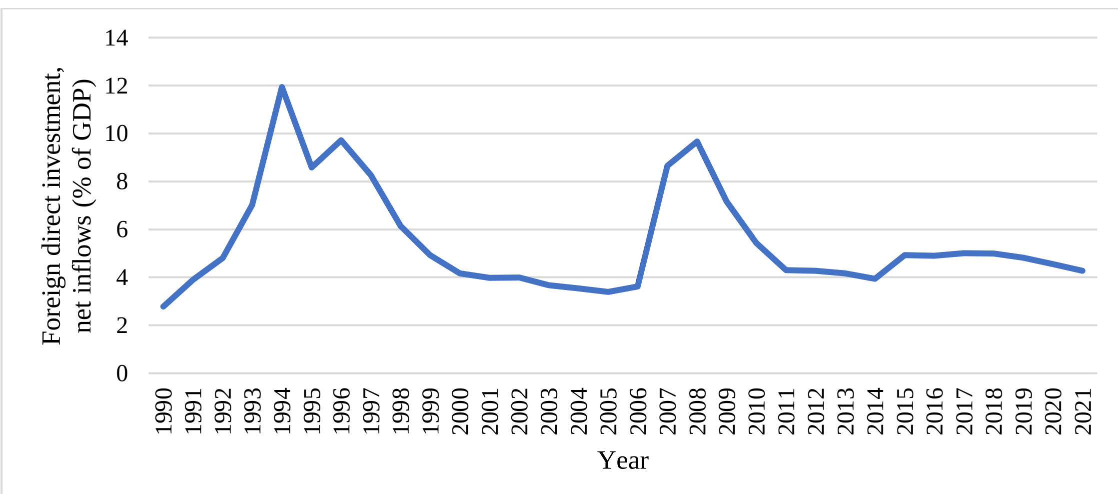
Methodology

Data and empirical model

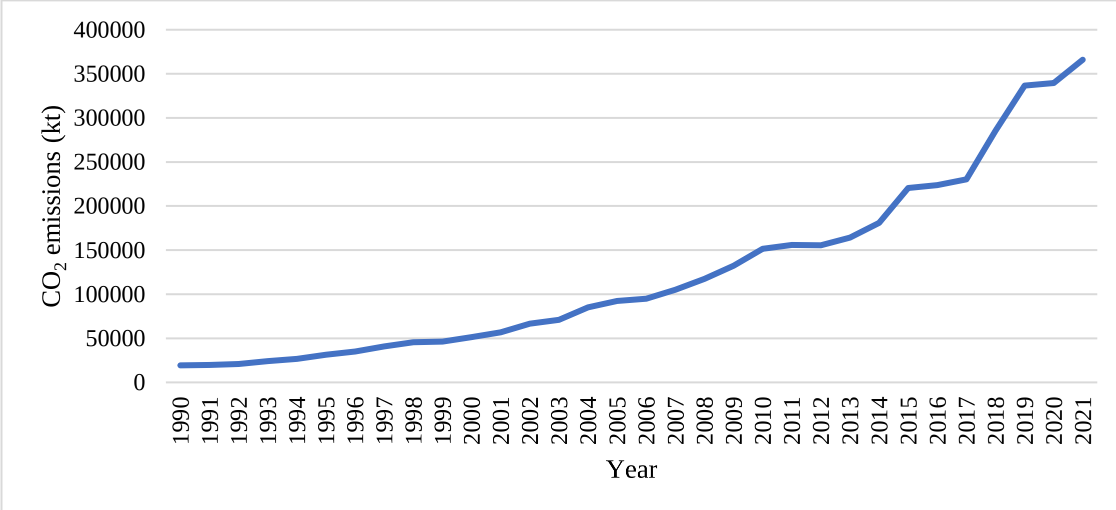
To assess the validity of the hypothesis pertaining to the association between the parameters, the methodology employed in this study involved the integration of ARDL bounds analysis with cointegrating regression investigation. The World Development Indicators (WDI) were specifically created to compile comprehensive time series data spanning the years 1992 to 2021. FDI is quantified as a proportion of the overall GDP, whereas CO_2 emissions are evaluated in terms of kilotons. Figure 1 illustrates the temporal trends of the variables.



(a) GDP



(b) FDI



(c) CO_2 emissions

Figure 1. The annually fads of GDP, FDI, and CO_2 emissions in Vietnam.

The present investigation employed a defined model at time t to illustrate the relationship between variables.

$$\mathrm{GDP_t} = \tau_0 + \tau_1 \mathrm{FDI_t} + \tau_2 \mathrm{CO2_t} + \varepsilon_t \quad (1)$$

Here, τ_1 and τ_2 are the coefficients, though ε is the error term. The logarithmic function was utilized to enhance the clarity of the data by manipulating the variables.

$$\mathrm{LGDP_t} = \tau_0 + \tau_1 \mathrm{LFDI_t} + \tau_2 \mathrm{LCO2_t} + \varepsilon_t \quad (2)$$

Stationarity check

The present study initially investigates the relationships between the response variable and its explanatory components in order to ascertain if the dataset exhibits stationarity at either integrated of order zero (I(0)) or integrated of order one (I(1)). Furthermore, it is not necessary for every regressor to exhibit a seasonal effect or be included with an order of one (Raihan & Tuspekova, 2022b; Raihan et al., 2023c). The avoidance of the I(2) sequence is deemed invalid and has the potential to generate misleading outcomes (Raihan & Tuspekova, 2023a; Raihan et al., 2023d). Furthermore, in the event that a variable exhibits nonstationarity, there is a possibility of obtaining erroneous results (Raihan et al., 2022d; Raihan & Tuspekova, 2023b; Raihan et al., 2023e). Nevertheless, the shift to I(2) is unparalleled, and the limited size of the sample raises apprehension (Raihan & Tuspekova, 2022c; Raihan et al., 2023f). The present study utilizes the Augmented Dickey-Fuller (ADF), Dickey-Fuller generalized least squares (DF-GLS), and Phillips-Perron (P-P) unit root tests in order to ascertain the absence of I(2) variables.

ARDL approach

The ARDL bounds testing technique for cointegration, as introduced by Pesaran et al. (2001), was employed to examine the enduring association between the parameters. The cointegration test mentioned in the text has several advantages compared to standard approaches in terms of the order of integration (Raihan & Tuspekova, 2022d; Raihan et al., 2022e; Voumik et al., 2023a; Raihan et al., 2023g). If the parameters are determined to be stable at either the integrated of order 1 (I(1)) or integrated of order 0 (I(0)) level, or the I(1)/I(0) level, then this approach can be employed (Raihan et al., 2022f; Raihan & Tuspekova, 2022e; Raihan et al., 2022g). The ARDL bounds testing econometric study employs an adequate amount of lags inside a general-to-specific modeling framework in order to effectively represent the data creation process (Raihan et al., 2023h; Raihan, 2023n). The ARDL framework allows for the computation of the ARDL F-statistic, which serves as a means to assess the existence of cointegration across variables (Raihan et al., 2023i; Raihan, 2023o). This is achieved by considering several optimal lags for each variable, as discussed by Raihan and Tuspekova (2022f). The establishment of cointegration among variables can be determined if the ARDL F-statistic exceeds a preset upper critical threshold (Raihan, 2023p). If the F-statistic of the ARDL model is below the lower critical limit, it indicates that the variables under consideration are not cointegrated (Raihan, 2023q). When the F-statistic of the ARDL model is within the range of the upper critical bound and the lower critical value, the empirical findings may lack persuasiveness (Raihan & Tuspekova, 2022g; Raihan et al., 2023j). The ARDL bounds analysis method, which is commonly used for studying cointegration, can be described by the following approximation model:

$$\Delta LGDP_t = \tau_0 + \tau_1 LGDP_{t-1} + \tau_2 LFDI_{t-1} + \tau_3 LCO2_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LGDP_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta LFDI_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta LCO2_{t-i} + \varepsilon_t \quad (3)$$

The symbol Δ represents the first difference operator, whereas the variable q denotes the optimal lag duration. The ARDL bounds testing approach has the capability to undergo linear transformation in order to derive the error correction model (ECM). Despite the use of very small sample sizes, this methodology produces dependable empirical findings (Raihan & Tuspekova, 2022h; Raihan, 2023r). In order to maintain a comprehensive outlook, the ECM integrates immediate intricacies with enduring stability (Raihan & Voumik, 2022b). The method employed in this study aims to ascertain the cointegrating vectors that arise from the empirical model when numerous cointegrating vectors are present (Raihan, 2023s). The symbol "θ" represents the coefficient of the ECM. The ECM exhibits a consistently positive value, seldom descending below 0 and never beyond 1. When the ECM exhibits a negative and statistically significant coefficient, it becomes imperative to address the variance in order to attain equilibrium (Raihan, 2024b). Following the establishment of the long-term relationship between the series, the investigation proceeded to calculate the short-run coefficients of the parameters utilizing Equation (4).

$$\Delta LGDP_t = \tau_0 + \tau_1 LGDP_{t-1} + \tau_2 LFDI_{t-1} + \tau_3 LCO2_{t-1} + \sum_{i=1}^{q} \gamma_1 \Delta LGDP_{t-i} + \sum_{i=1}^{q} \gamma_2 \Delta LFDI_{t-i} + \sum_{i=1}^{q} \gamma_3 \Delta LCO2_{t-i} + \theta ECM_{t-1} + \varepsilon_t \quad (4)$$

Results and Discussion

Table 1 presented below provides descriptive statistics. Grounded on the data that was collected and examined, it can be observed that the median and mean values of all parameters exhibit a high degree of similarity. All variables exhibit a normal distribution, as seen by their skewness values approaching zero, kurtosis values below three, and Jarque-Bera test statistics falling below their respective thresholds.

Table 1. Descriptive statistics

Variables	LGDP	LFDI	LCO2
Mean	25.59704	1.635640	11.37495
Median	25.62874	1.571155	11.44691
Maximum	26.52922	2.479851	12.81034
Minimum	24.53122	1.022927	9.869414
Std. Dev.	0.608397	0.356427	0.906434
Skewness	-0.119250	0.747708	-0.127089
Kurtosis	1.859924	2.674778	1.854348
Jarque-Bera	1.808874	3.122716	1.836166
Probability	0.404770	0.209851	0.399284

The initial stair is verifying that the order one, I(1), encompasses the complete dataset, particularly the response parameters. The accomplishment of this task involves the analysis of the strong suit of link concerning response parameters and analyst parameters. Furthermore, it is deemed improper to incorporate all first-order regressors or to illustrate transient unit roots. The ADF, DF-GLS, and P-P tests for three-unit root were devoted to assess the parameter order and verify adherence to the precondition. The conclusions of the unit root tests are presented in Table 2. Based on the information displayed, it was observed that all assessed metrics exhibited stationarity at the initial discrepancy. The data are therefore fitting for the use of the ARDL estimator.

Table 2. The results of unit root examinations

Logarithmic form of the variables	ADF		DF-GLS		P-P	
	Log levels	Log first difference	Log levels	Log first difference	Log levels	Log first difference
LGDP	-0.581	-4.178***	-0.383	-4.385***	-0.418	-4.329***
LFDI	-0.499	-4.117***	-0.414	-3.966***	-0.277	-4.009***
LCO2	-0.262	-5.753***	-0.161	-4.715***	-0.786	-7.302***

*** stand for significance at 1% level

Following the confirmation of the reliability of the unit roots of the variable, this study employed the ARDL bounds test to analyze the characteristics of the variables' enduring association. The empirical findings of using the ARDL bounds testing method to cointegration are shown in Table 3. Based on the observation that the estimated F-statistic exceeded the upper critical constraint, the experimental results presented compelling evidence supporting the presence of long-term cointegration among the variables under investigation.

Table 3. Results of ARDL bounds analysis

F-bounds test		Null hypothesis: No degrees of relationship		
Test statistic	Estimate	Significance	I(0)	I(1)
F-statistic	13.854226	At 10%	2.63	3.35
K	2	At 5%	3.10	3.87
		At 2.5%	3.55	4.38
		At 1%	4.13	5.00

Following the establishment of a durable association, this research endeavor aims to assess both the long-term and short-term variables. The outcome of both the long- and short-term investigations are showed in Table 4. Based on the findings derived from the ARDL analysis, it can be concluded that FDI exerts a positive and statistically significant sway on GDP in both the short-term and long-term periods. In the context of this study, it has been observed that a marginal rise of 1 percent in FDI leads to a corresponding short-term gain of 0.61 percent in GDP, while in the long term, this relationship is strengthened, resulting in a 1.36 percent increase in GDP. Trinh and Nguyen (2015), Quoc and Thi (2018), Cung (2020), and Nguyen et al. (2022) have together posited that FDI exerts a favorable impact on the GDP of Vietnam. The findings derived from the ARDL calculation provide empirical evidence that there exists a positive and statistically significant liaison between CO_2 emissions and GDP in both the short and long run. Given a fixed level of FDI, it can be shown that a 1% rise in CO_2 emissions leads to a subsequent increase in GDP by 1.11% in the long run and 0.29% in the short run. The ARDL research indicated a favorable relationship between elevated levels of CO_2 emissions and Vietnam's GDP. Raihan (2023b) provides empirical evidence that establishes a positive correlation between Vietnam's GDP and CO_2 emissions.

Table 4. ARDL results over the long and short term.

Variables	Long-run			Short-run		
	Coefficient	t-Statistic	p-value	Coefficient	t-Statistic	p-value
LFDI	1.361***	4.007	0.000	0.613***	3.102	0.001
LCO2	1.112***	3.089	0.000	0.291***	3.107	0.002
C	9.678	3.428	0.147	-	-	-
ECM (-1)	-	-	-	-0.601***	-3.692	0.000
R^2	0.9871					
Adjusted R^2	0.9765					

*** denotes significance at 1% level

The findings of this inquiry indicate a statistically significant negative appraisal of ECM, as determined at the 1% significance level. The estimation of the ECM allows for the determination of both the magnitude and sign of the ECM. These indicators can be utilized to make inferences on the speed at which a structure advances from a state of short-run uncertainty to a state of long-run equilibrium. This finding suggests that the state of long-term equilibrium is achieved once 60 percent of the short-term errors have been rectified. Furthermore, the R^2 and adjusted R^2 values for the long-run evaluation are 0.9871 and 0.9765, respectively. These values suggest that the regression model provided in this study has a high level of conformity with the data. This finding suggests that the independent factors have the ability to explain approximately 97% of the variability observed in the dependent variable. Table 5 displays the empirical estimations of various diagnostic statistics. The application of the Jarque-Bera test can be employed to ascertain the uniform distribution of residuals. The Lagrange multiplier (LM) technique was employed to examine the issue of serial correlation. The LM test outcome suggests that the model does not exhibit any issues related to serial correlation. The Breusch-Pagan-Godfrey analysis was utilized to examine the presence of heteroscedasticity in the forecast model. Based on the findings, it can be concluded that the proposed model does not display heteroscedasticity. The determination of the model's validity was conducted through the utilization of the Ramsey reset test.

Table 5. The findings obtained from diagnostic examinations.

Diagnostic probes	Coefficient	p-value	Decision
Jarque-Bera analysis	0.406007	0.8162	The residuals have a normal distribution
Breusch-Godfrey LM analysis	0.724124	0.5009	There is no serial correlation
Breusch-Pagan-Godfrey analysis	0.885297	0.5707	There is no heteroscedasticity
Ramsey RESET analysis	0.396329	0.6971	The model is precisely described

This study assessed the structural stability of the model by employing the summation cumulative of recursive residuals (CUSUM) and squares of the summation cumulative of recursive residuals (CUSUMSQ) functions. Figure 2 illustrates the graphical representation of the CUSUM and CUSUMQ studies. For example, the stability of model parameters can be determined by assessing scatter plots that exhibit deviations from the critical limit of no more than 5%. The graphs demonstrate that throughout the trial, the CUSUM and CUSUMSQ values consistently fell within the acceptable range of +/- 5%.

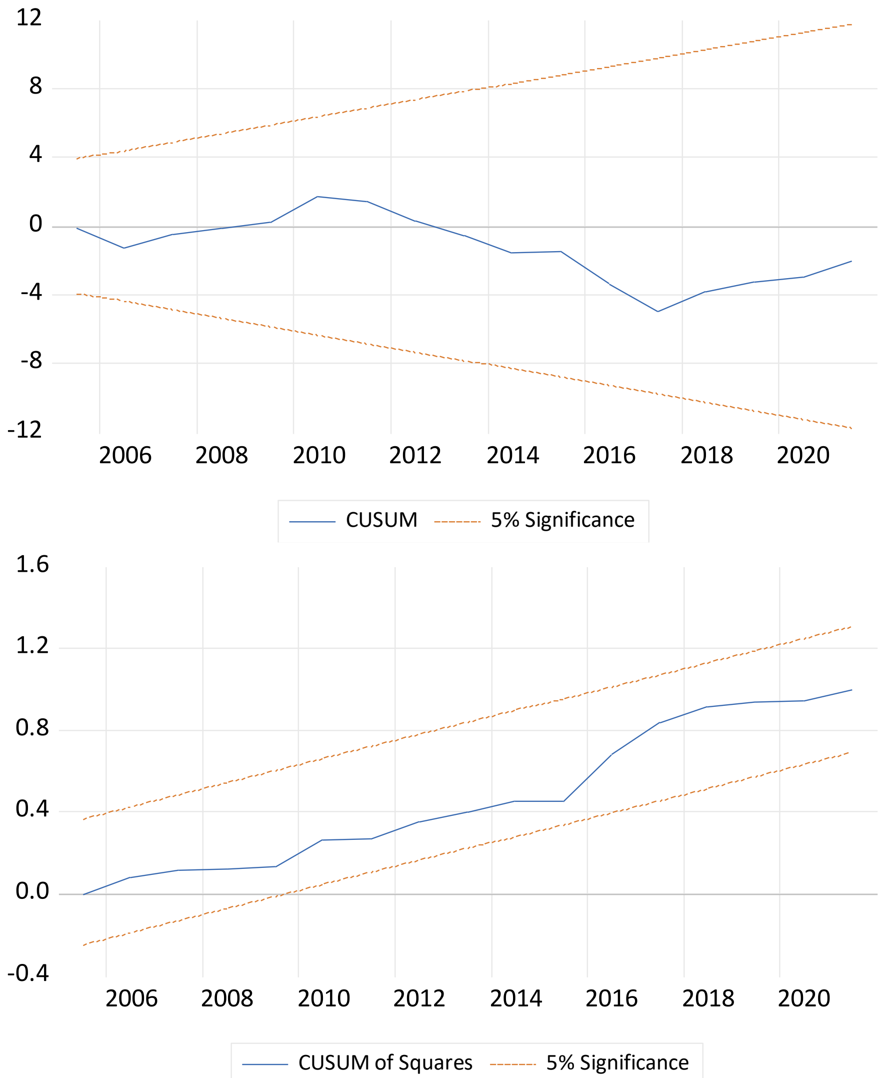


Figure 2. The findings of both the CUSUM and CUSUMQ analyses.

FDI is a significant macroeconomic determinant that exerts a profound impact on the process of economic development (Voumik et al., 2023b). The economy is directly impacted by various factors such as technological advancements, advancements in related fields, resource accumulation, and the manifestation of human inventiveness (Raihan & Tuspekova, 2022i). The aforementioned objectives are achieved by means of funding the deficit in the current account, facilitating investment finance for numerous host markets, generating positive externalities, integrating new managerial competencies across diverse sectors, and bolstering economic performance by generating a significant number of employment opportunities and government returns. Raihan and Tuspekova (2022j) posited that this phenomenon plays a significant role in fostering economic expansion. Hence, it is imperative for political and economic strategies to maintain a coherent connection between the growth of industries and the inflow of FDI. Vietnam continues to be a highly preferred destination for FDI. The attractiveness of the place for investments and its projected sustainability can be attributed to the indices of its macroeconomic environment and demographic composition, as elucidated by Nguyen et al. (2022). FDI has played a vital role in facilitating the advancement of Vietnam's machinery manufacturing, energy, computer, and telecommunications sectors. These industries necessitate technological complexity and yield high-value output (Cung, 2020). The importance of the impact of FDI on a nation's exports and imports, foreign currency accessibility, and balance of payments has progressively amplified through time.

In the meanwhile, the observation that CO_2 emissions yield favorable outcomes for economic progress underscores the necessity for implementing suitable measures to mitigate pollution inside the nation, thereby fostering sustainable economic growth (Sultana et al., 2023b). The decrease of GHG emissions can be achieved by the simultaneous advancement of renewable power technologies and the optimization of energy resource utilization (Raihan & Tuspekova, 2022k; Voumik et al., 2023c; Raihan, 2023t; Raihan, 2023u; Raihan, 2023v, Raihan, 2023w). At present, the Vietnamese government has enacted several regulations with the objective of mitigating the emission of GHGs within the nation. The policies encompassed under the scope are the "National Strategy on Green Growth," the "National Strategy on Climate Changes," and the "National Target Programme on Energy Efficiency." Furthermore, the country has demonstrated significant engagement in international organizations and conferences, aiming to collaborate with other nations in tackling this pressing global concern. However, Vietnam's efforts to mitigate GHG emissions encounter several challenges. Several challenges exist, including inadequate financial support and investments, limited utilization of sophisticated technology, and a lack of interagency collaboration mechanisms. In order to attain sustained economic growth and development, Vietnam must surmount a range of challenges.

Conclusions and Policy Implications

This analysis aimed to investigate the potential dynamic relationship between FDI, CO_2 emissions, and the economic growth of Vietnam. The analysis utilized a dataset spanning from 1992 to 2021. The stationarity of the data can be assessed by employing unit root tests, such as the ADF, the DF-GLS, and the P-P tests. Furthermore, the ARDL methodology was applied to examine the correlation between the variables under both long-term and short-term analysis. Based on the research outcomes, it can be observed that a marginal augmentation of one percent in both FDI and CO_2 emissions is associated with a corresponding long-term growth of 1.36 percent and 1.11 percent in GDP. Additionally, in the near term, such increments in FDI and CO_2 emissions are linked to a rise of 0.61 percent and 0.29 percent in GDP, respectively. The conclusions of this inquiry will offer constructive comprehensions for legislators in crafting policies that effectively promote sustainable development. Specifically, these policies would aim to strike a balance between capital growth resulting from foreign investments and economic expansion, while concurrently mitigating carbon emissions.

The outcomes of the research indicate that FDI shows a pivotal function in the economic advancement of Vietnam. The compiled data formed the foundation for the obtained outcomes. In order to prioritize economic improvement and attract FDI, there is a tendency to routinely reduce environmental protection criteria below the acceptable threshold. As a result, FDI exerts a significant influence on the environment, necessitating the implementation of environmental rules by the Vietnamese government across the nation. The persistent enhancement of the public administration system has resulted in an ongoing transformation of the current governance frameworks. Various factors, such as Vietnam's membership in international trade organizations and its participation in the signing of agreements, exert an influence on the scale and dynamics of its economic growth. The enactment of a new act by the National Assembly represents a substantial stride towards governmental reform and the advancement of many industries, with the aim of expediting domestic progress and aligning them with global benchmarks. The legislative embodiment under consideration is represented by the Law on Environmental Protection, Land, and Resource Management. This exemplifies the progression of the interplay between the state, enterprises, and citizens.

In the foreseeable future, irrespective of the government's dedication to environmental preservation, the Vietnamese government will be required to formulate suitable rules aimed at augmenting the economy and fostering a more liberalized trading environment. The formulation of these policies should be guided by the research findings. In order to attain a decrease in CO_2 emissions, with advancements in the economy and trade liberalization, it is imperative to construct methodologies for sustainable growth that are intricately linked to policies aimed at safeguarding the environment. The Vietnamese economy is experiencing a notable increase in its accessibility to worldwide commerce due to the implementation of growth plans that focus on attracting FDI and employing a amalgamation of import and export methods. The economy of Vietnam has been adversely impacted by the rise in trade openness, which is indicative of the broader global trend towards increased international integration. The implementation of environmental management changes is vital to attract both domestic and international investors. Furthermore, it is imperative to facilitate the dissemination of ecologically beneficial technologies and promote the advancement of sustainable development in order to effectively address the growing levels of pollution attributable to multinational enterprises. By implementing laws that promote the manufacture and utilization of ecologically sustainable energy sources and green technologies, lawmakers have the potential to effectively mitigate carbon emissions and achieve long-term economic growth that is environmentally sustainable. In addition, it is imperative that these policies effectively promote the widespread adoption of renewable technology. One limitation of this investigation is the absence of industry-specific data, which represents a notable downside. Given this context, the forthcoming studies would endeavor to use disaggregated data or data from diverse industries on the symmetry of econometric models.

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https://databank.worldbank.org/source/world-development-indicators

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REVIEW ARTICLE

Climate change and its impacts in rural areas of Pakistan: a Literature review

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Abstract
Pakistan, which is located in Southeast Asia, is one of the nations that is most susceptible to the effects of climate change, as seen by the increased frequency of floods and droughts. Variations in climate have a negative impact on a number of areas, such as the agricultural industry, groundwater levels, dietary resources, soil quality and organic matter content, public health, and poverty rates. This study's main goal is to evaluate the impact of climate change and the adaptations farms have made in response to variations in precipitation and temperature. Pakistani farmers have responded to climate change by implementing a variety of adaptive techniques. These tactics include changing the way that fertilizer is used, changing crop varieties, using pesticides, improving seed quality, diversifying the farm, planting shade trees, changing irrigation techniques, engaging in off-farm activities, and migrating both permanently and temporarily. As an additional adaptive step, some farmers have turned to asset sales. Additionally, research indicates that agricultural households in wetland areas experience less volatility in climate than those in arid regions.

Keywords: Climate Change; Impacts; Rural Areas; Pakistan

Introduction

Global warming has far-reaching consequences that can harm natural ecosystems and eventually have an influence on highland economies (Wang, 2024; Chow et al., 2024). Climate is a major factor in agricultural output; temperature and precipitation are two major factors that influence farm productivity (Ozdemir, 2022). The agriculture industry is by its very nature complicated, full of dangers, and unpredictable. Farmers must contend with the unpredictable nature of returns on their investments in agriculture as well as the possibility of declining agricultural output as a result of climate change (Syed, et al. 2022). The most vulnerable people to climate changes in emerging countries are small subsistence farmers and rural residents. They encounter difficulties as a result of restricted access to productive alternatives and weak adaptation abilities (Sohail, et al, 2022). Climate change consequences are very geographically varied, with large differences within and across places, particularly in non-industrialized and humid countries (Singh et al., 2024; Ma et al., 2023). These differences in climatic circumstances are predicted by researchers like, Abbass, et al. (2022); Kaiser, et al. 2022) to result in a higher frequency of unpredictable climate events and calamities such storms, cyclones, floods, and droughts.

These difficulties may be related to the global geographic distribution of vulnerable areas, resource scarcity, increased climate exposure, and the rapid population rise (Isfat and Raihan, 2022). Pakistan is one of the areas that is most susceptible to the effects of climatic catastrophes. Temperature changes, variations in rainfall, and a propensity for hazardous situations are only a few examples of these events (IPCC, 2014; Fahad, et al. 2022). Floods and droughts are the main natural disasters that put people at risk for economic and social problems, and they frequently result in fatalities. Because they have fewer resources and adaptive capacity, rural communities in underdeveloped nations are more vulnerable to floods (Fahad and Wang, 2020). Ecological and climatic changes have a significant impact on these nations' flood severity and intensity. Pakistan's agricultural sector has had significant challenges while making a significant economic contribution to the nation, mostly as a result of devastating floods (Ahmed et al., 2023; Rasool et al., 2021). Consequently, it is critical to modify the agricultural sector to address the effects of flooding in order to protect farming communities' means of subsistence. In terms of exposure to the effects of climatic variability, Pakistan was placed 12th in 2012, 8th in 2015, and 7th overall (Kreft and Eckstein, 2013). Pakistan has seen several extreme weather events in the past few years, such as storms, cyclones, droughts, and floods (Hussain, et al., 2020; Tingju et al., 2014). These natural disasters are occurring more often and resulting in larger losses (Ullah & Takaaki, 2016). Numerous rural residents in Pakistan have been severely affected by natural catastrophes, such as the floods that occurred between 2010 and 2014 (Fahad and Wang, 2020). Several studies have demonstrated how highly susceptible Pakistani farming communities are to fluctuations in the country's climate (Wade, & Jennings,2016; Elahi, et al., 2022). Scholars across have repeatedly recognized how these communities are affected by differences in the climate (Wheeler, & von Braun, 2013; Khan et al., 2023). The recurring occurrence of climate risks is a persistent concern for Pakistan; in spite of advancements in guidelines, regulations, affordable instruments, and feasible interventions, the nation still lacks proper implementation (Hussain, et al., 2023). Therefore, this research examines how Pakistani agricultural households have responded to changes in climate, adaptability, and variability.

Pakistan's rural regions are becoming more and more susceptible to the negative impacts of climate change, such as increased temperatures, altered precipitation patterns, and extreme weather events. Significant obstacles to Pakistani rural populations' livelihoods, agriculture, and general well-being are presented by these environmental changes (Mahmood & Hassan, 2022). Comprehensive study is yet desperately needed to determine the precise nature and scope of these effects, as well as to design and put into practice efficient plans for these regions' adaptation and mitigation to climate change. The purpose of this research is to examine the many effects of climate change in Pakistan's rural areas and evaluate current and future approaches to mitigating these issues. The study on the effects of climate change in Pakistan's rural regions innovates by addressing a perspective that is usually ignored and concentrating specifically on the unique difficulties that rural populations experience. In order to fully comprehend the complex consequences of climate change on rural communities, the research integrates ideas from environmental science, sociology, and economics through an interdisciplinary approach. The study promotes participatory approaches and community participation to include local viewpoints, hence promoting a more comprehensive and context-specific analysis. The research also seeks to offer practical suggestions and policy implications, focusing on solutions specific to the vulnerabilities noted in the literature review. This will help to create a more comprehensive and successful response to climate change in Pakistan's rural areas.

The paper will commence with an introduction offering a comprehensive overview of climate change in rural Pakistan, followed by a literature review that systematically analyzes the multifaceted impacts of climate change on agriculture (water, livelihood and community), poverty and health in these rural areas.

Methodology

A comprehensive literature search was conducted across various electronic databases, including Academic Search Complete, CAB abstracts, GEOBASE, Google Scholar, Sci ELO, Scopus, and Science Direct (de Araujo et al., 2021). Specific search terms such as "Climate Change," "Impacts," "Rural Areas," "Pakistan," and "Asia" were employed to identify pertinent peer-reviewed articles. In addition to academic databases, supplementary sources from the internet and organizational databases like the World Health Organization, UNFCCC, and the International Development Research Centre were also consulted. This dual-pronged approach aimed to encompass a diverse range of literature, including grey literature, reports, books, and other relevant publications pertaining to the impacts of climate change in rural areas of Pakistan. The criteria for inclusion were based on a direct and clear reference to the topic of climate change and its ramifications in rural regions. Harari et al., (2020) articulated that, the comprehensive search strategy across both academic and non-academic sources ensures a thorough and inclusive overview of the existing literature on the subject.

Results and Discussion

The combined search of publicly available reports and peer reviewed articles generated a total of 61 reports, of which 49 were found to be relevant to this review. The selected documents are predominantly case studies that have discussed agricultural practices and the effects of these on climate change. Most also documented the negative effects of climate change, temperature variations at the local level, often linking those effects with agricultural back off problems. Which were causing the damage to agricultural crops as well as local lives at greater extent.

Effects of climate change on agriculture

A vital industry in every country, agriculture constantly suffers from the negative effects of climate change. In recent decades, these effects of climatic variability have become more subtle (Patt et al., 2009). Climate change has profound implications for agriculture, affecting various facets of crop production, livestock management, and overall food security (Mutengwa et al., 2023). Predictions on climatic variability point to a dynamic climate characterized by increased susceptibilities, particularly in areas with lower incomes (Roy, et al., 2023; Celis, et al., 2023). The capacity to adjust to these threats substantially influences the magnitude of these climatic events' consequences (Ahmed, et al., 2021). The influence of non-climatic factors on adaptation decisions is a critical component of the adaptation process at the farm level. Decision-makers in agriculture, farm households traverse a multifaceted terrain made up of institutional, political, biophysical, and economic factors (Debelle, 2019). Furthermore, climate change can influence the proliferation of pests and diseases, introducing new threats to agricultural productivity. Crucial to mitigating these adverse effects is the implementation of adaptation strategies, including the development of climate-resilient crops, enhanced water management, and the adoption of sustainable farming practices, all of which are essential for ensuring global food security (Balasundram et al., 2023). Regarding the effects of climate change, Pakistan stands out as one of the developing nations most at risk (Parveen & Sharma, 2019). The frequency and intensity of climate disasters, such as floods, droughts, high temperatures, water scarcity, and an increase in pests and illnesses in some areas, have already increased throughout the country (Aslam, et al., 2020). Pakistan moved up to the 16th most susceptible position in 2010–2011, from its 2009–2010 ranking of 29th among the most vulnerable areas, according to the Global Climate Change Vulnerability Index (CCVI) study (Khan and Fee, 2014). Prominent meteorological incidents in Pakistan, such the floods that occurred in 2010, and 2014 and 2022, together with a protracted drought that lasted from 1999 to 2003, provide dramatic illustrations of the growing frequency of meteorological issues.

Due to high rates of poverty and a lack of material and financial resources, Pakistan struggles to adapt (Abid et al., 2015; Naureen, et al., 2022). Farmers' decisions on how to adjust to climatic variability and related hazards are influenced by these diverse experiences, either directly or indirectly (Abid et al., 2015; Adger et al., 2005; Ahmed, et al., 2019)."

The responses of farmers and their capacity for adaptation are further explained by a number of additional elements, such as agricultural methods, personal traits, and particular situations (Bryan et al., 2009). Extreme climate variability has a significant impact on social, economic, and natural ecosystems and adds to upcoming problems (Seddon et al., 2020). Climate variability increases the severity and frequency of natural events; indirect effects of climate variability include changes to the properties of land and water, variations in the rates of insect infestation, adjustments to the amount of moisture in the soil, and changes to the distribution of diseases. In less developed, agriculturally based economies, increased temperatures, erratic precipitation patterns, and lower crop yields directly affect food security. According to Godde et al. (2021), areas where agriculture is the main source of income are therefore especially susceptible to the negative consequences of climatic variability.

According to Thornton et al., (2014), climatic variability has a substantial effect on the agricultural industry by changing or reducing productive dimensions and by increasing risks associated with production, both direct and indirect. Wide-ranging effects of climate variability are seen in the environment and many socioeconomic areas, including as agriculture, food security, water resources, terrestrial ecosystems, biodiversity, and human health. Changes in the patterns of precipitation are probably going to make floods and water scarcity worse. Increased temperatures alter agricultural growing seasons, which affects food security and the spread of illnesses, raising the danger of diseases like malaria. According to UNFCCC (2008), rising temperatures also accelerate the rate of habitat damage and species extinction. Ahmed et al., (2023) further elaborated that, elevated temperatures can impact crop growth and development, leading to shifts in yield patterns and the geographical distribution of crops. Altered precipitation patterns may result in both water scarcity and excess, affecting crop irrigation and livestock water supply.

Climate Change and its impacts on poverty and health

Temperature variations can have a big effect on people's health. In 2000, it was discovered that variations in climate were accountable for around 2.4% of diarrhea cases worldwide and 6% of malaria instances in different low-income areas (WHO, 2002). Pakistan stands out among developing nations, especially those in Southeast Asia, backward in health (Khoso et al., 2022), for being very vulnerable to climate-related disasters including floods and droughts. Devastating floods occurred in Pakistan between 2010 and 2014, causing significant loss of life and property along with widespread population relocation. In Pakistan, insect infestations, seasonal and flash floods, and droughts are only a few other climate-related phenomena. Casson et al., (2023) stated that Climate change introduces various health risks. Increased temperatures can lead to heat-related illnesses, while altered precipitation patterns may result in waterborne diseases and the spread of vector-borne diseases like malaria and dengue. Extreme weather events can disrupt healthcare infrastructure, limiting access to medical services and exacerbating health disparities.

Strategies for adapting to climate change in Pakistan

The agricultural industry demonstrates a capacity to quickly adopt new technologies, modifications to resource management practices, and adaptable tactics (Rehman et al., 2022). Researchers Fahad and Wang (2020) used household surveys to study adaptation strategies in rural Khyber Pakhtunkhwa province, Pakistan. The study found that the region's main adaptation strategies included changing crop types and varieties, managing pesticides, improving seed quality, planting shade trees, diversifying farming activities, and storing water. It is a common occurrence for people to adapt to the effects of climatic fluctuation in general and on the farming industry in particular. Effective adaptation to climatic variability requires modifications and adaptations at all scales, from the local community to the national and international levels (Kalogiannidis et al. 2022).

In order to handle current and future climatic challenges, it is crucial to build community resilience through the adoption of appropriate technologies, the preservation of traditional knowledge, and the diversification of livelihoods. The need of appropriate crop replacement was also stressed by Mendelsohn et al. (2007) in their analysis of how climatic variability affects agriculture. The IPCC Third Assessment Report states that although adaption strategies are not foolproof and have a cost associated with them, they can lessen the negative consequences of climate variability and increase positive outcomes. Additionally, it is contended that strategic adaptation can support autonomous adaptation and that both human and natural systems will adapt to some degree spontaneously. So far, the implementing afforestation programs to enhance carbon sequestration and promote biodiversity. Restore degraded ecosystems to improve resilience against climate impacts and sustain ecosystem services (Sargani et al., 2023).

However, the potential for adaptation for human systems is greater than that for the preservation of natural systems (Solomon , 2007). It is essential to combine community and governmental actions with traditional knowledge and local coping strategies. Governmental and non-governmental organizations (NGOs) should include climate variability into their policies at all levels of decision-making in order to promote successful adaptation measures. Farmers use a variety of tactics, such as changing planting and harvesting times and applying a range of agronomic techniques, to deal with climatic unpredictability and optimize earnings (Agesa et al., 2019). Robert et al. (2016) conducted a research that employed household survey methodologies to identify major adaptation measures in the study region. These tactics included planting trees, changing planting dates, conserving soil, and utilizing various crop kinds. Nevertheless, even though there were discernible variations in temperature and precipitation, a sizable proportion of farm households did not make any changes to their farming methods. Crop diversity is an adaptation technique that focuses on reducing the risk of total crop failure instead than only increasing the production of a particular crop (Huong et al., 2017). Crop diversification is a commonly used adaptation method in Pakistan to mitigate the effects of climate events (Fahad and Wang, 2018). According to earlier research (Kristiansen, 2022), using a variety of crop kinds in the same season may help farm households save money and have more access to resources. Farmers can be less vulnerable to climate change, particularly if they have income sources other than farming (Johnston & Cooper, 2022).

Off-farm pursuits might involve labor or ancillary enterprises like Pakistani stores. Pakistani farmers have frequently used a variety of soil and water conservation techniques in an attempt to mitigate soil erosion and degradation, with the goal of restoring their fields as a result (Fahad and Wang, 2020; Fahad and Wang, 2018). Pakistani farmers acknowledge that one way they cope with climate dangers is by selling assets. One of the most important adaptation measures used in Pakistan is irrigation, which is also widely used.

A significant fraction of farmers in Pakistan live in distant locations, own tiny landholdings, and have no formal education. The best way to determine how farm households perceive climate change is through household surveys. Research by Abid et al. (2015) and Fahad and Wang (2018) has demonstrated a substantial relationship between the perception of climate change and the household head's age and agricultural experience. For example, compared to less educated and less experienced farmers, educated and experienced farmers are more likely to recognize climate change. It is also thought that knowledge of climatic fluctuations is favorably correlated with the education degree of the family head. Access to extension services and information on climate problems for farmers increases knowledge and creates a favorable environment for the adoption of new cropping patterns.

Conclusion

In conclusion, the literature analysis on the effects of climate change in Pakistan's rural regions highlights the necessity of using an interdisciplinary approach to address the unique problems that these people confront. The report calls for community participation to include local viewpoints into solutions by highlighting the complex relationships between environmental, social, and economic elements that contribute to vulnerabilities in rural areas. It suggests a holistic approach that encompasses community-based adaption strategies, policy lobbying, and the promotion of sustainable behaviors, and it asks for context-specific suggestions and policy implications. In order to improve resilience and promote sustainable development in the face of climate change in rural Pakistan, this review offers insightful information for next studies and useful solutions. By emphasizing the importance of considering local nuances and collaborating with communities, it paves the way for more effective and culturally sensitive interventions in the ongoing battle against the impacts of climate change.

Declaration: We (all authors) declare that the paper is our original work and is not published anywhere.

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RESEARCH ARTICLE

Correlation or Causation: Unraveling the Relationship between PM2.5 Air Pollution and COVID-19 Spread Across the United States

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Abstract

Numerous studies have examined the potential connection between air pollution, particularly PM2.5, and the incidence of COVID-19 cases during the pandemic. While several studies have demonstrated a strong correlation, caution is advised as correlation does not imply causation. To address this concern, our two-year observational study employs a comprehensive approach that utilizes a large sample size and draws on temporal and spatial data across the United States, surpassing the limitations of previous studies restricted to specific locations. Through rigorous correlation and regression analyses, we control for potential confounding factors. Air pollution data, a crucial component of our study, has been sourced from the United States Environmental Protection Agency (EPA). Additionally, COVID-19 case data is extracted from the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University, providing a robust and widely recognized dataset for our analyses. Notably, a significant spatial correlation exists between COVID-19 cases and population size ($r=0.98$, p-value <0.01), as confirmed by multivariate regression analysis, suggesting a confounding influence of population. It is crucial to emphasize that correlation does not automatically imply a direct cause-and-effect relationship. Moreover, to minimize the impact of population, we employ rates (COVID-19 cases/population of States), demonstrating that the rate of COVID-19 cases is independent of PM2.5 and population. Additionally, the rate of COVID-19 infection is not correlated with population density, implying the population's influence on infection is more likely due to probability rather than being a direct cause. In summary, while many studies report a correlation between air pollution and COVID-19 cases, the influence of confounding factors like population density necessitates further investigation to establish a definitive causal relationship. In conclusion, while many studies report a correlation between air pollution and COVID-19 cases, the influence of confounding factors like population density necessitates further investigation to establish a definitive causal relationship.

Keywords: COVID-19; population; air pollution; PM2.5; confounding

Introduction

A study conducted by Doremalen et al.(Van Doremalen et al., 2020)has demonstrated that SARS-CoV-2 can remain viable and infectious in aerosols for several hours and on certain surfaces. Building upon this research, the hypothesis arises for other researchers that COVID-19, caused by the coronavirus, might potentially interact with air pollution. Groulx et al(Groulx, Urch, Duchaine, Mubareka, & Scott, 2018)confirm that microbial agents of communicable diseases, such as viruses, have interactions with air pollution, affecting public health. A study conducted in Poland found a significant association between particulate matter and the number of new COVID-19 infections (Czwojdzińska, Terpińska, Kuźniarski, Płaczkowska, & Piwowar, 2021a). Similar studies across Europe suggest that short-term exposure to particulate matter (PM) is related to the spread of SARS-CoV-2, with PM levels in England and Italy specifically implicated(Renard et al., 2022; Zoran, Savastru, Savastru, & Tautan, 2020). In the Middle East, a study of Baghdad and Kuwait found that PM2.5 levels were positively related to deaths caused by COVID-19, with a decrease in particulate matter leading to a significant decrease in the death rate. In Kuwait, a 38.4% decrease in deaths was observed during the travel ban period, with an average decrease of 22.3% in PM2.5 levels. This study also found a positive relationship between air temperature and a negative relationship between humidity and the number of deaths (Halos, Al-Dousari, Anwer, & Anwer, 2021). Therefore, some studies have found a relationship between PM and COVID-19(Czwojdzińska, Terpińska, Kuźniarski, Płaczkowska, & Piwowar, 2021b; Renard, Surcin, Annesi-Maesano, & Poincelet, 2023b; Setti et al., 2020), while others have not found any significant association between the two (Bontempi, 2020). Some studies have merely identified a correlation between PM and the daily number of confirmed cases without providing a p-value(Zoran et al., 2020). In a study conducted in Delhi, researchers found that the number of COVID-19 cases exhibited a significant negative correlation with PM2.5 levels (correlation=−0.63, p-value<0.01) during the pre-lockdown phase. However, the number of COVID-19 cases during the lockdown phase also showed a positive correlation with PM2.5, with a correlation value of 0.56. Despite these contrasting correlations, the researchers concluded that there is a dependence of COVID-19 transmission on the concentration of PM2.5 in Delhi's environment(Chaudhary et al., 2022).

The study aims to investigate the reason behind the varied correlations in existing research, exploring the potential role of confounding factors, notably population, in influencing whether some studies observe a positive correlation while others find a negative association. The study unfolds systematically, commencing with a thorough introduction to the global impact of COVID-19 and its potential connection to air pollution. A comprehensive literature review examines existing research, paving the way for a detailed methodology encompassing study design, data sources, and statistical analyses. The data sources section clarifies the origins and reliability of air pollution and COVID-19 data. The ensuing analysis meticulously presents statistical findings while addressing potential biases. A nuanced discussion interprets results, exploring implications and limitations, and the conclusion succinctly summarizes key findings while proposing avenues for future research.

Literature review

The COVID-19 pandemic will have long-term effects on the worldwide economy(Al-kasasbeh, 2022). Meanwhile, Various studies have explored factors influencing COVID-19 transmission, including air pollution (Maniat et al., 2023)and preventative measures like handwashing (Otto, Opatoki, & Luyi, 2022). An observational study in USA California, using data from the Environmental Pollution Agency (EPA), reported negative correlations between PM2.5 levels and both COVID-19 cases (-0.45) and mortality (-0.42) (Bashir, Jiang, et al., 2020). Researchers Adhikari and Yin studied air pollution in Queens, New York, comparing levels of PM2.5 with

COVID-19 infection and mortality rates. While they found no significant relationship between daily PM2.5 and either COVID-19 infection or mortality, they did uncover a significant positive association with new confirmed cases(Adhikari & Yin, 2020). A study of 14,783 COVID-19 patients found long-term exposure to fine particulate matter (PM2.5) is associated with increased hospitalization risk. Among the participants, 13.6% were hospitalized. Researchers analyzed both average PM2.5 exposure over the past 10 years and estimated exposure for the year 2018. The study found that for every 1 μg/m³ increase in PM2.5, the odds of hospitalization rose by 18% (10-year average) and 14% (2018 estimate). While this suggests a link, further research is needed to confirm causation and explore the underlying mechanisms(Mendy et al., 2021). A study has revealed a potential link between increased air pollution and higher COVID-19 death rates. Researchers found that every 1 microgram per cubic meter (μg/m³) increase in fine particulate matter (PM2.5) was associated with an 8% rise in COVID-19 deaths. This association was statistically significant and remained consistent even after accounting for other potential influencing factors.(Wu, Nethery, Sabath, Braun, & Dominici, 2020). While some studies indicate a link between air pollution and COVID-19 severity, findings remain mixed. One study found no significant association between long-term exposure to PM2.5 or ozone (O3) and COVID-19 case-fatality rate. However, they did observe a weak but potentially important connection between higher PM2.5 levels (an increase of 2.6 micrograms per cubic meter) and a 14.9% increase in COVID-19 mortality rate, even after adjusting for other air pollutants. This suggests further investigation is needed to clarify the complex relationship between air pollution and COVID-19 outcomes(Liang et al., 2020). A study found a 10.5% ± 2.5% increase in mortality per 1 μg/m³ increase in air pollution. However, this impact lessened over time, suggesting potential factors like improved pandemic management and broader vaccination after mid-2021. Interestingly, despite potential differences in initial conditions, the relative trend of mortality increase with higher air pollution was consistent across the studied countries(Renard et al., 2022). A review paper by Arun Srivastava explores the relationship between various pollution parameters and the number of COVID-19 cases. The findings reveal diverse correlations, including some with no correlation, others exhibiting a negative relationship, and some indicating a positive association(Srivastava, 2021). The reason why some studies find a positive relationship between PM and COVID-19 cases, while others do not, can be attributed to the fact that correlation does not imply causation. To establish causation, researchers need to conduct carefully designed studies, such as randomized controlled trials or longitudinal studies, to demonstrate a direct cause-and-effect relationship between PM levels and COVID-19 outcomes.

Indeed, emissions from the combustion of diesel fuel in cars and other vehicles are recognized as a significant source of particulate matter (PM) in urban areas (McDuffie et al., 2021; Nava et al., 2020). As a result, regions with higher population density tend to have more transportation activities, contributing to increased levels of PM(Aljoufie, Zuidgeest, Brussel, & Van Maarseveen, 2011; Maniat, Abdoli, Raufi, & Marous) During the COVID-19 lockdowns implemented in response to the pandemic, there were significant reductions in urban activity, including a decrease in transportation and industrial activities. As a result, there was a noticeable reduction in emissions, including those of particulate matter. This reduction in human activity led to improvements in air quality in many urban areas during the lockdown periods(Manjeet, Airon, Kumar, & Saifi, 2022). Population is a crucial factor in urban areas, as it reflects the concentration of individuals in a given space. Areas with higher populations are more likely to experience quick spreading of infectious diseases, including COVID-19(Ahmed, Jaman, Saha, & Ghosh, 2021). While areas with larger populations tend to have more reported COVID-19 cases (correlation), it does not necessarily mean that, the population itself directly causes the spread of the virus (causation). Just like flipping a coin multiple times increases the likelihood of observing both heads and tails, having a larger population in an area might lead to more reported COVID-19 cases due to an increased chance of encountering infected individuals. However, this correlation does not imply that population size directly causes the occurrence of COVID-19 cases. Two studies Malaysia found a strong positive and statistically significant correlation between the total population and COVID-19 cases, indicating that larger populations were associated with higher case numbers. However, the relationship between population density and the spread of COVID-19 was weaker(Aw et al., 2021; H. S. Wong, Hasan, Sharif, & Rahman, 2023). Using cumulative frequency reports of COVID-19 cases or deaths in research studies can lead to several common mistakes and misinterpretations. Cumulative data grows over time, and using it directly in analysis may introduce a time-dependent bias. Cumulative data may not adequately control for confounding factors such as public health interventions, population mobility, healthcare capacity, and socioeconomic variables. Failing to account for these factors can lead to spurious correlations. For instance, two studies found a correlation between population density and COVID-19 in the USA (Sy, White, & Nichols, 2021; D. W. Wong & Li, 2020), using cumulative frequency reports of COVID-19. Of course, the population density in specific places, such as hospitals, public transportation, and cruise ships(Rocklöv & Sjödin, 2020), can significantly contribute to the transmission of COVID-19 in localized settings, it is crucial to clarify that our study's primary objective is to investigate this phenomenon on a broader macro scale, covering provinces, cities, and countries. We seek to discern the distinction between physical distancing and population density. It is imperative to recognize that while the density, calculated as city population divided by area, may be high in a city, it does not necessarily correlate with low levels of physical distancing. In the study (D. W. Wong & Li, 2020)there is an assumption that the level of physical distancing is contingent on population density, implying that areas with higher population density experience a greater incidence of the coronavirus. Consequently, the study concludes that population density is a significant variable influencing COVID-19 cases. However, it's essential to approach this assumption with a nuanced perspective. While there may be a correlation between population density and COVID-19 cases, establishing a direct causation is complex. The relationship is influenced by various factors, including local public health interventions, cultural practices, healthcare infrastructure, and individual behaviors. Our research seeks to explore this intricate relationship on a broader macro scale, encompassing provinces, cities, and countries. By considering multiple variables and potential confounders, we aim to contribute to a more comprehensive understanding of the factors influencing COVID-19 transmission dynamics. In another study conducted in America, focusing on 913 counties, they found that metropolitan population density played a significant role as a predictor of infection rates. However, they observed that county density, by itself, was not significantly related to the infection rate. Instead, the study highlighted that connectivity, which involves factors beyond just density, appears to have a more significant impact on infection rates(Hamidi, Sabouri, & Ewing, 2020).

Considering the complexities of the association between air pollution and the spread of COVID-19, it would be reasonable to expect that regions with higher wind speeds, resulting in lower pollution levels, would also have fewer COVID-19 cases if all other factors were equal. However, despite this logical expectation, studies have not consistently shown a correlation between wind speed, pollution, and COVID-19 cases. The Gaussian air pollutant dispersion equation is indeed one of the earliest and simplest forms of pollutant dispersion modeling. It describes how air pollutants disperse and spread in the atmosphere under the influence of wind and other meteorological factors(Abdel-Rahman, 2008) Higher wind speeds can enhance the dispersion of air pollutants, leading to lower local pollution levels in densely populated cities. In areas with high wind speeds, it is expected that air pollutants would disperse more effectively, potentially reducing the concentration of pollutants in the air. In the study conducted in New York, the Spearman Correlation Coefficient of +0.172 suggests a positive correlation between wind speed and COVID-19 cases. This means that higher wind speeds were associated with higher COVID-19 case counts in that particular area(Bashir, Ma, et al., 2020). On the other hand, the study in Jakarta, Indonesia, revealed a significantly negative correlation ($r = -0.314$; $p < 0.05$) between low wind speed and higher COVID-19 cases(Rendana, 2020). Moreover, the study by Shao et al. found a positive and negative correlation between wind and the number of infected, indicating a connection between pollution and COVID-19 (Shao et al., 2022). The limitations observed in existing investigations stem from the fact that both air pollution and COVID-19 infections are correlated both spatially and temporally. Both spatial and temporal correlations between air pollution and infections can introduce biases in the estimation of results. Typically, researchers choose to consider either spatial or temporal correlations, depending on the research question and the nature of the data being analyzed. Our study possesses several advantages. Firstly, it benefits from a large number of statistical samples, which enhances the robustness and reliability of the findings. Additionally, the research employs two different types of correlations, namely spatial and temporal to thoroughly investigate the relationship between air pollution and COVID-19. This comprehensive approach allows for a more comprehensive understanding of the potential link between air pollution and the incidence of the disease. By utilizing various correlation methods and a substantial dataset, this study aims to provide valuable insights into the impact of air pollution on COVID-19.

Methodology

Sample

This study centers on fifty-one (N= 51) states in the USA, one of the countries significantly impacted by the COVID-19 pandemic, with over 54 million cases reported over the course of two years (2020 and 2021). Due to the larger dataset of people infected with COVID-19 compared to the number of deaths, this study utilized data on the number of infected individuals for analysis.

Sources

Wind speed and air pollution data were obtained from the United States Environmental Protection Agency (EPA) website (Agency, 2020,2021) the study also obtained temperature data in Fahrenheit from the National Centers for Environmental Information(Information). COVID-19 Data Repository by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University(jhu, 2022).

Measurements

The data of PM2.5 is often reported using the Air Quality Index (AQI), which provides an overall measure of air quality based on various pollutants, including PM2.5. However, the AQI is a dimensionless index and not directly usable for quantitative analyses due to its scale and unitless nature. To facilitate statistical analysis and comparisons, researchers often convert AQI values to a more quantitative and usable unit such as micrograms per cubic meter (µg/m³) using appropriate conversion equations. This conversion allows for the data to be expressed in a standard unit that can be utilized in statistical models and helps to establish a more meaningful relationship between PM2.5 concentrations and other variables. While the correlation between AQI and µg/m³ values not be 1, converting AQI to µg/m³ provides a more accurate representation of PM2.5 concentrations, enabling researchers to better understand its relationship with other variables in quantitative analyses. The AQI is given by Equation (1)(Kanchan, Gorai, & Goyal, 2015).

$$AQI = \frac{AQI_{Hi} - AQI_{Lo}}{conc_{Hi} - conc_{Lo}} \times (conc_i - conc_{Lo}) + AQI_{Lo} \qquad (1)$$

Where;
$Conc_i$(PM2.5)= input concentration for a given pollutant(pm2.5)
$Conc_{Lo}$= the concentration breakpoint that is less than or equal to $Conc_i$

$Conc_{Hi}$(PM2.5)= the concentration breakpoint that is greater than or equal to $Conc_i$
AQI_{Lo}= the AQI breakpoint corresponding to $Conc_{Lo}$
AQI_{Hi}= the AQI breakpoint corresponding to $Conc_{Hi}$
The average wind speed is measured in meters per second (m/s) using the Instrumental - RM Young Model 05103, which is designed to measure wind speed at low altitudes. It is important to note that wind speed can vary with height, and therefore, different devices and methods may yield different results due to the variations in wind patterns at different altitudes.
Time series data for COVID-19 confirmed cases in the United States for the years 2020 and 2021 can be obtained from the CSSE (Center for Systems Science and Engineering) at Johns Hopkins University public archive data (University). In the archive, the data is initially provided as cumulative frequency, which represents the total number of COVID-19 cases up to a specific date. To use this data for analysis, it needs to be transformed into daily frequency by taking the difference between consecutive data points. To clarify, for each day, the number of new COVID-19 cases (frequency) can be calculated by subtracting the cumulative count on the previous day (t_0) from the cumulative count on the current day (t_1), denoted as $x(t_1)$ - $x(t_0)$. In addition, the ratio of the number of cases to the total time the population is at risk of disease can also be calculated. This ratio provides insights into the incidence rate of COVID-19 cases per unit of time for each state. Furthermore, to determine population density, one can obtain the population of each state and divide it by the area of each state. In the majority of studies, researchers commonly employ Pearson correlation for assessing the relationship between variables. While some studies use Kendall and Spearman correlation, the differences in results are not significant. To facilitate comparison with other research, we also utilize Pearson correlation. Pearson's correlation coefficient (r) is a widely used measure that evaluates the strength, type, and direction of the relationship between two variables. The Pearson correlation (r) is defined as shown in Equation (2)(Akoglu, 2018).

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 (y_i - \bar{y})^2}} \quad (2)$$

where:
r=correlation coefficient,
x_i , y_i are the values of the variable in a sample i,
$\bar{x}$, $\bar{y}$= mean of the values of the y-variable.
In research that investigates a potential cause-and-effect relationship, a confounding variable is an unmeasured third variable that influences both the supposed cause and the supposed effect. Confounding is one of three types of bias that can distort the results of epidemiologic studies and potentially lead to erroneous conclusions(Howards, 2018)
It’s important to consider potential confounding variables and account for them in your research design to ensure your results are valid. Left unchecked, confounding variables can introduce many research biases to your work, causing you to misinterpret your results. Confounding variables (a.k.a. confounders or confounding factors) are a type of extraneous variable that are related to a study’s independent and dependent variables. A variable must meet two conditions to be a confounder(McNamee, 2003):
It must be correlated with the independent variable. This may be a causal relationship, but it does not have to be.
It must be causally related to the dependent variable.
The conceptual model incorporates the idea of these two conditions, with the confounding variable being present in Figure 1.

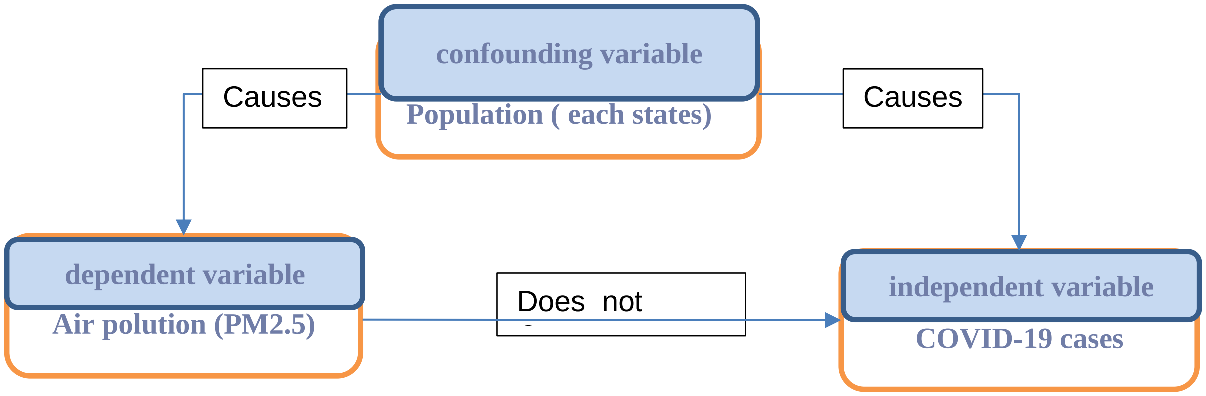

Figure 1. Conceptual model confounding variable

The technique of multivariable regression analysis has been extensively employed to manage confounding factors, and its utilization saw significant augmentation, especially when modeling tools became easily accessible(Kahlert, Gribsholt, Gammelager, Dekkers, & Luta, 2017). Multiple regression analysis serves the purpose of evaluating the presence of confounding. Through multiple linear regression analysis, we can estimate the relationship between a specific independent variable and the outcome while keeping all other variables constant. This approach allows for the adjustment or accounting of potential confounding variables incorporated into the model. Consider a scenario with a risk factor or exposure variable denoted as X1 (e.g., X_1=Air pollution or X_1=Temperature) and an outcome or dependent variable denoted as Y. The estimation of a simple linear regression equation relating the risk factor to the dependent variable is expressed as follows in equation (3).

$$Y=b_0+b_1X \quad (3)$$

Suppose the aim is to assess whether a third variable (e.g., population) acts as a confounder. This potential confounder is denoted as X_2, and the estimation involves a multiple linear regression (4).

$$Y=b_0+b_1X+b_2X_2 \quad (4)$$

Some researchers evaluate confounding by examining the extent of change in the regression coefficient associated with the risk factor after adjusting for the potential confounder. In this context, a comparison is made between b1 from the simple linear regression model and b1 from the multiple linear regression model. As a general guideline, when there is a shift of more than 10% in the regression coefficient derived from the simple linear regression model, it is commonly considered that X_2 functions as a confounding variable(Harrell Jr, Lee, & Mark, 1996; Sudin, Aziz, Saad, Khalid, & Ibrahim, 2021; Vittinghoff, Shiboski, Glidden, & McCulloch, 2005).

Results

Figure 2 depicts the number of confirmed COVID-19 cases in the United States throughout the years 2020 and 2021. The data shows that the peak of COVID-19 infections in 2020 occurred in December, while in 2021, the highest number of cases was reported in January. Over the entire year of 2020, a total of 20,126,950 confirmed COVID-19 cases were recorded in the United States, and this number surged to 34,505,103 in 2021. The Fig2 effectively presents the overall trend of COVID-19 cases over the two-year period, highlighting fluctuations and changes in infection rates across different months in both years.

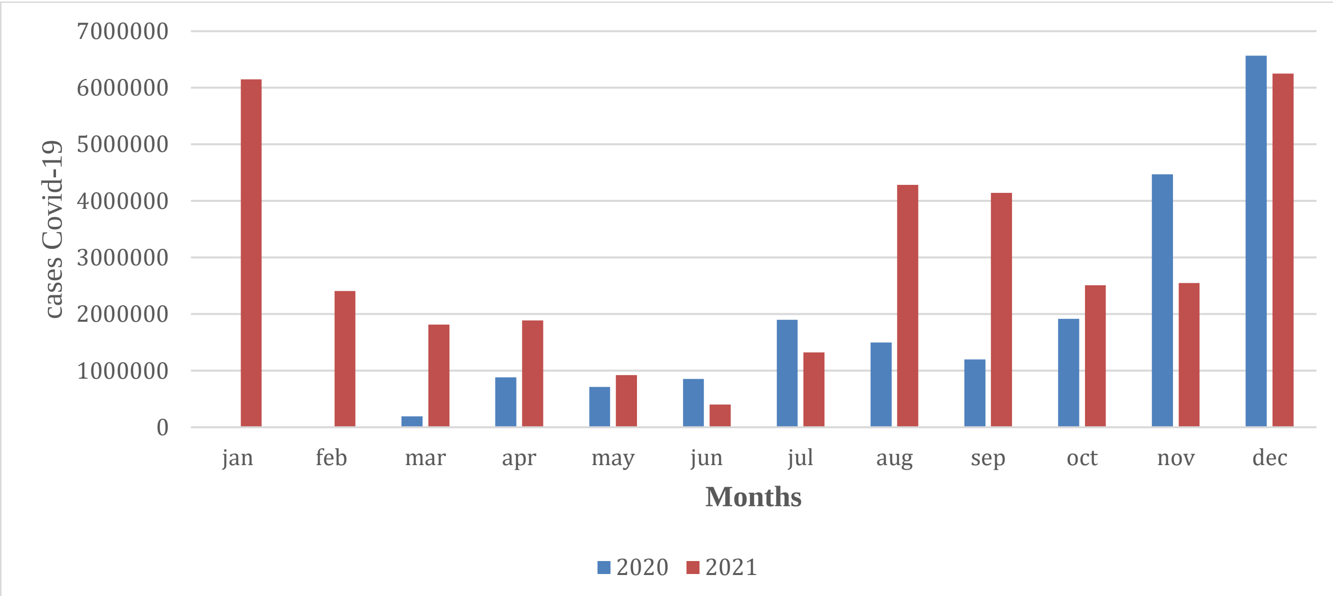

Figure 2. The number of confirmed COVID-19 cases in the years 2020 and 2021 Source authors `s analysis

The data analysis presented in Figure 3 consistently demonstrates a high prevalence of COVID-19 cases in California, Florida, New York, and Texas throughout the two-year period. The three graphs indicate that the pattern of COVID-19 cases in these states closely correlates with their respective population sizes. States with larger populations tend to have a higher number of COVID-19 cases.

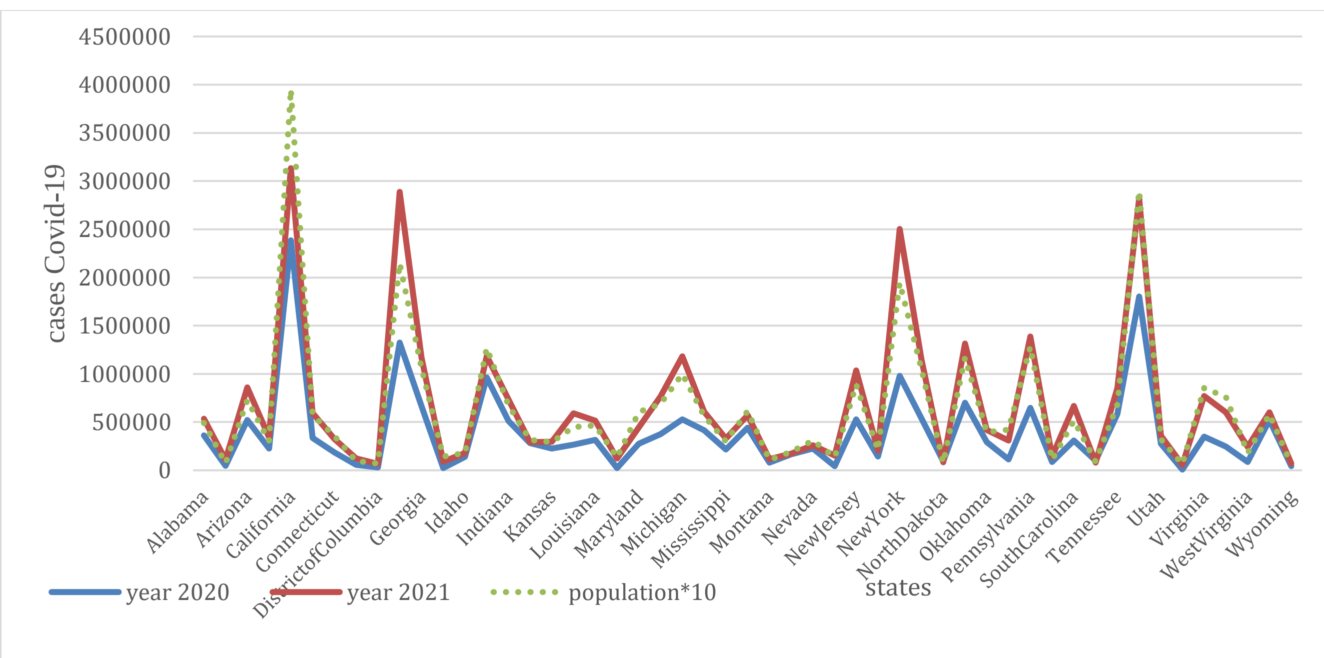

Figure 3. Number of confirmed COVID-19 in the years 2020 and 2021 Source authors `s analysis

The strong spatial correlation between COVID-19 cases in 2020 and 2021 suggests that the pattern of infections for each state repeated in the following year (Table1). There is a significant positive correlation between the population and COVID-19 cases(r=0.98), supporting the idea discussed in the introduction that population size can influence the likelihood of infection. The weak correlations, close to zero, between the rate of COVID-19 cases and population, as well as population density and COVID-19 cases. Wind speed shows no correlation with COVID-19 cases, indicating it has little impact on transmission dynamics. Temperature, on the other hand, exhibits a positive correlation with COVID-19 cases. Regarding PM2.5, COVID-19 cases in 2020 show a significant positive correlation (r=0.468) with PM2.5, while in 2021, the correlation remains positive (r=0.168) but not significant. Additionally, the correlation between the rate of COVID-19 cases and PM2.5 is close to zero, suggesting their independence.

Table 1. Spatial correlation and COVID-19 cases in different states Source authors `s analysis

	COVID-20	COVID-21	r2020	r2021	pop	density	pm2020	pm2021	temp2020	temp2021	wind2020	wind2021
COVID-20	1	.948**	0.045	-0.023	.982**	-0.095	.468**	.289*	.338*	.333*	-0.012	-0.011
COVID-21	.948**	1	-0.071	0.1	.967**	-0.084	.340*	0.168	.349*	.338*	-0.092	-0.101
rate2020	0.045	-0.071	1	0.253	-0.083	-0.169	0.09	.368**	-0.13	-0.113	.374**	.392**
rate2021	-0.023	0.1	0.253	1	-0.054	-0.082	-0.139	-0.067	-0.105	-0.136	-.286*	-.304*
population	.982**	.967**	-0.083	-0.054	1	-0.082	.450**	0.244	.324*	.316*	-0.065	-0.065
density	-0.095	-0.084	-0.169	-0.082	-0.082	1	0.092	0.09	0.12	0.104	-0.1	-0.104
pm2020	.468**	.340*	0.09	-0.139	.450**	0.092	1	.803**	0.076	0.071	0.032	0.057
pm2021	.289*	0.168	.368**	-0.067	0.244	0.09	.803**	1	-0.052	-0.046	0.17	0.188
temp2020	.338*	.349*	-0.13	-0.105	.324*	0.12	0.076	-0.052	1	.998**	-0.115	-0.083
temp2021	.333*	.338*	-0.113	-0.136	.316*	0.104	0.071	-0.046	.998**	1	-0.078	-0.046
wind2020	-0.012	-0.092	.374**	-.286*	-0.065	-0.1	0.032	0.17	-0.115	-0.078	1	.973**
wind2021	-0.011	-0.101	.392**	-.304*	-0.065	-0.104	0.057	0.188	-0.083	-0.046	.973**	1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 2 displays the Temporal correlation between different variables. The correlation between COVID-19 cases in 2020 and 2021 is found to be r=0.384, which is much weaker than the spatial correlation observed earlier. This suggests that the relationship between COVID-19 cases is dependent on spatial variables, not temporal variables. . The correlation between temperatures in 2020 and 2021 is high, indicating that the temperature pattern remains consistent in most states of America and is repeated year after year. The 7th and 8th months of the year are typically the hottest months. Additionally, there is a high and significant correlation between wind speed in 2020 and 2021 (r=0.899). Wind speed and temperature tend to have an inverse relationship, where higher wind speeds are associated with cooler temperatures. Furthermore, the correlation between wind speed and PM2.5 is -0.685 and -0.613 (p-value <0.01) for the years 2020 and 2021, respectively. This indicates that when wind speed is higher, PM2.5 levels tend to be lower. Regarding COVID-19 cases, there is a positive correlation with PM2.5 in both 2020 (r=0.111) and 2021 (r=0.235).

Table 2. Temporal correlation between pollution and COVID-19 cases Source authors `s analysis

	COVID-2020	COVID-2021	temp2020	temp2021	wind2020	wind2021	pm2020	pm2021
COVID-20	1	0.384	-0.175	-0.104	-0.273	-0.182	0.111	-0.005
COVID-21	0.384	1	-0.455	-0.398	-0.375	-0.176	0.355	0.235
temp2020	-0.175	-0.455	1	.986**	-0.529	-.620*	0.295	0.528
temp2021	-0.104	-0.398	.986**	1	-0.551	-.603*	0.327	0.477
wind2020	-0.273	-0.375	-0.529	-0.551	1	.899**	-.685*	-.689*
wind2021	-0.182	-0.176	-.620*	-.603*	.899**	1	-0.556	-.613*
pm2020	0.111	0.355	0.295	0.327	-.685*	-0.556	1	0.331
pm2021	-0.005	0.235	0.528	0.477	-.689*	-.613*	0.331	1

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

In the context of multiple regression, the Table 3 provides an overview of the R-Square, Std. Error of the Estimate, R-Square Change, F Change, and Significance of F Change for each model, incorporating various sets of predictors such as the constant, pm, temperature, wind, and population. Model 4 is the best model as it has the highest R-squared value of 0.847. the R-squared change value of 0.656 suggests that population explains 65.6% of the remaining variance in the dependent variable after accounting for the other independent variables in the model. This is a significant increase, and it suggests that population is indeed a confounding variable.

Table 3. Model Summary Source authors `s analysis

Model		R Square	Std. Error of the Estimate	R Square Change	F Change	Sig. F Change
1	a. Predictors: (Constant), pm	0.087	596876.16057	0.087	9.517	0.003
2	b. Predictors: (Constant), pm, temperature	0.185	566575.96405	0.099	11.982	0.001
3	c. Predictors: (Constant), pm, temperature, wind	0.190	567708.50660	0.005	0.605	0.438
4	d. Predictors: (Constant), pm, temperature, wind, population	0.847	248202.09317	0.656	415.703	0.000

Table 4. regression results Coefficients Source authors `s analysis

		Unstandardized Coefficients		Standardized Coefficients			95,0% Confidence Interval for B	
Model		B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound
1	(Constant)	-79946.814	207796.301		-0.385	0.701	-492208.757	332315.130
	pm	59529.328	19297.089	0.295	3.085	0.003	21244.453	97814.202
2	(Constant)	-1255637.504	392769.598		-3.197	0.002	-2034977.599	-476297.410
	pm	58455.988	18320.104	0.289	3.191	0.002	22104.928	94807.048
	temperature	21971.717	6347.476	0.314	3.461	0.001	9376.948	34566.487
3	(Constant)	-1139117.126	421084.237		-2.705	0.008	-1974745.090	-303489.162
	pm	60440.713	18533.106	0.299	3.261	0.002	23662.368	97219.059
	temperature	21588.773	6379.179	0.309	3.384	0.001	8929.500	34248.045
	wind	-27986.691	35969.267	-0.072	-0.778	0.438	-99366.529	43393.148
4	(Constant)	-16004.504	192162.430		-0.083	0.934	-397393.734	365384.725
	pm	-4459.725	8705.497	-0.022	-0.512	0.610	-21737.727	12818.277
	temperature	1756.935	2953.726	0.025	0.595	0.553	-4105.394	7619.265
	wind	-65.921	15785.272	0.000	-0.004	0.997	-31395.316	31263.473
	population	0.078	0.004	0.919	20.389	0.000	0.070	0.086

The standardized coefficient for population in model 4 is 0.919, which is very significant. Indeed, based on Table 4, it is evident that the population (variable) exhibits a significant influence on the dependent variable. This indicates that population is a confounding variable, meaning that it is an extraneous factor that is correlated with both the independent variable (PM) and the dependent variable (COVID-19 cases). This can make it difficult to isolate the true relationship between PM and COVID-19 cases. The fact that the coefficient for PM decreases by more than 10% after controlling for population suggests that population is indeed a confounding variable. This means that PM is not the sole cause of COVID-19 cases, and that population must also be considered a factor.

Discussion

Our study employed spatial and temporal correlation analyses to explore the relationships between wind, temperature, pollution, population density, and COVID-19 cases. The findings suggest correlations between pollution and COVID-19 cases but caution against making direct causative conclusions. While many studies have shown a correlation between air pollution and the number of COVID-19 infections, it does not imply causality. During lockdown periods, we observed a decrease in pollution, and studies have shown that the disease itself caused a decrease in air pollution(Su et al., 2023). However, this correlation does not indicate causation but rather reflects the simultaneous occurrence of two phenomena. Observing similar patterns between the graphs of mortality and infection rates in Europe(Renard, Surcin, Annesi-Maesano, & Poincelet, 2023a), researchers may be inclined to automatically assume that pollution has a strong effect on COVID-19. There are several reasons why caution is necessary in making such conclusions:

1-Correlation does not imply causation: Just because two variables (in this case, air pollution and COVID-19 outcomes) show similar patterns does not necessarily mean that one directly causes the other. There could be other factors at play that are responsible for the observed associations. To demonstrate the potential for such errors, you used the rate of infected people (the number of infected individuals divided by the population of the state) and found that its correlation with air pollution was close to zero. This finding suggests that there is no strong linear relationship between air pollution and the rate of COVID-19 infections.

2-Confounding factors: The observed patterns in COVID-19 cases could be influenced by numerous confounding factors, such as population. These factors may influence both air pollution levels and the spread of COVID-19 independently(Kelly et al., 2023). Although the spatial correlation in Table 1 shows the effect of population on COVID-19 and pollution at a significant level (p-value<0.01). Population is one such confounding factor that can impact both air pollution levels and the spread of COVID-19 independently. A larger population in an area may lead to more reported COVID-19 cases due to the increased likelihood of encountering infected individuals. However, this correlation does not imply that population size directly causes the occurrence of COVID-19 cases. If population size were the primary determinant of COVID-19 cases, then population density would also have a similar effect on both COVID-19 cases and air pollution (But the correlation is close to zero).

3-Regional variations: Consistent with previous research(Coşkun, Yıldırım, & Gündüz, 2021; Rendana, 2020) areas experiencing higher wind speeds tend to have lower levels of PM2.5 pollution. Interestingly, we also observed a temporal correlation between lower wind speeds and increased COVID-19 cases. This temporal correlation suggests that reduced wind speeds might contribute to higher COVID-19 case numbers. However, when examining the spatial correlation, we found a positive association. This suggests that factors beyond just wind speed and pollution may influence the spatial distribution of COVID-19 cases.

Conclusions

The global impact of the COVID-19 pandemic, stemming from a highly contagious virus within the SARS family, has been widespread, affecting over 200 countries and leading to more than 6.9 million deaths as of the current date (Rahimi, Chen, & Gandomi, 2023).The study identifies a correlation between air pollution and COVID-19 cases, emphasizing the need for cautious interpretation. Although a correlation exists, it does not necessarily imply a causal relationship, prompting consideration of other variables such as population and wind speed. The intricate relationship among air pollution, COVID-19, and various factors requires further research. It is stressed that the correlation between two variables does not automatically suggest a direct cause-and-effect connection; additional factors may account for the observed correlation. The study recognizes confounding factors, with population identified as one such factor, correlated with both air pollution and COVID-19 cases, while wind speed shows the correlation solely with air pollution. While exposure to air pollution is linked to heightened vulnerability in COVID-19 patients, it cannot be definitively stated that pollution directly causes exacerbation of COVID-19. Various contributors, including temperature, lifestyle, population density, and nutrition, play roles in the incidence of COVID-19. Notably, the rate of COVID-19 infection is not correlated with population and population density, categorizing the impact of population on infection as a probability effect rather than an effective and causal variable. To achieve a more comprehensive understanding of the intricate interactions between air pollution and COVID-19, it is essential to collect data from different states or cities. Establishing a robust causal relationship demands rigorous scientific investigations, including longitudinal studies with meticulous control of confounding factors, as well as experimental studies and causal modeling. While mounting evidence suggests that air pollution may exacerbate respiratory conditions and increase vulnerability to infections, including COVID-19, it is crucial to refrain from drawing definitive conclusions solely based on visual observations of graphs. A careful and nuanced approach is essential in unraveling the complexities of the relationship between air pollution and COVID-19 outcomes.

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RESEARCH ARTICLE

The Threshold level of Institutional Quality in the Nexus between Financial Development and Environmental Sustainability in Nigeria

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Abstract
Empirics on the relationship between financial development and environmental sustainability remain ambiguous in the literature. The threshold level at which institutional quality facilitates the relationship between financial development and environmental sustainability in respect to the Nigerian economy is still an open question. This study investigates the threshold level of institutional quality in the link between financial development and environmental sustainability in Nigeria from 1986 to 2020. Times series threshold autoregression technique was applied to determine the threshold level of institutional quality. The result of the threshold revealed that 4.32 is the threshold level of institutional quality in Nigeria. Below the threshold level financial development is not stimulated to improve environmental sustainability but above the threshold level institutional quality stimulates financial development to improve environmental sustainability. This study suggests that institutional credibility and transparency should be enhanced beyond the threshold level to effect the needed change in increasing environmental preservation in Nigeria.

Keywords: Environmental sustainability; financial development; institutional quality; Nigeria

Introduction

Environmental sustainability is a global agenda that every country strives to attain to promote prosperity, human welfare, environmental sustenance, generational wealth and enhancement of human survival. Environmental sustainability deals with the ability to maintain the reproductive capacity of the ecosystem to meet the economic needs of future generations and sustain a safe environment for all. However, some developing nations have focused on economic growth while ignoring its environmental implications (Dada *et al*., 2022). For instance, the growth of industrial activities, use of automobiles, energy consumption and inappropriate waste management system contributes to the increase of greenhouse gasses and environmental degradation in Nigeria (Effiom & Uche, 2021). The World bank reports that Gas flaring in Nigeria caused numerous health and respiratory issues for individuals in the Niger-delta region of Nigeria (Ifere & Abim, 2019). The Nigerian economy is plagued by inconceivable environmental hazards and pollutants, which degradates the environment (Ojong, 2018). These pollutants are caused by Gas flares, flooding and dumping of wastes into rivers and seas (Ogar *et al*., 2018). Also, toxic wastes, industrial wastes, and plastics dumped into water bodies in Nigeria frequently decompose into micro-plastics and other chemical substances that endanger human lives (Ifere & Abim, 2019).

This occur as a result of negative environmental activities by Nigerians that causes climate vulnerabilities and increase in carbon emissions (Ojong, 2018). In mitigating climate irregularities and reducing carbon emissions, the financial sector plays a crucial role of mobilizing the capital required for investments in climate adaptation which increases resistance to climate change. It also provides the capital needed for climate mitigation which lowers greenhouse gas emissions especially in response to price signals like carbon taxes (Grippa, Schmittmann & Suntheim, 2019). To partially offset the cost of natural disasters and negative externalities, financial markets also offer financial protection through insurance and other risk-sharing tools like catastrophe bonds, climate bonds and green bonds. These bonds help to raise capital for climate, environmental and natural resource projects.

A well-regulated financial sector assists the economy to foster environmental sustainability by using green methods and green technologies in its daily activities to abate environmental damage (Hunjra *et al.*, 2020). More so, financial development can facilitate eco-investment and natural resource optimization that improves environmental sustainability (Baloch et al., 2021). The financial sector is charged with the responsibility of aiding the economy in the management of natural resources by funding projects that are channeled towards sustainable forestry (Khan *et al*., 2019). On the other hand, a poorly-regulated financial sector may boost environmental pollution. Financial development can spur economic growth and economic growth comes with environmental consequences (Acheampong, 2019). This is due to the fact that environmental resources are used as inputs for the production of goods and services leading to increased exploitation of natural resources (Khan *et al*., 2022). Financial institutions also provide financial support to the transportation and energy industries, which are responsible for a rise in carbon emissions (Dada *et al*., 2022). The transportation sector works with vehicles like cars, trucks, ships, trains, and airplanes. The use of these automobiles and planes emit carbon dioxide, which results from the combustion of environmentally hazardous fossil fuels (Dada *et al*., 2022). Nevertheless, the effect of financial development on the environment depends on the institutional distinguishing characteristics of an economy. According to Liu et al (2020), developing countries are faced with environmental challenges because of its poor quality of institutions. Weak institutions may not enforce environmental standards and monitor the activities of the financial sector when it is plagued with corruption and disrespect for the rule of law (Law & Ibrahim, 2016). The financial sector in Nigeria is not exempted from this weakness as Kanu et al (2020) noticed that the green bond markets in Nigeria is poorly successful in meeting up with the objectives of the environmental, social and governance policies of the Nigerian economy. Thus, the Nigerian financial system still functions under institutional policies that lack an orchestrated and well-defined coherent structure which has crippled its sustainability impact on the environment (Fagbemi & Ajibike, 2018).

The performance of Nigeria on environmental sustainability and financial development proxied by adjusted net savings and financial development index, is presented in Figure 1 and 2, respectively. Figure 1, show a declining trend of adjusted net savings from 1986 to 2020 depicting that Nigeria is not on the path of sustainability. The Nigerian economy is yet to improve its level of sustained growth to account for improvement in its environmental quality, resource maximization, savings behaviour and reduction in its consumption lifestyle. Also, Figure 2, which shows the trend of financial development in Nigeria, depicts that there are structural deficiencies in the financial sector as the performance of the broad-based financial system in Nigeria was below 30% for 35 years (1986 to 2020). Extant studies revealed that institutional quality is a critical factor that greatly influences the relationship between financial development and environmental sustainability (Gyamfi et al., 2020; Hunjra et al., 2021; 2020; Khan, welli & Khan, 2022). Nonetheless, weak institutions may not advance the quest to achieve a sustainable environment. In 2019, Nigeria was ranked the 2nd most corrupt country in West Africa and the 31st most corrupt country in the world (Corruption perception index, 2022). Corruption hinders the effectiveness of institutional quality in achieving environmental development (Khan et al., 2022). Nigeria's inadequate and ineffective policy implementation in terms of promoting development and enhancing environmental sustainability has been mostly attributed to government instability (Okolo, 2020). Consequently, institutional weakness may allow the ecosystem to deteriorate since it lacks the competence to enforce environmental rules and regulations (Zakaria & Bibi, 2019). This means institutions need to improve its quality to a certain level of effectiveness to effect necessary changes in the financial system and in the environment as a whole. Then the question becomes, 'at what level of institutional quality, would the financial sector be empowered and controlled to facilitate environmental sustainability? This question is yet to be addressed in the literature with particular reference to Nigeria. Thus, this study advances the existing body of knowledge on financial development and environmental sustainability in a number of ways. First, this study employs a more robust measure of financial development which accounts for the access, depth and efficiency of both financial markets and financial institutions in the economy. Previous studies have applied private credit to GDP and stock capitalization to GDP as measures of financial development (Wackernagel & Galli, 2007; Li et al., 2022) which only captures the depth of financial development neglecting other aspects of the economy. Second, the effect of institutional quality on financial development and environmental sustainability is evaluated by determining the threshold level of institutional quality in the link between financial development and environmental sustainability in Nigeria. This incentive is drawn from the assumption that sound institutions are indispensable in boosting and enhancing the financial sector in the pursuit of environmental sustainability. Third, in contrast to cross-country analysis on financial development and environmental sustainability that is ambiguous in the literature, this study focusses on country-specific analysis. This is because extant studies neglected the fact that institutional framework, financial development and economic behaviour differ between countries.

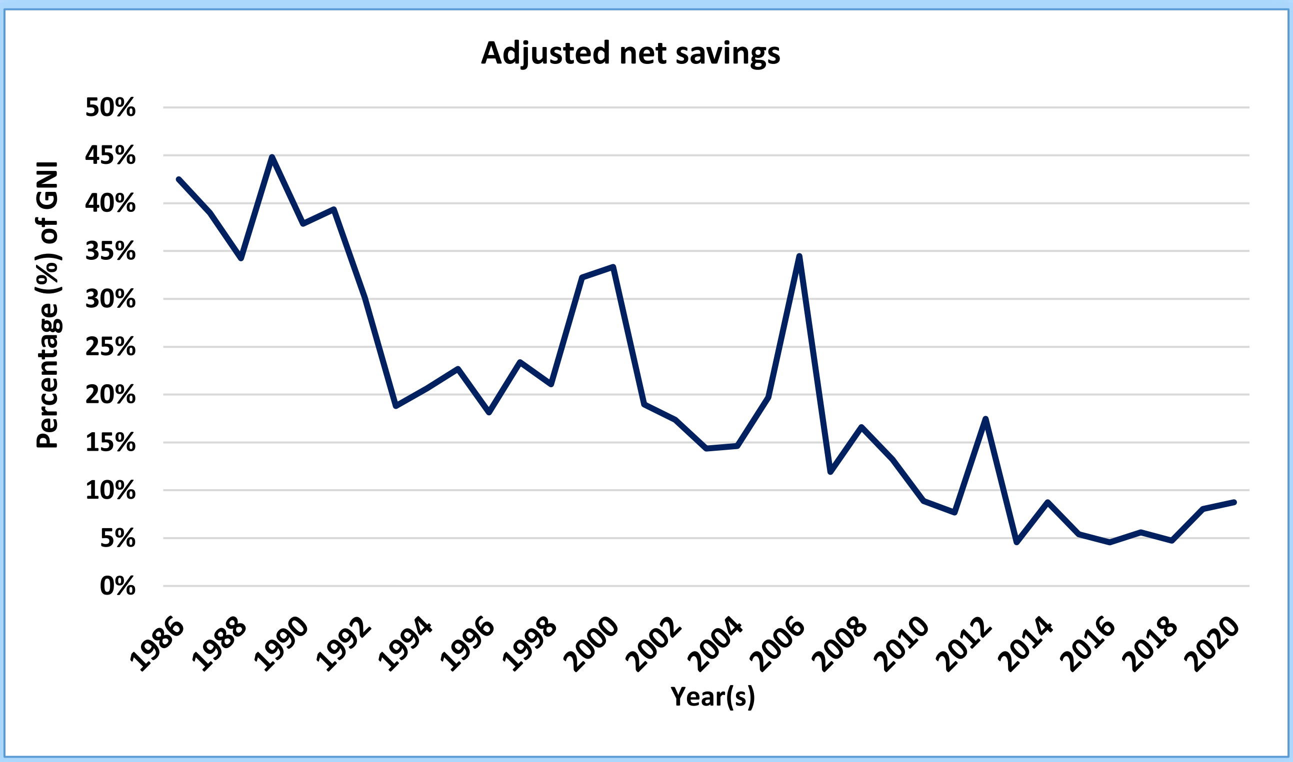

Figure 1: Adjusted net savings for Nigeria (1986-2020)
Source: World Development Indicators (2022)

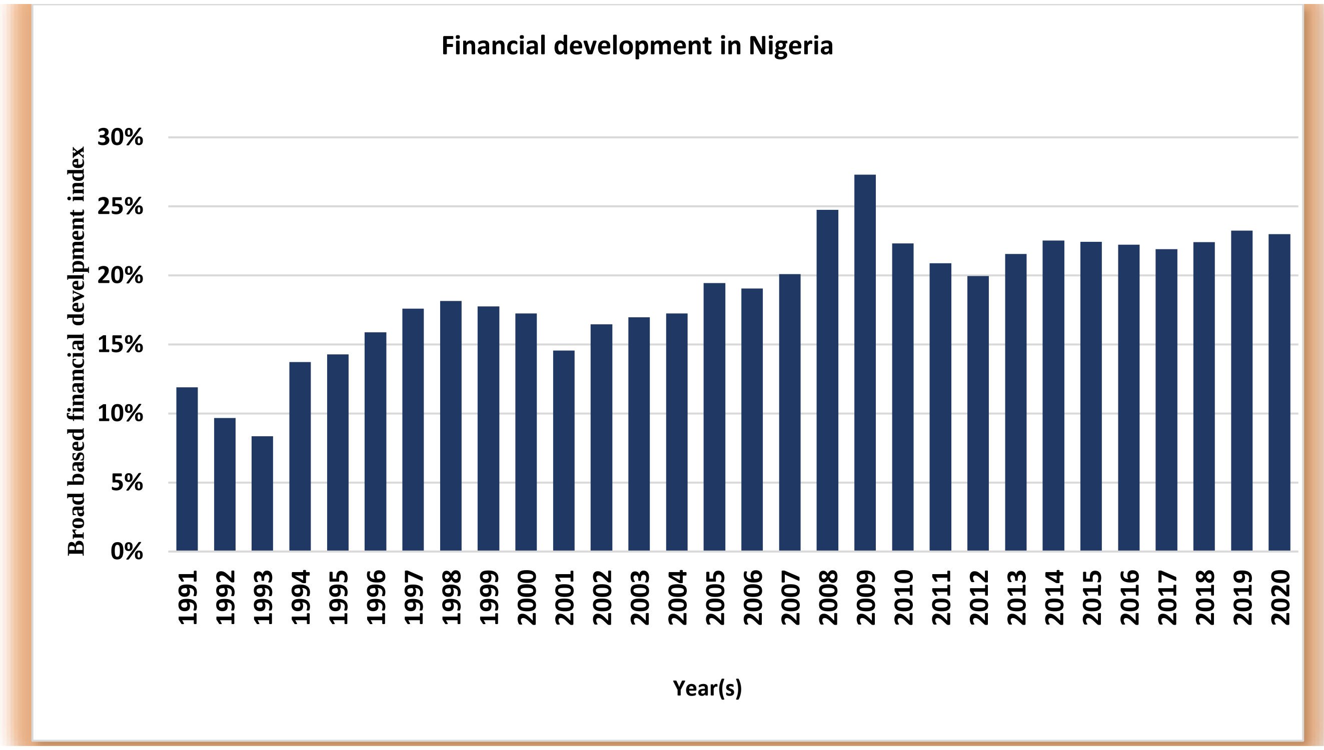

Figure 2. Financial development in Nigeria (1986-2020).
Source: International Monetary Fund (2022)

Literature review

Theoretical underpinning

The foremost theoretical construct of sustainability is based on the theory of weak sustainability, propounded by Hartwick (1977) and Solow (1974). Hartwick (1977) and Solow (1974) proposed the savings-investment rule with the central assumption that natural capital and manufactured capital are perfectly substitutable. Hartwick (1977) evaluated the challenges of weak sustainability by defining the investment-savings rule, known as the "Hartwick's rule". Hartwick's rule for sustainability deals with reinvesting the rents actualized from the depletion in natural resources. Solow (1974) assumed that the maximal allocation and reinvestment of resources, can be used to compensate for the natural resources that were lost, so that stock of total capital will not be depreciated over time. One benefit of weak sustainability is that it promotes scientific and technological advancements, as natural and manufactured capital can be substituted easily to meet the demands of the economy and the environment. In practice, sustainability is typically assessed by utilizing the natural environment sustainably. Empirics on financial development and environmental sustainability in the literature, have found the significant effect of this theory on Malaysia, Asia and sub-Saharan African countries (Pardi et al., 2015; Koirala & Pradhan, 2019; Ojeyinka & Osinubi, 2022).

The relationship between financial development, institutional quality, and environmental sustainability was explained by previous studies using the environmental Kuznets hypothesis (Effiom & Uche, 2021; Gyamfi et al., 2020; Zakaria & Bibi, 2019). The environmental Kuznets hypothesis is flawed due to its inability to account for the impact of institutional and structural factors that may have an impact on the environment (Dada et al., 2021). This is due to the fact that GDP, a crude indicator of development, is used by the Environment Kuznets Curve theory which is limited to explaining the relationship between economic growth and the environment. On the other hand, the weak sustainability theory explains the relationship between development and sustainability. Currently, the global society prioritizes sustainability over economic growth.

Financial development and environmental sustainability

There is a contention in the literature on the relationship between financial development and environmental sustainability. While some empirical result revealed that financial development positively influences the environment by improving access to advanced technologies (Shabaz, Hye, Tawari & Leito, 2013; Tamazian and Rao, 2010; Kumbaroglu, 2008; Tadesse, 2005), others argue that financial development increases environmental pollution (Omri *et al.*, 2015; Ozturk & Acaravci, 2013). For example, Shen *et al* (2021) noticed that financial development increases the emission of carbon while green technology helps to minimize environmental degradation. Another study also showed that financial development is detrimental to environmental sustainability as Roub *et al*. (2021) discovered that financial development boost environmental damage in Turkey for 56 years. The authors affirmed that financial development leads to an increase in fossil fuel consumption and agriculture really helps the environment when advanced agricultural equipment are used. Likewise, Adebayo *et al*. (2021) discovered that for 28 years, renewable energy increased the quality of the environment while economic growth increased environmental damage in Brazil.

The environment plays a key role in the survival of man as human activities takes place in the environment. The environment is so crucial to sustaining human life that every economy aims to preserve its resources. However, the high rate of natural resource deterioration has called for serious concern amongst economies in the world which has led to some empirical studies on environmental sustainability. In affirmation, Khan *et al.* (2022) revealed that control of corruption and government effectiveness increased carbon emission while regulatory quality and rule of law increases environmental quality in Iran. In the same vein, Hunjra *et al.* (2020) affirmed that financial development and foreign direct investment degradated the environment in Nepal, India, Bangladesh, Sri Lanka and Pakistan for 38 years. Developed and developing economies that aim at improving environmental sustainability, strives to tackle the issue of carbon emission. This is because a high carbon environment is harmful to both humans and the ecosystem. Jianguo *et al.* (2022) confirmed that technological innovations and institutional quality improves environmental quality. In addition, Kousar *et al.* (2020) noticed that financial development, trade openness and institutional quality reduced environmental degradation in Pakistan for 22 years.

Most of these studies are faulted on certain aspects. The theoretical approach of these studies was centred on the environmental kurtnet curve. The major weakness of this theory is that it is based on the assumption that all pollution will behave the same way both in lower and higher-income economies. In reality, economic and institutional peculiarity exist which can make some countries control and reduce environmental pollution more than others. The framework of the environmental Kutznet hypothesis lacks the ability to accommodate institutional and macroeconomic variables. More so, the environmental kutznet hypothesis lacks model adequacy as it is seen to be more of an empirical idea than a theoretical one (Stern, 2004).

Institutional Quality and Environmental Sustainability

The increasing activities and consumption pattern connected to economic growth and growing populations in the world has engendered environmental threats. This has drawn the attention of governmental institutions and scholars around the world to look into possible solutions to these problems. However, there are mixed reactions on the nexus between institutional quality and environmental sustainability in the literature. Some empirical studies confirmed that institutional quality degrades the ecosystem (Hassan *et al*., 2020; Yamineva & Liu, 2019), while other results revealed that certain indices of institutional quality such as bureaucratic quality, quality of regulation and control of corruption improves environmental quality (Adams & Klobodu, 2017; Ulucak et al., 2020; Rizk & Slimane, 2018).

Ecological footprint was also employed by (Khan *et al.*, 2021) to capture the level of environmental sustainability in BRIC countries in order to examine that role of that financial development and institutional quality play in facilitating environmental quality. The authors applied the two step GMM and fixed and random effect on a 34-year period to conclude that some institutional factors enhance the environment while other factors impede environmental development. The reasons for the conflicting results in these studies could be as a result of differing institutional structures among countries.

Financial Development, Institutional Quality and Environmental Sustainability

Developed and developing economies that aim at improving environmental sustainability, strives to tackle the issue of carbon emission. This is because a high carbon environment is harmful to both humans and the ecosystem. In light of this, Jianguo *et al.* (2022) studied the effect of financial development, technological innovation, institutional quality, on environmental quality in 37 OECD countries for 30 years using the 2 step GMM approach. The authors affirmed that technological innovations and institution quality improves environmental quality. In addition, Kousar *et al.* (2020) evaluated the effect of financial development and institutional quality on environmental sustainability Pakistan for 22 years using the NARDL approach. The authors confirmed that financial development, trade openness and institutional quality reduces environmental degradation in Pakistan

These studies used carbon emission as a metric of environmental sustainability. Carbon emission only captures the carbon level of an economy neglecting the areas of energy, net forest and mineral resource depletion. Hence, these studies are faulted on the grounds of using a proxy that does not capture other basic aspects of the environment that can give a robust view of environmental sustainability.

Methodology

Theoretical framework

Environmental sustainability deals with making decisions to optimize the use of natural resources to maximize social welfare and improve environmental preservation. In the light of this, this study employs the weak sustainability theory propounded by Hartwick (1977) and Solow (1974) which is an extension of the Solow neoclassical growth model. Weak sustainability theory is centred on the assumption that manufactured capital and natural capital can be perfectly substituted. In order words, the assumptions of weak sustainability are expounded on the interchangeability between the market economy (manufactured capital) and the environment (natural capital). This theory requires that the economy maintains a sustained level of consumption pattern across generations based on the optimal use of natural resources. The underlying assumption of this theory is premised on the production function in which the level of a nation's output is determined by the level of its factor inputs. The fundamental notion of the production function is centred on physical capital (K) and labour (L) as the important factors of production but the neoclassicists (Solow, 1956; Stieglitz, 1969; Dagupsta & Heal, 1978; Solow, 1974) introduced a variable (R), which represents natural capital. Romer (1990) extends the Solow model to include human capital. The production function is denoted as;

$$Y = F\ (K,\ H,\ R,\ T) \tag{1}$$

Where Y is the annual real output (GDP), which is a dependent function of factor inputs such as manufactured capital (K), labour (L), land (T) and natural capital (R). Specifically, R is energy resources, mineral resources and net forest resources such as crude oil, coal bauxite, phosphate, copper, Gold, Zinc, diamond, trees, plants and timber. It is assumed that no production in any sector of the economy is possible without land and natural resources (Solow,1974). Hartwick (1977) and Solow (1974) introduced the assumption of "unbounded resource productivity" which states that national output is not totally constrained by the flow in resources. Solow (1956) proposed that in preserving natural resources, policies must be enacted to advance both human species and the ecosystem. Solow (1956) opined that for resources to be sustained overtime, each generation must consume less resources to reserve more resources for future generations to meet their own needs. As a result, Solow (1956) justify the application of the Cobb-Douglas production function which is expressed as;

$$Y_t=(K_T)^{\alpha}(R_t)^{\beta}(T_t)^{\gamma}(H_t)^{1-\alpha-b-\gamma} \tag{2}$$

$\alpha>0,\quad \beta>0,\quad \gamma>0\ ,\quad \alpha+b+\gamma=1$

α, β, γ are the respective output elasticities of capital, natural capital and land respectively which is characterized by a constant and unitary elasticity of substitution. All exponents are assumed to be positive ($\alpha>0$, $\beta>0$, $\gamma>0$). Subscript t denotes time period. Solow (1956) advocates that the substitution between manufactured capital and natural resources is possible when the output elasticity of manufactured capital is greater than the output elasticity of natural resources ($\alpha > b$), this way a constant level of consumption can be sustained. Similarly, Stieglitz (1969), incorporates total factor productivity (A) into the Cobb-Douglas product function. Thus, equation 3.3 is modified and augmented with total factor productivity and presented as

$$Y_t=A(K_T)^{\alpha}(R_t)^{\beta}(T_t)^{\gamma}(H_t)^{1-\alpha-b-\gamma} \tag{3}$$

Total factor productivity play an immense role in the production output of an economy. The type of equipment used in production can affect the quality of an environmental. Hence, Solow (1974) suggests that technological development is needed for environmental quality to be sustained. Thus, the exogenous growth rate of total factor productivity (A) is defined as;

$$g_A=\frac{A(t)}{A\ (t)}= AOe^{gt+fo} \tag{4}$$

Total factor productivity grows at an exogenous rate of g which carries a vector of F and O. F and O are added to depict the impact of the financial sector and institutional quality on technological progress as technological advancement improves the efficiency of investment, innovating capacities and natural resource optimization in the economy that enhances environmental sustainability. Stieglitz (1974) argues that technological progress is instrumental in compensating for the depletion in natural resources as technological progress can aid in the reduction of environmental pollution. Natural resources are found on a fixed portion of land (T) supply which denotes that in the long-run, the use of land cannot increase or decrease in supply. Hence the growth rate of land remains unchanged. This is illustrated in equation 3.5

$$g_T = \frac{\dot{T}_t}{T_t} = 0 \tag{5}$$

Land is frequently inhabited by man and used for a variety of purposes. Even with the increase in migration and the rise of cities, excessive land use has no impact on its size. But, when humans use natural resources on land excessively, it become depleted. Natural resources deplete overtime due to the activities of humans as resources are being used up and exploited beyond their regenerative capacity. The rapid depletion of natural resources is mostly accelerated by the expanding global population. According to Romer (1990), pollution caused by production activities and other environmental issues can be a major impediment to sustainability. In the case of exhaustible resources, annual depletion rate of natural capital such as energy resources and mineral resources is assumed to be negative because when these resources are used up, they cannot be gotten back as excess extraction of these resources reduces its availability for future generations. Annual rate of natural capital depletion can be positive if net forest resources such as trees can regrow and can be improved by effective fertilization. Hence the dynamics of natural capital as developed by D' Alessandro (2007) is denoted as

$$g_R = mR\left(\frac{R}{CT} - 1\right)\left(I - \frac{R}{CC}\right) - F + W^V \tag{6}$$

Equation (6) illustrates the growth rate of the stock of natural resources, where m stands for the rate of resource regeneration, CC for the carrying capacity of the environment, CT for the extraction threshold, W for the investment in restoring degraded resources, and F for the quantity of resources that can be utilized for economic activity. The long-term feasibility of achieving equilibrium with the stock of natural resources is demonstrated by the dynamics of natural capital (Kornafel & Telega, 2020). The topic of environmental sustainability is covered in this aspect. The Hartwick and Solow model of weak sustainability, however, stipulates that the rents gotten from the sale of natural resources should be invested in enhancing manufactured capital (K) and human capital (H). In other to accumulate capital, households, firms and government saves (S) a constant fraction of their income (Y) in a closed economy (C+I+G). This gross savings (Sy_t) comprises of both private and public domestic saving. Hence, the dynamics of manufactured capital is expressed as

$$g_k = \frac{dk}{dt} = S_k Y_t - \delta k_t \tag{7}$$

From equation (7), g_k denotes the growth rate of manufactured capital were S_k denotes the fraction of income invested in manufactured capital to replace worn out capital (δkt). As much as an economy strives to improve and expand its capital base, its human capital resource stands as an important part of the capital base. Romer (1990) added human capital to this model to depict how important investment in education is to the national output of an economy. The assumption of Romer (1990) on human capital is given as; H_t = L(t) P(E). Where L denotes number of workers and P (•) is a function depicting years of education per worker. Labour is assumed to grow at an exogenous growth rate of n (Lt=ε^{nt}**)**. The quality of labour (P>0) is improved by the quality of education and health services offered to the populace. Romer (1990) made the assumption that as a worker acquires more education, his human capital increases (P' (•)>0). This is because education equips individuals with the knowledge of sustainability. Education keeps communities and cities informed on how consumption patterns and lifestyle affects the environment. This would help individuals to curb their excessive consumption that negatively affects the environment. Hence, the dynamics of human capital is expressed as;

$$g_{H=\frac{dH}{dt}= S_h Y_t - \delta k_t} \tag{8}$$

Human capital accumulates based on the level of investment that has been made to the educational and health sectors. S_H denotes the income invested in human capital while δ represents the rate at which the quality of education and health care services depreciates in value due to lack of investment which affects the productivity of the labour force. In the steady state, national output (Y) total factor productivity (A), natural capital (R) and land (T) all grow at a constant rate (g). The steady state is based on the optimum level at which all factor inputs are sustained. To derive the steady state, we take logs of equation (2)

$$InY_t = InA_t + \alpha InK_t + \beta InR_t + \gamma InT_t + (1 - \alpha - \beta - \gamma) InH_t \quad (9)$$

The action of each factor input on the balanced growth path is shown by the steady states. Capital per labor (K/L) and output per labor (Y/L) are expected to be constant across time on the balanced growth path. As a result, k/y, which is represented as per-capita income, is also constant across time. This is due to the fact that in the steady state, the manufactured capital determines the output (Y)/(K). More investment is utilized to replace worn-out capital (δ) on the balanced growth path. In this sense, the pace of increase of manufactured capital;

$$g_k = \frac{dk}{dt} = \left(\frac{S_k Y_t}{K_t}\right) \quad (10)$$

Equation 10 depicts the income per capita also known as the net savings rate. However, to examine the behavior of all factor inputs on the balanced growth path, the growth rates of each factor inputs is applied on equation 3.9

$$g_y = g + fo + \alpha\left(\frac{S_k Y_t}{K_t}\right) + \beta g_R + \gamma g_T + (1 - \alpha - \beta - \gamma)\, g_H \quad (11)$$

Since savings is a paramount factor that influences the increase in output, the savings model helps to explain how the current generation is storing up wealth and preserving the environment for future generations. The savings model is derived by arranging the net savings rate to the right side, this becomes,

$$\left(\frac{S_k Y_t}{K_t}\right) = g + fo + \alpha g_y + \beta\, g_R + \gamma g_T + (1 - \alpha - \beta - \gamma)\, g_H \quad (12)$$

From equation 12, $\left(\frac{S_k Y_t}{K_t}\right)$ represents environmental sustainability, g represents total factor productivity, f represents financial development O represents institutional quality, αg_y represents per capita income, βg_R represents natural resource rents and $(1 - \alpha - \beta - \gamma)\, g_H$ represents human development.

Model specification

In line with the theoretical framework, the relationship between, environmental sustainability, financial development and institutional quality has been presented. A set of control variables are included into the model. These variables are per capita income, natural resource rents, trade openness and foreign direct investment. Per-capita income is an important aspect of an economy that influences the environment. As a tool for assessing a population's level of living and quality of life, per-capita income calculates the average annual income per person in a nation. Per-capita income is included into the model to evaluate how the income of each individual has contributed to the environmental development of the economy. For a resource dependent nation like Nigeria, the level to which Nigeria depends on its natural resources to generate income, will depict the level to which it's level of environmental sustainability is being undermined (Koirala & Pradhan, 2020). Natural resource rents is included in this model to reveal how well natural resources have been utilised and sustained to build the economy. Trade openness helps in achieving environmental sustainability through its capacity to boost a country's means of generating wealth. It facilitates environmental development as it aids in the allocation of scarce resources and grants easy access to advanced technologies that promote environmental preservation (Alshery & Belloumi, 2020). Trade openness is added to this model to show the extent to which the economy is open to international trade and how trade has contributed to the sustainability of the environment. The inflow of foreign investment can to a large extent affect the environment. The inflow of green technology into an economy can enhance the environment. However, foreign direct investment creates an avenue were obsolete or advanced technology can be made available to individuals and firms which can affect the demand and use of energy in an economy.

$$ES = F(FD, INST, PCI, NRR, TO, FDI) \quad (13)$$

The use of polluting equipment from foreign and indigenous companies can deteriorate the environment but the use of green technology can improve environmental protection. Foreign direct investment is added to this model to show how foreign direct investment has affected environmental quality in the economy,
Equation 13 can be expressed in econometric form as follows;

$$InES_T = \alpha_0 + \beta_1 InFD_t + \lambda_2 InINST_t + \delta_3 InPCI_t + \phi_4 InNRR_t + \eta_5 InTO_t + \varphi_6 InUFDI_t + \varepsilon_t$$
(14)

ES stands for environmental sustainability which is the dependent variable while a_0 is the intercept which represents the difference between the mean of ES_T and the product of the slope and mean of $FD, INST, PCI, NRR, TO$ and FDI. While β_1, λ_2, δ_3, μ_4 and $\phi_{5,}$, η_6, φ_7 are slope coefficients that captures the influence of financial development, institutional quality, per-capita income, natural resource rents, trade openness and foreign direct investment on environmental sustainability in time t. Financial development is captured using financial development index, institutional quality is measured using institutional quality index, per-capita income is measured as GDP per capita , trade openness is measured using the ratio of total exports and imports to nominal GDP, natural resource rents is measured using natural resource rents and foreign direct investment is measured using Foreign direct investment, net inflows (BoP, current US$). ε_t denotes the disturbance term which helps to address other variables outside the model that can influence the outcome of the dependent variable. All variables are transformed into their logs to address their size differences and interpret their elasticity. Subscript t depicts the number of years in the study which would be analysed from 1986 to 2020.

Estimation strategy

To achieve this study objective, threshold regression is applied. Threshold models are applied help to explain an underlying process that causes an economy to encounter changes. These changes are explained by a parameter from a threshold model. This parameter is called the threshold parameter (Madni & Wu, 2021). Threshold extends the linear regression to allow coefficients to differ across regions. Those regions are identified by a threshold variable being above or below a threshold value. These regions are also called regimes. By adding a threshold, the linear regression is expanded to include regime variations in the coefficients.

Specifying the linear regression for this study, is shown as;

$$InES_T = \alpha_0 + \beta_1 InFD_t + \lambda_2 InINST_t + \delta_3 InPCI_t + \phi_4 InNRR_t + \eta_5 InTO_t + \varphi_6 InFDI_t + \varepsilon_t \quad (15)$$

To obtain the threshold level of institutional quality, the work of Wu and Madni (2021) is adopted

$$InES_T = \begin{cases} \alpha_0^1 + \beta_1^1 InFD_t + \varepsilon_t, & INS_t < T \\ \alpha_0^2 + \beta_1^2 InFD_t + \varepsilon_t, & INS_t \geq \text{T} \end{cases} \quad (16)$$

In equation 3.21, institutional quality is used as the threshold variable. $INST_t < T$ denotes the first regime were institutional quality is the below the threshold, while $INST_t \geq$ T indicates the second regime were institutional quality is above the threshold as the sample is being splitted into 2 regimes. The discreet threshold technique is used to determine the number of thresholds. T represents the threshold parameter as β_1^1 indicates low regime for the first sample while β_1^2 indicates high regime for the second sample split

Data, Measurements and Sources

This study used annual time series data from 1986 to 2020, to evaluate the effect of financial development and institutional quality on environmental sustainability in Nigeria. The study period covered the SAP and Post-SAP periods in Nigeria as well as the period when the 17 sustainable development goals were made to help global economies implement sustainable development and achieve environmental sustainability. Adjusted net savings is measured as net savings, plus current expenditure on education, minus rents from depletion of natural capital and damages from carbon dioxide emissions which is divided by gross national income at market prices. Adjusted net savings overcomes the challenge of using carbon emission because it incorporates the three pillars of sustainability. These three pillars are; the economic pillars, the social pillars and the environmental pillars of sustainability. However, Previous empirical results hypothesized that few variables can influence environmental sustainability. For this study, environmental sustainability is controlled along with per-capita income, natural resource rents, trade openness to create a robust and realistic estimation. To tackle omitted variable bias, these control variables are added because they are connected with the changes that can likely persist between financial development, institutional quality and environmental sustainability. This study used the Financial Development index to assess financial development in accordance with recent literature (Svirydzenka, 2016; Khan, 2019; Liu et al., 2019; Dada et al., 2022). This index measures the accessibility, depth, and efficiency of financial markets and financial institutions. The financial institution (FI) index and the financial market (FM) index make up this proxy, which was produced by the International Monetary Fund (2019). The indexes here vary from 0 to 1. While 0 depicts weak financial sector, 1 depicts strong financial sector. The control variables in this study such as per-capita income, foreign direct investment, natural resource rents and trade openness were all sourced from World Development Indicators (2022). Institutional quality is measured using four institutional quality index from the International Country Risk Guide. This institutional index are, control of corruption, law and order, government stability and bureaucratic quality. These four sub-indexes are chosen because of its peculiarity to the Nigerian economy due to its effect on Nigeria's institutional system (Fabemi, 2018; Olaniyi & Oladji, 2020). Control of corruption and law and order are scaled from 0-6, government stability is scaled from 0 to 12, while bureaucratic quality is scaled from 0 to 4. Following the works of Olaniyi & Oladji (2020), the four institutional indicators are re-scaled from 0 to 10.

Results and discussions

Descriptive statistics

The results of the descriptive statistics for this study, is shown in Table 1. It is important to know the behaviour of a series before carrying out further analysis. To examine the behavior of the series, descriptive statistics is used to describe the data set of adjusted net savings, ecological footprint, institutional quality, financial development and foreign direct investment using mean, median, standard deviation, minimum, maximum values and Jarque Bera statistics. Table 1 show that all the series display some level of consistency as their mean and median values fall within their minimum and the maximum values. The average value of adjusted net savings for the sample period stands at 20.1% which is quite lower than 50% on a percentage scale. This depicts the high rate of natural resource depletion in Nigeria which has reduced the availability of adequate resources for future generations. The best environmental performance the Nigerian economy ever had was in 1989 with a 44.8% value in adjusted net savings and the lowest performance in 2016 dropping to 4.55% in value over the 35 years of observation.

Financial development index for Nigeria shows a value of 0.18 which depicts a weak financial system.This suggests that the financial system in Nigeria is crippled by deficiencies in financial operations and structural weakness in the financial markets. In 2008, Nigeria experienced its highest level of financial development with a value of 0.27 and its lowest level of development in 1997 with a value of 0.11. The standard deviation for financial development is quite low compared to its mean. This means that the financial sector in Nigeria has not recorded significant changes in its level of development across the years in the sampled period.

The results for Nigeria's institutional quality is 3.72 which is below the average on the scale of 0-10. In essence, the quality of institutions in Nigeria are poor and less productive in respect to its control of corruption, law and order, bureaucratic quality and government stability. Nonetheless, the highest level of institutional development in the Nigerian economy was recorded in 1996 with an institutional performance of 4.8 and its lowest level of institutional development in 1986 with an institutional performance of 2.65.

Table 1: Descriptive statistics

Var	Unit of measurement	Mean	Median	Max	Min	Std.dev	J.B	Prob	Obs
ANS	ANS (% of GNI)	20.108	18.142	44.816	4.5575	12.176	2.70	0.25	35
FD	FD index scale (0-1)	0.1873	0.1815	0.2730	0.1188	0.0388	0.84	0.65	35
INS	INS index scale (1-10)	3.7200	3.5675	4.8950	2.6575	0.5135	0.77	0.68	35
FDI	FDI net inflows (Bop, Us$)	2.8E+9	1.8E+9	8.8E+9	1.9E+8	2.6E+9	5.96	0.06	35
PCI	GDP per-capita (current, Us$)	1317.6	786.80	3200.9	270.02	922.82	3.74	0.15	35
NRR	Total NRR (% of GDP)	15.329	15.645	31.770	4.7909	6.2374	0.62	0.73	35
TOP	Trade (% of GDP)	34.694	34.457	53.277	9.1358	0.6512	1.02	0.59	35

Source: Author's computation (2023)

It is also displayed from the results that the standard deviation of institutional quality is lower than its average value. This connotes that Nigeria which is challenged with poor quality of institutions, has not experienced a wide variety of changes in its institutional system throughout the study period.

For the control variables, FDI show a net inflow of investment worth $2.8billion dollars in respect to Nigeria's balance of payment. This shows that the inflow of equity capital, reinvestment of earnings, long term and short-term capital from foreigners into Nigeria throughout the period observed, is quite high. As a result, the highest inflow of foreign investment into Nigeria was noticed in 2011, with a net inflow of $8.8billion dollars. According to World investment report (2012), Nigeria was Africa's top destination for foreign direct investment in 2011, drawing in foreign investors from Europe and the United States. The lowest inflow of foreign direct investment into Nigeria was discovered in 1986 with a net-worth of $193million. The value of standard deviation for Foreign direct

investment is lower than its average value. This denotes that the Nigerian economy have not experienced large changes in its inflow of investment in the years observed in the study.
The average per capita income for Nigeria stands at $1,317. This implies that Nigeria is a lower-middle-income country from sub-Sahara Africa as classified by the World Bank. The Nigerian economy generated its highest level of per capita income in 2014 with a value of $3,200 and its lowest in 1993 having a value of $270. Nigeria which is tagged as a low income economy, has noticed little changes in its levels of per-capita income from 1986 to 2020. Besides, the total natural resource rents from the sale of oil, natural gas, coal and mineral resources in Nigeria only accounts for 15% of Nigeria's GDP. Natural resource rents contributed immensely to the GDP of the Nigerian economy in 1993, accounting for 31% of Nigeria's GDP. However, in 2016, natural resource rents drop to its lowest level of economic value only accounting for 4.7% of Nigeria GDP. The results of for natural resource show that its average value is higher than its standard deviation. This implies that there have been slight differences in the contribution of natural resource rents to Nigeria's GDP throughout the years observed in the study.
The average sum of Nigeria's trade openness throughout the 35 years examined, is 34.6%. This indicates that the openness of the Nigerian economy to trade relationships is below the average as the sum of Nigeria's imports and exports accounted for less than 50% of Nigeria's GDP. Nigeria's trade relationships with other countries in the world improved the gross domestic product of the Nigerian economy by 53% in 2011. This was the highest contribution of Nigeria's trade openness to GDP which occurred as a result of the high inflow of foreign direct investment into Nigeria in 2011. However, Nigeria's trade openness contributed minimally to the GDP in 1986 by increasing the market value of goods and services produced in Nigeria by 9.1%. Furthermore, the standard deviation of trade openness is lower than its mean value. This denotes that few changes have been noticed in the levels of import and export of goods and services in and out of Nigeria from 1986 to 2020. The results of the Jarque Bera statistics reveal that all the variables are normally distributed as they are all above the 5% level of significance.

Correlation matrix

The results of the correlation matrix between the explanatory variables are shown in Table 2 using Pearson correlation coefficient. Correlation matrix is a statistical tool used to examine the degree of association between two variables. It is also used to check for multicollinearity amongst variables. The problem of multicollinearity exist when two or more predictor variables in a multiple regression model are highly correlated. Following the works of Abaidoo and Agyapong (2023), the threshold limit of 85% for the correlation coefficients was used. From the results it can be seen that there are no issues of multicollinearity in the results as none of the correlation coefficient is above the threshold limit of 0.85. This suggests that multicollinearity is not present among the explanatory variables in the model.

Unit root test

The unit root test of the response and predictor variables are displayed in Table 3. It is important to examine the stationary properties of a series before further analysis is conducted. This is because a pre-estimation test will help to ascertain which methodology is appropriate to estimate the series. Stationarity test is also important because using time series data that are non- stationary, will lead to spurious result. One basic disadvantage of a spurious result is that it cannot be used for prediction, forecasting and hypothesis testing. In other words, a spurious result is completely unreliable and can lead to wrong conclusions. To prevent this statistical error, unit root test is performed on the series in the study. Table 3 shows the unit root test on the variables of the study using Dickey Fuller Generalized Least Square (Elliot, Rothenberg and stock, 1996) and the Ng and Perron test (Ng & Perron, 2001).

Table 2: Correlation matrix

Var	FD	INS	FDI	NRR	PCI	TOP
FD	1.0000					
INS	-0.3680	1.0000				
FDI	0.6453	-0.2007	1.0000			
NRR	-0.5202	0.5689	-0.0384	1.0000		
PCI	0.8325	-0.3647	0.7335	-0.4491	1.0000	
TOP	- 0.0260	0.4654	0.2645	0.4729	-0.0417	1.0000

Source: Author’s computation (2023)

Table 3: Unit root test results

Unit root test (individual intercept)

	DF-GLS			Ng and Perron		
Variable	Levels	1st diff	Order	Levels	1st diff	Order
ANS	-0.7993	-9.9726***	I(1)	0.4847	0.2026**	I(1)
EFP	-0.5812	-9.0946***	I(1)	0.9095	0.1915**	I(1)
FD	-1.1441	-4.2747***	I(1)	0.3836	0.1828**	I(1)
INS	-1.4375	-4.1497***	I(1)	0.4544	0.1810**	I(1)
PCI	-0.2900	-4.5855***	I(1)	0.7289	0.1729**	I(1)
NRR	-1.2355	-4.5900***	I(1)	0.3660	0.1748**	I(1)
TOP	-1.7851*	______	I(0)	0.3575	0.1636***	I(1)
FDI	-1.6171	-2.7016***	I(1)	0.3360	0.2531*	I(1)
Level of sign.		CRITICAL VALUES				
1%	-2.6347	-2.6347		0.1740	0.1740	
5%	-1.9510	-1.9510		0.2369	0.2369	
10%	-1.6109	-1.6109		0.2750	0.2750	

Note: ***,**,* represents the 1%, 5% and 10% of significance respectively
Source: Author’s computation (2023)

The DF-GLS and Ng and Perron unit root tests was selected for this study because the conventional Augmented Dickey Fuller (ADF) and Phillip Perron (PP) unit root test are susceptible to power distortions with processes that possesses low moving average (Arltova & Fedorova, 2016) While DF-GLS tests is the modified version of the ADF tests, Ng and Perron is the modified version of the Phillip-Perron tests. ADF and PP test have lower power in the case of a root process that is close to a unit root. That is to say, their low power capacity reduces the validity and reliability of their tests which can lead to wrong conclusions. However, the DF-GLS and NG and Perron tests are classified as efficient unit root test because they exhibit higher power compared to ADF and PP test. For robustness sake, the study employed both intercept and intercept and trend options. The DF-GLS results with intercept show that adjusted net savings, ecological footprint, financial development, per-capita income, institutional quality, natural resource rents and foreign direct investments are non-stationary at levels I(0) but stationary at first difference I(1). This suggests that the mean, variance, and covariance of their series is not constant overtime and also that the series are time variant.

Table 4 : Unit root test (Individual intercept and trend)

	DF-GLS			Ng and Perron		
Variables	Levels	1st diff	Order	Levels	1st diff	Order
ANS	-4.8135***	_____	I(0)	0.1712*	____	I(0)
EFP	-1.0334	-9.7106***	I(1)	0.3674	0.1991***	I(1)
FD	-3.0038*	_____	I(0)	0.1773*	____	I(0)
INS	-1.9363	-4.5917***	I(1)	0.3833	0.1778*	I(1)
PCI	-1.2523	-4.9138***	I(1)	0.3956	0.1713*	I(1)
NRR	-3.3067**	_____	I(0)	0.2110*	_____	I(0)
TOP	-2.5377	-5.8335***	I(1)	0.2385	0.1735*	I(1)
FDI	-2.0752	-8.1787***	I(1)	0.2001	0.1833*	I(1)
Level of sign.		CRITICAL VALUES				
1%	-3.7700	-3.7700		0.1400	0.1400	
5%	-3.1900	-3.1900		0.1700	0.1700	
10%	-2.8900	-2.8900		0.2300	0.2300	

Note: ***,**,* represents the 1%, 5% and 10% of significance respectively
Source: Author's computation (2023)

Table 3 and Table 4, revealed that there are mixed order of integration in the series. Since the variables are a mixture of I(1) and I(0), a threshold autoregression model can be used

The Threshold level of institutional quality in the link between financial development and environmental sustainability in Nigeria.

The outcome of the threshold analysis is presented in Table.5. Threshold regression is a linear regression that shows regime variations in the coefficients, when a threshold variable is above or below a threshold parameter. For this study, a single threshold parameter is considered which display two regimes. In estimating the threshold, adjusted net savings is used as the pivotal variable which measures environmental sustainability while institutional quality is the threshold variable and financial development is the dependent variable. The first regimes show when institutional quality performs below the threshold parameter while the second regime show when institutional quality perform at or above the threshold limit. Discreet threshold technique was applied to arrive at the threshold value of 4.32.

The basic reason why two regimes are chosen for this study, is to ascertain the regime were institutional quality in Nigeria influenced financial development to improve environmental sustainability and also to ascertain the regime were institutional quality influenced financial development to reduce environmental sustainability in Nigeria in the 35 years of the study. The results in Table 5 show that when institutional quality is below the threshold value of 4.32 in the first regime, financial development in Nigeria exert a negative and insignificant effect on adjusted net savings. However, when institutional quality is above the threshold value of 4.32 in the second regime, financial development exerts a positive and significant effect on adjusted net savings. In order words, when institutional quality is below the threshold, financial development reduces environmental sustainability by 0.08%. However, when institutional quality is above the threshold, financial development increases environmental sustainability by 4.52%. This affirms that the financial sector in Nigeria can help in fostering environmental sustainability when sound institutions are in place to ensure that environmental standards are being followed. Hence, below the threshold value of 4.32, financial development impedes environment sustainability. Nigeria's environmental performance may have been impacted and decreased by institutional quality, through her poor bureaucracy, and corruption, which is a significant but often overlooked factor. In other words, Institutional failure in Nigeria has resulted in the financial sector's inefficiencies as well as the deterioration of the ecosystems. This indicates that the institutional framework in Nigeria has to improve beyond the threshold level before it can stimulate the financial sector to promote environmental sustainability. more so, below the threshold level of 4.32, there is a high tendency for institutions in Nigeria to give room for corrupt, illegal and unsustainable environmental practices that is detrimental to environmental development.

On the average, Nigeria’s quality of institutions has performed below the threshold level. As shown in Table 1, the average value of Nigeria’s institutional quality index which is 3.72, is less than the threshold value of 4.32. Hence, the Nigerian economy has operated below the threshold value for the 35-year period that is covered in the study. The International Country Risk Guide data used for this study reveal that Nigeria was above the threshold value in 1992, 1993, 1994, 1995, 1996 and 1997. Notwithstanding, the best institutional performance was observed in 1996, while the lowest level of institutional performance was recorded in 1986 which was displayed in Table 1. This indicate that there have been a high level of institutional inconsistency and inefficiency in Nigeria.

Table 5 : Threshold analysis

	Dependent variable : Adjusted Net Savings					
Panel A : Estimates						
	Regime 1 (INS < 4.32 (29 Obs)			Regime 2 (INS ≥ 4.32 (6 Obs)		
Var	Coef	T-stat	prob	Coef	T-stat	Prob
LFIN	- 0.0817	-0.1729	0.8640	4.5240**	2.4005	0.0235
C	6.8725	2.4358	0.0088	14.794	4.2925	0.0002
	Non-threshold variables					
Var	Coef	Std.error		T- stat	Prob	
LFDI	0.0572	0.1474		0.3833	0.1778*	
LPCI	- 0.7512	0.2496		0.3956	0.1713*	
LNRR	0.7835	0.2244		3.4907	0.0017	
LTOP	- 0.6255	0.2220		-2.8167	0.1735*	
Panel B : Diagnostic test						
Jarque Bera		0.5410				
Serial correlation		0.6902				
Heteroscedasticity		0.4050				
Ramsey rest test		0.1988				

Dependent variable : Adjusted Net Savings

Panel A : Estimates						
	Regime 1 (INS < 4.32 (29 Obs)			Regime 2 (INS ≥ 4.32 (6 Obs)		
Var	Coef	T-stat	prob	Coef	T-stat	Prob
LFIN	- 0.0817	-0.1729	0.8640	4.5240**	2.4005	0.0235
C	6.8725	2.4358	0.0088	14.794	4.2925	0.0002
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Var	Coef	Std.error		T- stat	Prob	
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Panel B : Diagnostic test						
Jarque Bera		0.5410				
Serial correlation		0.6902				
Heteroscedasticity		0.4050				
Ramsey rest test		0.1988				

Dependent variable : Adjusted Net Savings						
Panel A : Estimates						
	Regime 1 (INS < 4.32 (29 Obs)			Regime 2 (INS ⩾ 4.32 (6 Obs)		
Var	Coef	T-stat	prob	Coef	T-stat	Prob
LFD	- 0.0817	-0.1729	0.8640	4.5240**	2.4005	0.0235
C	6.8725	2.4358	0.0088	14.794	4.2925	0.0002
		Non-threshold variables				
Var	Coef	Std.error		T- stat	Prob	
LFDI	0.0572	0.1474		0.3833	0.1778*	
LPCI	- 0.7512	0.2496		0.3956	0.1713*	
LNRR	0.7835	0.2244		3.4907	0.0017	
LTOP	- 0.6255	0.2220		-2.8167	0.1735*	
Panel B :	Diagnostic test					
Jarque Bera		0.5410				
Serial correlation		0.6902				
Heteroscedasticity		0.4050				
Ramsey rest test		0.1988				

Note : ** $p < 0.05$, ***$p < 0.01$, and *$p < 0.1$ denotes 1%, 5% and 10% level of significance.

Source: Author’s computation (2023)

Out of the 35 years observed, Nigeria operated below the threshold value for 29 years, showing that the institutional structure in Nigeria has been indeed weak and less productive overtime. This is why below the threshold level, financial development reduces environmental sustainability since institutions are weak to impose the norms of environmental sustainability on the financial sector, unregulated financial markets in Nigeria divert loans to highly polluting companies that deteriorate the environment.

The Nigerian economy has been more focused on improving economic growth without considering the side effects of these economic expansion on environmental conservation. The increase in financial services and access to credit is having environmental and societal consequences in Nigeria. The demand for transportation increases along with the use of energy when individuals and businesses have easy access to credit.

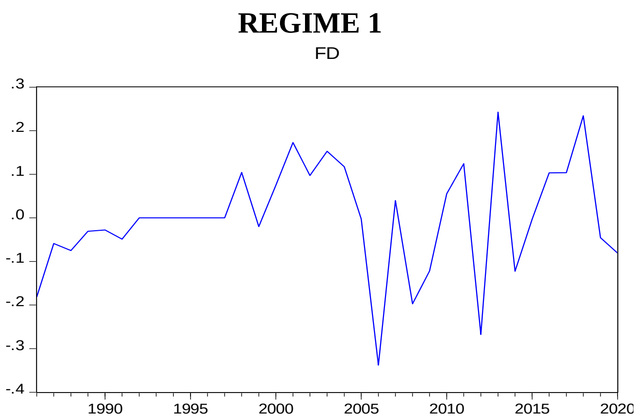
The preliminary stages of financial development are the stages of development in the financial sector that mostly considers financial deepening far more than environmental protection. This is the case of the Nigerian financial system as Yinusa (2020) recounts that the Nigerian financial sector is still developing and is not fully strengthened. Institutional quality plays an important role in increasing the environmental performance of the financial sector in Nigeria by incorporating environmental reforms into the financial system to lessen the harmful effects of the increasing demand for energy by firms in Nigeria. Sibanda et al. (2023) argued that the level of institutional quality operating in African countries has not been effective enough to tackle the issues of carbon emission and environmental pollution like the developed countries. Institutional quality is the backbone of environmental performance in any economy and its efficiency is of utmost relevance in meeting the conditions of sustainability in a country (Madni & Wu, 2021). High quality institutions ensure that effective environmental policies are effected and implemented (Federal Ministry of Environment Nigeria , 2019). Nevertheless, a lot of economies are faced with environmental challenges due to economic and industrial expansion which are caused by development in the financial sector (Ibrahim & law, 2015).

Financial markets and financial institutions in Nigeria increase environmental pollution when institutions operate at a low level of productivity. This can be seen in the years when institutional quality in Nigeria performed below the threshold which was between 1986 to 1991 and 1998 to 2020. If institutions in Nigeria do not perform above the threshold level, financial markets and financial institutions will degradate the environment and worsen environmental issues in Nigeria. This is because institutional factors such as control of corruption, rule of law and bureaucratic quality to a large extent determines how the financial sector impacts the environment. Abid (2016) argued that institutional quality can significantly reduce carbon-dioxide and curb environmental pollution. The findings of this study are in line with that of Madni and Wu (2021) on OBOR economies. The authors affirm that when institutional quality performs beyond the threshold level, Carbon emissions would be significantly reduced and environmental quality would be preserved even in the face of rising industrialization.

The results of the non- threshold variables show that per capita income and trade openness have a negative and significant effect on environmental sustainability. In other words, an increase in per-capita income will result to a 0.7% decrease in environmental sustainability. Also, a 1% increase in trade openness will lead to a 0.6% decrease in environmental sustainability. This means that an increase in per-capita income will worsen environmental sustainability in Nigeria. This exemplifies that trade relationship has also exposed the Nigerian economy to obsolete technology as well as a result of dumping in the attempt to acquire cheap production equipment that are highly substandard. Re-affirming this outcome, Solarin et al (2017) discovered that trade openness reduces environmental quality in Ghana. On the other hand, natural resource rents show a positive and significant effect on environmental sustainability. A 1% increase in natural resource rents will lead to a 0.78% increase in environmental sustainability. Sibanda et al (2023) reckoned that natural resource rents have helped to improve the economy of developing economies.

To examine the reliability of the results in the threshold auregression, a diagnostic test was obtained which is shown in panel B of Table 5. In the test, the model showed a normal distribution with a probability value of 0.54. This means that there are no structural issues in the model. Also, the results revealed that the residuals are homoscedastic and are free from serial correlation issues. This was determined using the Breush Pagan and the serial correlation LM test. The Ramsey reset test also indicates that the tests are well specified.

Figure 3 and 4 is the graphical presentation of the results in Table 5, showing the development of the financial sector in regime 1 and 2. The first regime show that the financial sector had a negative effect on environmental sustainability as the graph shows a break year in 2006 were institutional quality performed below the threshold level of 4.32 having a value of 3.73 as observed by the ICRG data in 2006. Low regime of institutional quality in Nigeria is displayed in the diagram from 2006 to 2020. While the second regime show a break year in 1992 where the institutional quality in Nigeria performed at the threshold level having a value of 4.32. This could be as result of the environmental laws made in 1992. The environmental impact assessment Act was established in 1992 to make the public and private sector of the economy not to authorize projects without considering its effect on the environments. Hence, the level at which institutional quality stimulates the financial sector without neglecting the relevance of environmental development is crucial for any economy.



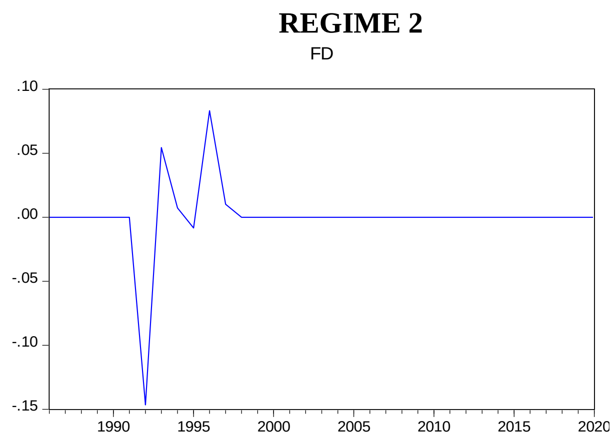


Figure 3: Financial development (INS <4.32 (29(Obs)
Figure 4: Financial development (INS >4.32 (6 Obs)

Conclusion

This empirical study examined the threshold level of institutional quality in the link between financial development and environmental sustainability. Specifically, this study evaluates the threshold level of institutional quality in the nexus between financial development and environmental sustainability in Nigeria from 1986 to 2020 using the threshold autoregression model. The outcome of the findings revealed that when institutional quality is below the threshold, financial development decreases environmental sustainability. Trade openness and per-capita income decreases environmental sustainability in Nigeria while foreign direct investment and natural resource rents increases environmental sustainability in Nigeria. Institutional quality enables the financial sector to improve environmental sustainability in Nigeria. Institutional quality needs to be enhanced in other to strengthen the environmental performance of the financial sector in Nigeria. The institutional weakness in the institutional framework of the Nigerian economy needs to be tackled and removed to ensure that environmental standards are met.

This study provides some important policy recommendation. First, The Nigerian government should work towards achieving a low carbon economy in Nigeria. To achieve this, policy makers should regulate the environmental practices of both individuals and firms. In addition, environmental agencies should be involved in carrying out random checks on industries and on residential and commercial areas to discipline individuals or companies that flout environmental orders. The monetary authority should employ regulatory measures by carrying out random checks on the activities of financial markets to ensure that the financial sector direct financial institutions to channel their loans to industries that use cleaner technologies. Hence, it is important that institutional credibility and transparency is enhanced to effect the needed change in increasing environmental preservation. Hence, the institutional body in Nigeria should ensure that institutional quality is improved beyond the threshold level as deliberate efforts should be made towards improving bureaucratic quality and promoting law and order.

Declarations

Availability of data: Data are readily available upon request.

Conflict of interests: The author declares that there is no conflict of interests

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RESEARCH ARTICLE

Exploring the link between technological innovation, economic development, and CO2 emissions in the US. Application of the ANN and EKC techniques

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Abstract
The developed world, which includes the United States of America (US), constantly works to reduce carbon dioxide emissions for the benefit of its people's health while advancing technical innovation to achieve impressive economic development. This motivates this study to use artificial neural network (ANN) and the Environmental Kuznets Curve (EKC) technique to explore the relationship between technological innovation, economic development, and CO2 emissions in the US in order to add to the body of knowledge already in existence. For this study, secondary data from 1990 to 2023 was gathered from the World Bank and globaleconomy.com. The results show that, whereas the artificial neural network shows that economic development contributes more to C02 emissions, the Environmental Kuznets Curve shows that higher levels of technical innovation and economic development lower C02 emissions. Hence, in order to maintain C02 emissions at the lowest possible level and improve the nation's atmospheric conditions, the US government should guarantee sustainable policies that will promote economic development and technological innovation.

Keywords: Technological innovation; Economic development; CO2 emissions; EKC; ANN

Introduction

Worldwide, society faces the urgent task of reducing the harmful impacts of human-caused carbon dioxide (CO2) emissions and their impact on climate change due to the growing emphasis on economic growth (Chen et al., 2016; Gardiner & Hajek, 2020; Lv et al., 2019). Environmental pollution is believed to increase during the initial phase of economic development and then decline as income levels rise, according to Grossman and Krueger (1995). According to Saha et al. (2020), 41 states in the US, including Washington, D.C., are reducing CO2 emissions while raising the US GDP. This provided additional support for the findings of Wang and Kim (2024), who found that several U.S. states had just attained absolute decoupling—a reduction in CO2 emissions while maintaining economic growth. The use of low-emission technologies, such as nuclear power, the conversion of coal to gas, and the restructuring of the economy to create a more sustainable one, are partially to blame for this.

The negative effect of economic growth on environmental quality has resurfaced because of the significant rise in CO_2 emissions caused by global warming and climate change. The pressing need to tackle this dilemma has led to a heightened emphasis on the relationship between energy usage, technological advancement, and ecological sustainability. This intricate connection is a significant topic in scholarly and policy debates since it has the capacity to influence the direction of our environmental, economic, and social destiny. Technological developments are crucial to the global initiative to decrease CO_2 emissions (Gu et al., 2019; Khan et al., 2020). These advances include a wide range of areas, such as energy generation, transportation, industry, and construction.

Technological innovation is crucial in creating new, efficient, and environmentally friendly solutions as societies want to shift towards cleaner and more sustainable energy systems (Bibri et al., 2023). Advancements in renewable energy technology, energy-efficient appliances, electric vehicles, and sustainable materials have greatly changed our energy situation and provided optimism for a more environmentally friendly and sustainable future. Technological innovation's growing popularity is crucial, but it does not function independently. The energy industry contributes significantly to worldwide CO_2 emissions and is strongly connected to economic and political factors (Babatunde et al., 2017; Rehman et al., 2022). The energy intensity of economies, which quantifies the energy spent per unit of economic production, is a crucial indicator for understanding this connection. High energy intensity indicates inefficiencies in energy utilisation and implies a higher environmental impact per unit of economic output. As nations develop, their energy usage typically rises, leading to a possible increase in CO_2 emissions (Waheed et al., 2019; Wang et al., 2016).

Technological advancements that enhance energy efficiency can break the link between economic growth and energy consumption by enabling economic expansion while keeping energy usage the same or decreasing it. Economic and political uncertainty has become a crucial issue that could help explain the mechanisms and trajectory of energy systems and environmental results. Economic downturns, political conflicts, and policy changes can greatly impact technical innovation, energy intensity, and CO_2 emissions, according to Geels (2013) and Adebayo et al. (2023). These uncertainties can either facilitate or impede countries' shift towards cleaner energy sources and energy-efficient practices by interacting with other factors. Uncertainty in the economic and political spheres can affect the connection between energy intensity and CO_2 emissions. It can also either enhance or reduce the impact of energy intensity on CO_2 emissions. Businesses may be motivated to implement sustainable practices in response to economic and political concerns (Su et al., 2022). For example, they can use resources to enhance energy efficiency in order to lower expenses and guarantee stability amid unpredictable political and economic conditions. This scenario may result in decreased energy intensity and fewer CO_2 emissions. Moreover, political instability may lead to a greater emphasis on addressing climate change and investing in renewable energy (Ren et al., 2023). Policymakers should view the development of green technology as a means to enhance economic stability and promote job growth. The anticipated economic and political uncertainties are projected to have a positive effect on the partnership by encouraging technical innovation. In periods of economic and political instability, governments and businesses may be inclined to seek out and implement new strategies to tackle increasing environmental issues (Su et al., 2022). Economic uncertainty, including financial market instability or economic downturns, can affect enterprises' motivation and ability to invest in and participate in research and development for technology that reduces CO_2 emissions. Amid economic volatility, corporations can reduce research and development (R&D) funding, leading to a deceleration in the advancement and implementation of sustainable technology and a possible rise in CO_2 emissions. Businesses might be reluctant to allocate limited resources to research and development if they are uncertain about the stability of the regulatory environment (Dunyo & Odei, 2023). Economic uncertainty can influence the relationship between technical innovation and CO_2 emissions reduction by affecting R&D investment, resource allocation, risk aversion, and policy support for countries' emission reduction initiatives. Minimising these uncertainties by maintaining stable economic conditions and implementing clear, consistent emissions rules is essential to promoting technological innovation activities focused on efficiently tackling CO2 emissions. This study objective contributes to the growing literature by exploring the link between technological innovation, economic development, and CO2 emissions in the US using the application of ANN (a machine learning technique) and the EKC technique, which will significantly improve previous related studies.

Literature review and hypothesis development

A portion of the literature on the connection between global economic growth, technological innovation, and CO2 emissions was examined in this research study. The relationship between CO2 emissions and economic growth has been the subject of a global research explosion and broad scholarly awareness (e.g., Gardiner & Hajek, 2020; Adebayo et al., 2023; Waheed et al., 2019). However, a number of shortcomings exist in this emerging field of research that limit our ability to completely understand the influences on the variables controlling global CO2 emissions. Research exploring the causal relationship between energy intensity, technological innovation, and CO2 emissions between high- and low-income nations concurrently is scarce, despite the relevance of this connection being theorised and seen. Because it attempts to close a gap in the literature, this paradigm adds interest to the current investigation. Moreover, although an expanding corpus of studies has improved our comprehension of the relevance and impacts that carbon dioxide emissions may have on economic growth (Rehman et al., 2022; Ren et al., 2023), we still know very little about the potential mechanisms through which carbon dioxide emissions may influence the performance of economic growth. This is significant because it supports the idea that reducing CO2 emissions promotes green growth and is necessary for sustainable development (Bai et al., 2022; Hickel & Kallis, 2020). According to Saha and Jaeger's (2020) report, more than 80% of U.S. states have disconnected their emissions from economic growth. The states mentioned vary in size and are distributed across different regions of the country, such as Maine and New York in the Northeast, Alabama and Georgia in the South, Indiana and Ohio in the Midwest, and Alaska and Nevada in the West. Maryland had the highest reduction in emissions at 38%, followed by New Hampshire at 37%, the District of Columbia at 33%, Maine at 33%, Alaska at 29%, and Georgia at 28% among the 41 states. Despite federal reversals of climate regulations, this discovery suggests that the United States can still make substantial advancements in addressing climate change at the state level.

In order to investigate the relationship between technological innovation, carbon dioxide emissions, and economic growth from 1985 to 2019 in 35 Belt and Road countries, Khan et al. (2023) used three-stage least square models, ordinary least squares, two-step system generalised method of moments, two-step difference generalised method of moments, seemingly unrelated regression, and three-stage least square models. Their findings show that technological innovation improves environmental quality while reducing carbon dioxide emissions.

Furthermore, Javed et al. (2023) examined oil prices, economic growth, and foreign direct investment in Italy between 1971 and 2019. The study's findings indicate that GDP positively affects carbon emissions, while the GDP square term negatively affects emissions, supporting the environmental Kuznets curve hypothesis using non-Linear ARDL. Wang et al. (2024) claim that the effect of economic growth on environmental degradation first increases with rising income levels before showing a declining tendency. Furthermore, trade protection appears to be detrimental to enhancing the quality of the environment globally, supporting the validity of the EKC hypothesis within the parameters of the study.

The Environmental Kuznets Curve (EKC) was used by Adebanjo et al. (2022) to investigate the relationship between air pollution and the Jordanian economy. Their research indicates that the country's CO2 emissions are negatively impacted by Jordan's economic growth, which is consistent with the EKC hypothesis, which suggested an inverse relationship between CO2 emissions and economic growth (inverse U-shaped hypothesis). According to Ozokcu (2017), the Environmental Kuznets Curve (EKC) is a theory that suggests a relationship between environmental deterioration and economic growth, with a pattern that resembles an inverted U. In the interim, it's

critical to emphasise that economic expansion has the potential to increase carbon dioxide emissions. However, it is imperative to acknowledge that this correlation may undergo a reversal at a given level. Therefore, it is plausible to argue that, as demonstrated by Halicioglu (2009), a rise in economic growth will probably lead to a steady drop in carbon dioxide (CO2) emissions. As a result, one could contend that achieving economic growth is a feasible way to achieve a state that is more environmentally sustainable. By examining the relationship between technological innovation, economic development, and CO2 emissions in the US using the application of ANN (a machine learning technique) and EKC technique—which will greatly enhance previous related studies—the main goal of this study is to close a gap that has been identified in the body of current scholarly work.
The following is a development of the study's hypothesis, which is based on the EKC theory.
H1: Economic development significantly declines CO2 emissions
H2: Technological innovation significantly reduces CO2 emissions.

Data and methodology

Data description

Secondary data was collected from the World Bank Development Indicator and TheGlobalEconomy.com, respectively, with a period of 1990 to 2024 because it is more recent to align with the current happenings and based on the data availability using the purposive sampling technique. The US technological innovation proxied by the innovation index is collected via the USA Innovation Index (data, chart | TheGlobalEconomy.com) (measured in points), while the carbon dioxide (CO2) emissions and economic development proxied by the GDP and per capita income are collected via World Bank development indicators. The CO2 emissions are measured in million kilotons, the GDP is measured in billions of dollars, and the per capita income, which is calculated by the US gross national income divided by their population, is measured in dollars.

Methodology

This study adopted a quantitative causal design that examines the links between the variables of interest in this study, and the method of analysis includes summary statistics to summarise the dataset using the mean and standard deviation, the Environmental Kuznets Curve (EKC), which is an econometrics technique, and machine learning techniques such as artificial neural networks (ANN). The correlation matrix was also applied to examine the direction and strength of the link between the variables. The SPSS and STATA software were used for the analysis of this study.

EKC model structure

The EKC hypothesis according to the work of Adebanjo et al. (2022) and Ozokcu (2017) which can be model mathematically as

$$InCO2_t = \beta o + \beta_1 InGDP_t + \beta_2 (InGDP_t)^2 + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$InCO2_t = \beta o + \beta_1 PCI_t + \beta_2 (InPCI_{it})^2 + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$InCO2_t = \beta o + \beta_1 Tech_t + \beta_2 (InTech_t)^2 + \varepsilon_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This study uses the EKC to comprehend how environmental degradation and GDP, or other indicators of economic development, relate to one another (Adebanjo et al., 2022). The inverse U-shaped hypothesis would be typical, as seen in figure 1 below. The study's focus and the outcome variable of the EKC model are environmental degradation, such as carbon dioxide (CO_2) emissions in the US, with GDP, per capita income (PCI), and technological innovation (Tech) serving as the independent variables. The constant term in the model is denoted by β_0, while the independent variable's coefficient estimates are represented by β_1 to β_2, and the period in years is indicated by t.
According to Ozokcu (2017), the EKC hypothesis shows an inverse relationship between economic growth and CO_2 emissions. A growth in personal income in the early phases of economic development also results in an increase in personal affluence. Up to a certain point (the turning point), the level of specialisation increases. The rate at which the environment deteriorates per capita decreases with sustained economic expansion. This is depicted in the standard EKC figure below. The EKC curve, which represents the hypothesised link between wealth per capita and degradation per capita, predicts whether or not the latter will remain high while maintaining the current level of degradation. The EKC theory is as follows: The first impact of economic activity on the base of resources usually results in a minor quantity of pollution that is biodegradable. Industrialization is accompanied by an acceleration of resource depletion and waste generation, especially in agriculture and other extractive and industrial operations. While low levels of development allow for gradual pollutant discharge, acceleration, and levelling off, higher levels of development result in a decrease in environmental pollution through structural change in information-intensive industries and services, along with rising environmental regulations and costs (Panayotou, 1993). The Kuznets-Phillips curve (EKC) is the value, as shown in figure 1, at which the indicator of environmental deterioration E reaches its maximum. This value is expressed as $Y^* = \exp(-\beta_1/2\beta_2)$, according to Panayotou (1993). As a diagnostic strategy for the machine learning and EKC models used in this study, the dataset's normality and the model's stability were examined in the interim.

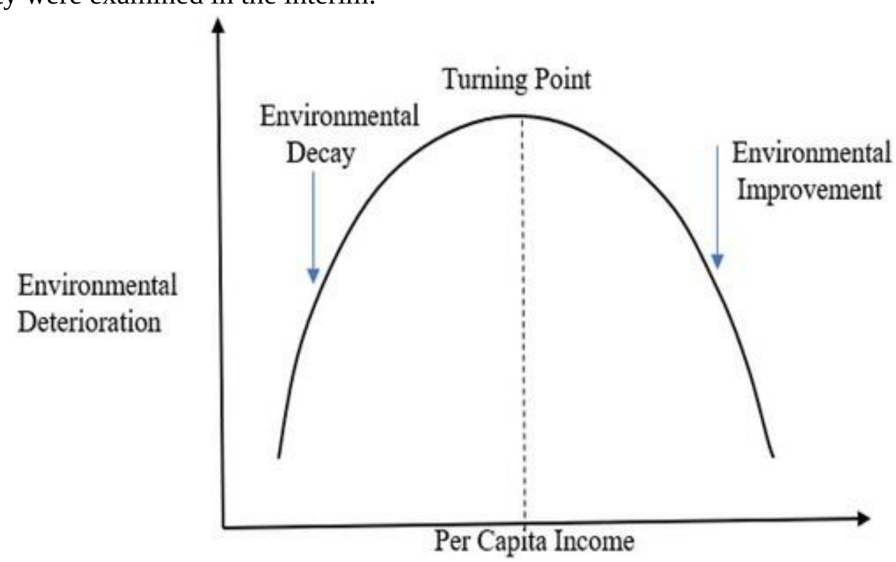

Figure 1: EKC structure

Artificial neural network (ANN)

It's a useful method that models the two hidden layers, the input variables, and the output variable (CO_2 emission). Here, it makes perfect sense to use an artificial neural network to determine or predict carbon dioxide emissions. It is not only a superior tool for predictive analytics but also a substitute for regression analysis.

The neural network equation is formed by combining the independent variables, their corresponding weights, and the intercept term for each neuron in a linear fashion. The neural network equation looks like this:

$$\ln K = \delta_o + \ln\delta_1 X_1 + \ln\delta_2 X_2 + \ln\delta_3 X_3 \ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

Where K is the output variable of ANN model.

δ_1 to δ_3 are the weights or the beta coefficients

X_1 to X_3 are the independent variables or the inputs such the GDP, PCI and TECH, and the Hidden layers pattern are H (1,1) to H (1,3).

Intercept = δ_0

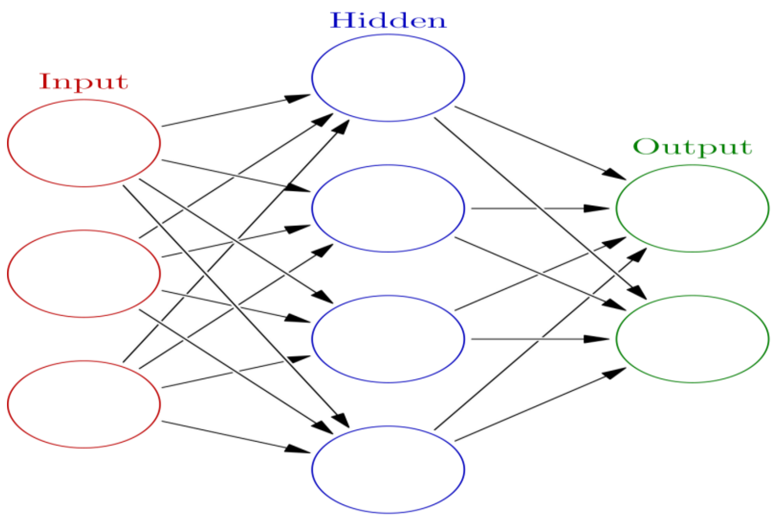

Figure 2: Typical structure of artificial neural network

Results and Discussion

Table 1 summarises the dataset with mean and standard deviation, which shows that the average log of the per capita income of US individuals has a mean value of about 10.7 USD, exceeding other variables like the average log of CO2, the average log of GDP, and the average log of technological innovation, followed by the log of GDP with a mean value of about 9.5 billion USD, and the variable with the least variability is the log of technological innovation with a standard deviation value of about 0.06 points.

Table 1: Summary statistics

Variables	N	Mean	Standard Deviation
lnCO2	34	1.651	0.072
lnGDP	34	9.464	0.431
lnTech	34	4.036	0.063
lnPCI	34	10.686	0.345

Source: Author's computation

Table 2: EKC equations

Overall Model P-value = 0.0000, R-squared = 0.4907, Root MSE = 0.05291				
lnCO2	Coefficient	Std. err	Test Statistic	P-value
lnGDP	5.074	0.983	5.16	0.000
$InGDP^2$	-0.271	0.052	-5.20	0.000
Constant	-22.032	4.623	-4.77	0.000
Overall Model P-value = 0.0272, R-squared = 0.2074, Root MSE = 0.066				
lnCO2	Coefficient	Std. err	Test Statistic	P-value
lnTech	50.733	25.570	1.98	0.056
$lnTech^2$	-6.338	3.172	-2.00	0.055
Constant	-99.834	51.524	-1.94	0.062
Overall Model P-value = 0.0001, R-squared = 0.4490, Root MSE = .05503				
lnCO2	Coefficient	Std. err	Test Statistic	P-value
lnPCI	8.687	1.830	4.75	0.000
PCI^2	-0.410	0.085	-4.77	0.000
Constant	-44.349	9.745	-4.55	0.000

Source: Author's computation

Table 2 shows that coefficient estimates of the squared of the log of the GDP and PCI have a significant negative effect at 5% level on the carbon dioxide (CO2) emissions, which implies that the economic development proxied by the GDP and the per capita income contribute negatively significantly to the CO2 emissions in the US, indicating that a high level of US GDP and per capita income helps to reduce the CO2 emissions in the United States of America, supporting the EKC theory and the first research hypothesis (H1) that economic development significantly declines CO2 emissions. The coefficient estimates of the squared of the technological innovation are statistically significant at the 10% level and have a significant negative influence on the CO2 emissions, implying that high technological innovation in the US will minimise the CO2 emissions within the United States, supporting the second research hypothesis (H2) that the technological innovation significantly reduces CO2 emissions. Besides, among the three EKC equations, the first one outperformed the other with the highest R-squared of about 49.1% and the least root mean square error of about 0.05.

Figure 3 shows the CUSUM plot for the best-fit EKC model, and we can see that the model parameters in the red line fall within the two 95% confidence intervals, indicating that the model is stable. Besides, Figure 4 demonstrated the graph of CO2 emissions against the GDP, technological innovation (Tech), and per capita income (PCI), which agrees with the inverse U-shaped postulated by the EKC theory.

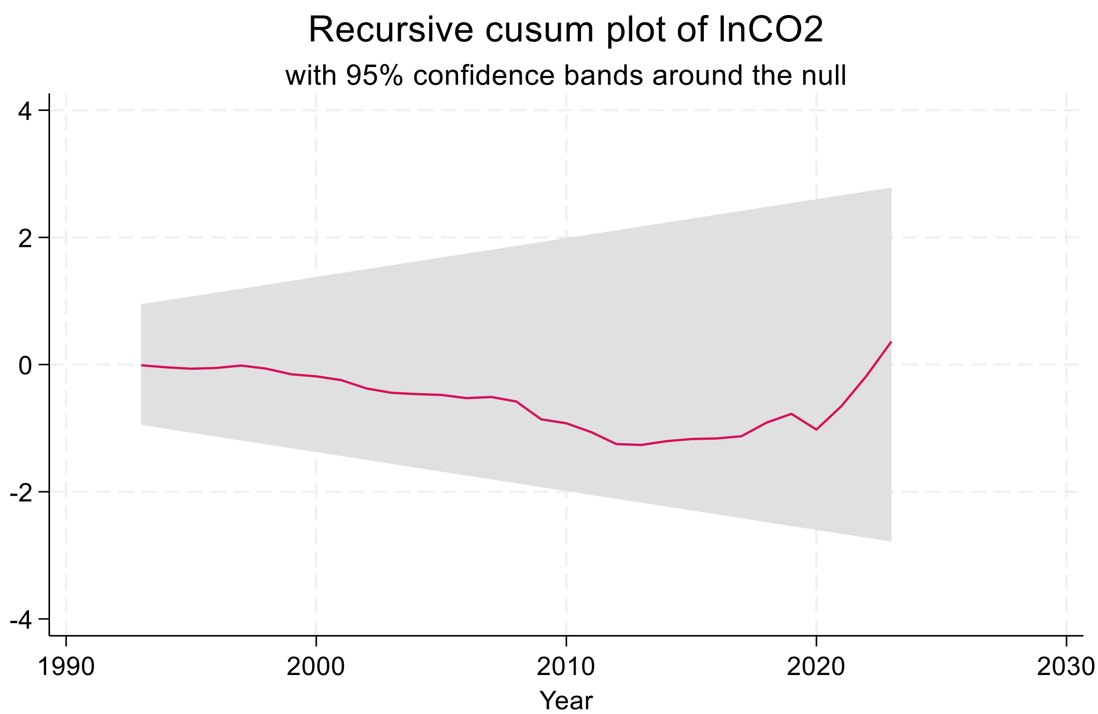

Figure 3: CUSUM test for EKC model stability

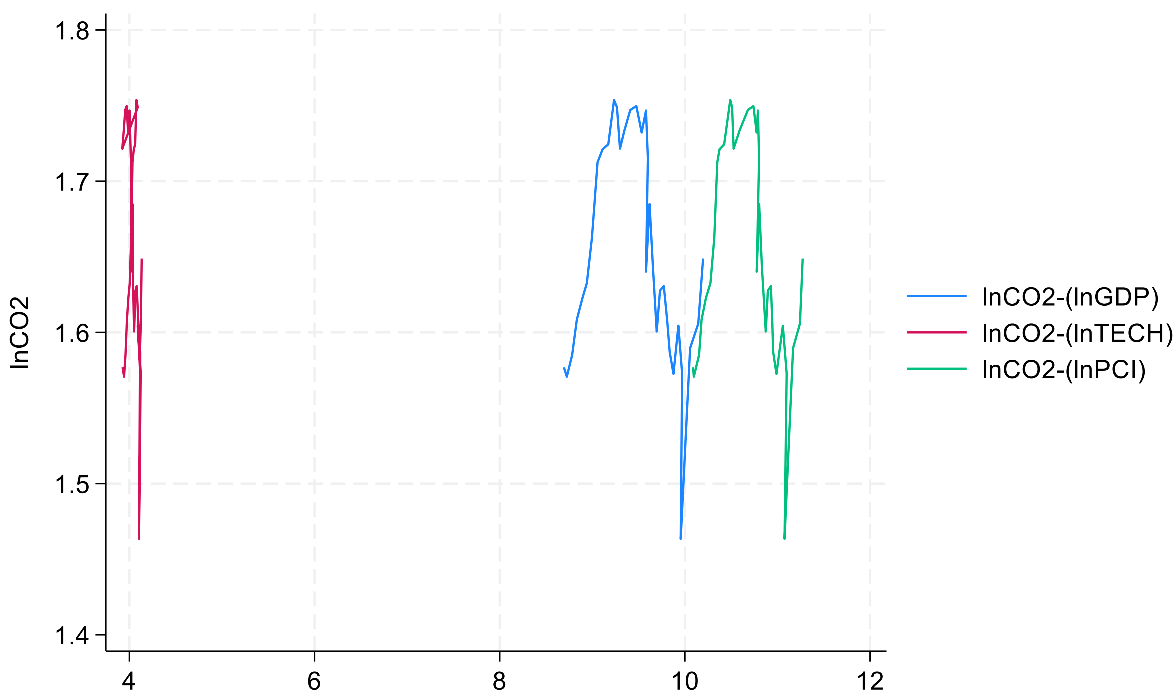

Figure 4: Graph of CO_2 emission against the GDP, Technological innovation (TECH) and Per capita income (PCI)

Figure 5 demonstrates the output of the artificial neural network model structure with the hidden layers H (1,1), H (1,2), and H (1,3) representing the input and output with a minimal error bias of 0.001 (see Table 3). The input variables are the log of the GDP, the log of technological innovation, and the log of per capita income, while the output variable is the log of CO2 emissions. Figure 6 shows the contribution of the independent or input variables, and we can see that the log of GDP has the highest contribution growth pattern, followed by the log of per capita income and the log of technological innovation.

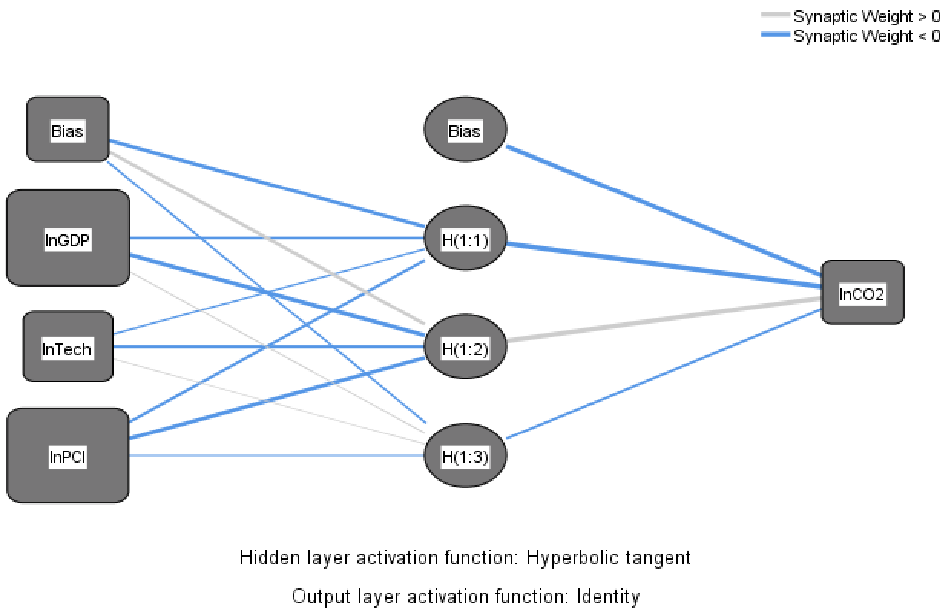

Figure 5: ANN Model Structure

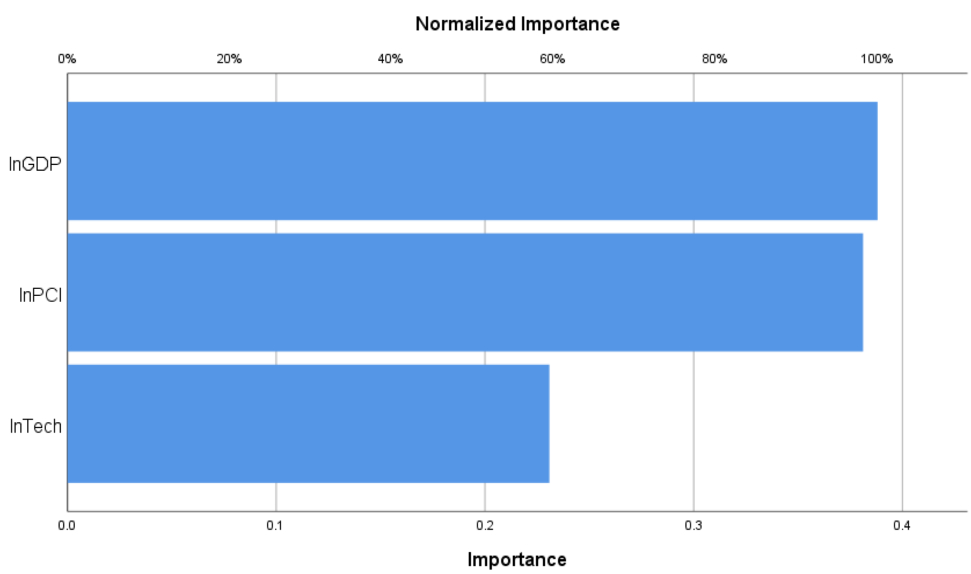

Figure 6: Independent variables contribution chart

Table 3: Independent Variables importance and the ANN model summary

	Importance	Normalized Importance
lnGDP	0.388	100.0%
lnTech	0.231	59.5%
lnPCI	0.381	98.2%
Model	Percent	Error
Testing	76.5	0.001
Training	23.5	

Source: Author's computation

Table 3 shows the importance of the independent variables in the ANN model, and it reveals that the log of GDP has the highest contribution of 100%, followed by the log of per capita income with a contribution of 98.2%, and the log of technological innovation with a contribution of 59.5%. The ANN model's testing accuracy is 76.5% with a very minimal error bias of 0.001.

Table 4: Correlation matrix

	lnCO2	lnGDP	lnTech	I lnPCI
lnCO2	1.000			
lnGDP	-0.2150	1.000		
lnTech	-0.3245	0.7447	1.000	
lnPCI	-0.2109	0.9986	0.7251	1.000

Source: Author's computation

Table 4 shows that the log of CO2 has a weak and negative correlation with the log of GDP, the log of technological innovation, and the log of per capita income, indicating that the higher the technological innovation and the economic development of the US proxied by the GDP and per capita income, the lower the CO2 emissions. Besides, the log of technological innovation has a strong and positive link with economic development, indicating that the higher the US technological innovation, the higher the country's economic development. This suggests that improved technological innovation aids the economic development of a nation.

Table 5: Skewness and kurtosis tests for normality

Variables	N	Pr(skewness)	Pr(kurtosis)	Prob>chi2
lnCO2	34	0.5730	0.6970	0.7854
lnGDP	34	0.5884	0.0630	0.1370
lnTech	34	0.6197	0.0193	0.0649
lnPCI	34	0.6238	0.0484	0.1177

Source: Author's computation

Table 5 shows the normality of the dataset using the skewness and kurtosis tests, which show that $P > 0.05$, indicating that we do not reject the null hypothesis and suggesting that the data is normally distributed.

Discussion of findings

The analysis of this study shows that the squared log of GDP and PCI coefficients have a significant negative impact at a 5% level on carbon dioxide (CO_2) emissions. This suggests that higher levels of GDP and per capita income in the US contribute significantly to reducing CO_2 emissions, supporting the Environmental Kuznets Curve theory and the first research hypothesis (H1) that economic development leads to a decline in CO_2 emissions. The regression analysis shows that the coefficient estimates for the squared technological innovation are statistically significant at the 10% level. They have a significant negative impact on CO_2 emissions, indicating that high technological innovation in the US will reduce CO_2 emissions within the country. This supports the second research hypothesis (H2) that technological innovation significantly decreases CO_2 emissions. Among the three EKC equations, the first one demonstrated superior performance, with the highest R-squared value of approximately 49.1% and the lowest root mean square error of around 0.05. This corroborates Khan et al.'s (2023) research, which demonstrates that technological innovation enhances environmental quality and decreases carbon dioxide emissions. According to the Environmental Kuznets Curve (EKC) hypothesis, economic growth has a negative effect on a country's CO_2 emissions. This is in line with the findings of Adebanjo et al. (2022), which show that economic growth and CO_2 emissions are related in an inverse U-shaped way. This also supports the findings of Saha and Jaeger (2020) that over 80% of U.S. states have decoupled their emissions from economic development.

The results indicate that the ANN model improved the precision of the model outcomes. The log of GDP had the highest contribution of 100%, followed by the log of per capita income with a contribution of 98.2%, and the log of technological innovation with a contribution of 59.5%. The testing accuracy of the ANN model is 76.5% with a negligible error bias of 0.001.

The correlation matrix revealed that the logarithm of CO_2 emissions has a weak negative correlation with the logarithm of GDP, technological innovation, and per capita income. This suggests that higher levels of technological innovation and economic development, as represented by GDP and per capita income, are associated with lower CO_2 emissions in the US. Furthermore, there is a clear and positive correlation between the rate of technological innovation and economic growth, suggesting that as technological innovation increases in the US, so does the country's economic development. Improved technological innovation in the United States and other countries contributes to economic development.

Conclusion

Nations worldwide, especially industrialised ones like the US, work to reduce carbon dioxide emissions to promote a healthy environment for their population and enhance technical innovation for significant economic growth. This study aims to enhance current knowledge by investigating the relationship among technological innovation, economic growth, and CO_2 emissions in the US. This will be achieved through the utilisation of ANN (a machine learning method) and the EKC technique, leading to advancements in previous research in this area. The results suggest that economic development, as measured by GDP and per capita income, has a greater contribution to CO_2 emissions, according to the Artificial Neural Network (ANN) model. Additionally, the Environmental Kuznets Curve (EKC) indicates that increased economic development and technological innovation lead to a decrease in CO_2 emissions. The correlation matrix showed that there is a positive relationship between the level of technical innovation in the US and the country's economic development. The US government should implement sustainable policies to increase economic development and technical advancements, thereby reducing CO_2 emissions and improving the country's atmospheric conditions, which will enhance environmental quality.

Declaration

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Authors contribution: The authors work hand in hand with each other from the beginning of the research until the end

Data availability: Data is available with the corresponding author and can be accessed upon diligent request.

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RESEARCH ARTICLE

Navigating a Greener Future: The Role of Geopolitical Risk, Financial Inclusion, and AI Innovation in the BRICS – An Empirical Analysis

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Abstract
This study examines the impact of Geopolitical Risk, Financial Inclusion, and AI Innovation on CO_2 emissions in BRICS countries from 2000 to 2019, alongside Renewable Energy Use and Economic Growth. Econometric tests revealed cross-sectional dependence and heterogeneity across the panel, with unit root tests confirming stationarity. A second-generation panel cointegration test established a long-run equilibrium relationship among the variables. Using the Panel Autoregressive Distributed Lag (ARDL) model, the analysis found that GDP and Geopolitical Risk significantly increase CO_2 emissions in both the short and long run. In contrast, AI Innovation, Financial Inclusion, and Renewable Energy Use substantially reduce emissions across time horizons. Robustness checks employing Driscoll-Kraay Standard Errors, Augmented Mean Group, and Common Correlated Effects Mean Group methods confirmed the consistency of the findings. The study concludes that promoting AI innovation, enhancing financial inclusion, and encouraging renewable energy adoption are essential strategies for reducing CO_2 emissions in the BRICS countries, especially in the context of rising geopolitical uncertainties.

Keywords: Geopolitical Risk; financial Inclusion; AI Innovation; Renewable Energy; BRICS Region

Introduction

The persistent pursuit of fiscal objectives by a nation over a period of time is the fundamental reason behind certain elements that lead to the destruction of ecosystems (Hassan et al., 2024; Hossain et al.,2023). The rise of industry has caused severe ecological degradation, particularly pollution of the environment and air, global warming, the depletion of natural assets, and erosion in biodiversity (Sezgin et al., 2024). Various contaminants, whether occurring naturally or as a consequence of human action, have the potential to exacerbate the atmosphere. Emissions of CO2 are a hazardous pollutant that adversely affects the ecosystem (Sadiq et al., 2024). The world's greatest developing nations BRICS, have seen a huge increase in CO_2 production (Mngumi et al., 2024). At a time when researchers are delving deeper into the conflicting balance between economic expansion and the environment, they find themselves at a critical crossroads (Sadik-Zada and Gatto, 2023). According to Tang et al. (2022) and Ming et al. (2022), these countries were liable for 14,759 billion tons of CO_2 in 2019. This figure reflects almost 43.19% of the global CO_2 emissions generated. Furthermore, making up about 40% of global emissions, the BRICS countries bear a large portion of the blame for the releases of CO_2. They are categorized as one of the five carbon-emitting nations due to their significant 41% contribution to worldwide CO_2 emissions (Du et al., 2022; Sharif et al., 2020). This demonstrates the vital function they play in combating climate change and transitioning to clean energy sources (Wei et al., 2023; Ridwan,2023). The BRICS group comprises the world's most significant emerging economies, holding for 42% of the worldwide population. UNCTAD (2023) reveal that the BRICS's GDP share of the global economy grew from 18% in 2010 to 26% in 2021. These concerning statistics highlight the importance of ongoing research from the BRICS region's perspective. By considering significant factors such as financial inclusion, AI innovation, and geopolitical risk, we can achieve notable outcomes. Policymakers may implement the findings of the inquiry to promote environmental sustainability in the chosen area. The most important type of green innovation is thought to be sustainable energy technologies and will likely be the primary force behind the development of clean energy sources (Khattak et al., 2024). We must understand the current state of green power investments in the BRICS territory in the context of their historical power policy and economic growth trajectory (Yadav et al.,2024). The BRICS economies' shift towards energy efficiency is indicative of the shifts occurring place in their finances and policies (Azam, 2019). Multiple studies (including Nunez et al., 2023) have underscored the efficacy of employing renewable power resources to lessen the outcome of global warming. Despite exerting significant efforts, these countries have only achieved a capability for environmentally friendly energy that holds about 36% of the global overall. In comparison, the European Union (EU) now possesses 44% of the world's total sustainable power capacity (Wei et al.,2022). The BRICS states have expressed their dedication to participating in worldwide efforts to reduce greenhouse gas emissions within the 2015 Paris Agreement and the hosting of the COP 26 in 2021 (Abbas et al., 2024). Consequently, they are committed to collaborating to accomplish zero emissions by 2050 (Udeagha & Muchapondwa, 2023; Islam et al.,2023).

Our work adds significantly to the current corpus of material. In order to distinguish it from other studies, this research primarily focuses on the frequently ignored field of AI innovation and financial inclusion from the perspective of the BRICS countries. The paper seeks to provide greater details of the correlation between CO_2 emissions and AI within the discussed setting, with the goal of assisting in the development of environmentally friendly legislation. Furthermore, it utilizes unique AI data sourced from Our World in Data, specifically focusing on annual AI patent applications. This analysis focuses on trends as well as major study problems within the BRICS zone, namely FNI, GPR, AI, GDP expansion, REN, and CO_2 emissions. An important addition to the collection of knowledge is the analysis of CO_2 pollution in the BRICS area, which provides researchers with fresh perspectives. This study, being the first to our knowledge to conduct a comprehensive literature analysis, makes us to pursue the following study goals: How do FNI and AI affect the environment in the BRICS countries? What effects do GDP and GPR have on environmental sustainability? This research's importance stems from its attention to the neglected domains of financial inclusion and AI innovation, which have not received much attention from previous studies. To create a sustainable and habitable environment, further research in this area is essential, especially in light of the public's growing interest in green cities and ecological challenges. Using ARDL methodology along with a novel Cobb-Douglas production function, this study looks at how GDP, AI, FNI, REN, and GPR affect carbon emissions from 1990 to 2018. It also uses DKSE, AMG, and CCEMG techniques to ensure the results are robust. Policymakers in the BRICS region and beyond can benefit from the insights this study offer, which will aid in achieving the SDGs and fostering sustainable economic growth.

There are five parts to this paper. The literature review, positioned after this introduction, reviews the relevant work before identifying the research gap. The third section covers the explanations of the analysis variables, methodology, and information sources. The fourth segment covers the outcomes and discussions. The last portion addresses the conclusions and suggestions for policy.

Literature Review

Many economic tools and methodologies have been used in recent studies, combining a variety of different explanatory variables across many geographical locations, and frequently producing contradictory conclusions. Furthermore, little research has been done on the central economic partnerships among the BRICS nations, which could have an impact on the global market. Consequently, in this section, we provide a succinct and critical analysis of the connection between these factors and CO2 pollutions.

GDP and CO2 Emission Nexus

Researchers have conducted numerous studies over the years to examine the link between CO2 emissions and GDP development. More inquiry is required to assess the link between GDP and CO2 emissions in the BRICS area. Voumik et al. (2023a) adopted the ARDL method to examine the CO2 emissions of Kenya over the years 1972 to 2021. The outcomes suggest that there prevails an upward connection between a country's emissions level and GDP. Pattak et al. (2023) undertook research in Italy from 1972 to 2021 utilizing the STIRPAT and ARDL methods. They declared that a 1% rise in Italy's GDP in long-term turns 8.08% boost in the release of CO2. Similarly, multiple investigations, such as He et al. (2019) in China, Finland, and Malaysia, Tufail et al. (2021) in developed nations, Raihan et al. (2023b) in Malaysia, and Ridwan et al. (2023) in France, have identified an encouraging relationship between CO2 pollutions and GDP. In contrast, Raihan et al. (2024a) undertook an inquiry examining the implication of GDP expansion on CO2 emissions in India covering 1965 to 2022. Their findings suggested that as the economy grew, there was a slight decline in pollutants. Raihan et al. (2023a) claim that faster GDP growth in China could potentially lead to lower emission levels in the future. In addition, Ridwan et al. (2024a) found that GDP had a major effect on reducing CO2 emissions, both in the short term and in the long term. Destek et al. (2020) offered decision-makers fresh views on using economic development as a means to enhance the longevity of the environment.

Geopolitical Risk and CO2 Emission Nexus

Geopolitical risk (GPR) and other social trends among state environmentalists and policymakers have brought up several serious environmental-related challenges (Uddin et al., 2023). Syed et al. (2022) performed an investigation into whether GPR affected the ecosystem in the BRICST countries. Conclusions deployed that CO2 emissions are falling in the middle and upper quartiles but rising in the lowest quartiles as a result of GPR. Bai (2021) published a study to explore the implications of GPR on the EF in Brazil, Colombia, Mexico, and Russia. They concluded that using GPR reduces carbon footprint. In their study, Adams et al. (2020) assessed the link between GPR and CO2 emissions in the leading resource-rich nations from 1996 to 2017. Their findings confirm that GPR is associated with a drop in CO2 emissions. Furthermore, Zhao et al. (2021) found that GPR has an unequal effect on CO2 emissions, specifically in the BRICS region. Conversely, Cui et al. (2024)

employed sophisticated econometric methods, including CS-ARDL, FMOLS, DOLS, and AMG, to conduct a study in the BRICS nations between 1992 and 2021. Environmental degradation increases in tandem with geopolitical danger, according to the study. Similarly, Li et al. (2024) discovered that, over time, higher emissions of carbon are associated with geopolitical risk in 38 chosen countries. In addition, according to Hunjra et al. (2024), heightened geopolitical danger causes a spike in CO2 emissions and the EF of 21 selected states. In addition, Wang et al. (2022) determined that the govt. of China can successfully consider GPR to control CO2 emissions by boosting environmentally friendly investments and implementing ecological strategies.

Financial Inclusion and CO2 Emission Nexus

Financial inclusion (FNI) is a fundamental element of the economy that is under constant consideration (Sohail et al.,2019). Energy-efficient technologies, enhanced environmental regulations, and readily accessible lending at reduced rates are just a few of the numerous ways in which financial growth exhibit a beneficial influence on our planet (Zaidi et al., 2019; Tanchangya et al.,2024; Ridwan & Hossain, 2024). Raihan et al. (2024c) interpret the effects of financial integration on the release of CO2 in the G-7 zone. According to the ARDL model, the availability of financial resources causes a surge in pollutions level. In addition, Ahmad et al. (2022) deployed the link between FNI and CO2 emissions in BRICS nations and concluded that FNI is a contributing cause for ecological degradation. Hussain et al. (2024) implemented principal component analysis (PCA) to determine that FNI had a detrimental effect on CO2 emissions in the short term but an advantageous impact in the long run in 26 Asian nations. In contrast, Du et al. (2022) utilized several techniques to look at the association between FNI and CO2 emissions. Their study demonstrated that FNI had a destructive association with CO2 emissions, thereby improving the natural well-being of selected developing countries. Renzhi and Baek (2020) determined that FNI is reducing CO2 emissions and made the case that raising environmental consciousness might be an effective way to lessen the adverse impacts of financial growth. According to the AMG's findings, it lowers CO2 emissions, which greatly enhances environmental sustainability. To prevent the adverse impacts of financial openness and to safeguard biodiversity, policymakers should improve the standards of their organizations in the MENA region (Boussaidi and Hakimi, 2024).

AI and CO2 Emission Nexus

To "promote a low-carbon in industry and consistently boost the carbon neutralization of carbon peaks," as well as to help achieve the "double carbon goal," it is imperative that artificial intelligence (AI) be promoted (Xi, 2022; Ridwan et al.,2024e; Rahman et al.,2024). Research on the possible effects of artificial intelligence (AI) on CO2 emissions has begun to emerge as the world undergoes transformation and experiences new kinds of advances in technology. For example, Dong et al. (2024) used dynamic panel data from 30 provinces in mainland China covering the years 2006 to 2019 to build econometric models with the goal of examining the impacts and underlying causes of AI on CO2 emissions. Empirical evidence shows that using AI significantly reduces CO2 emissions. Chen et al. (2022) discovered actual proof indicating that the use of robots greatly decreases CO2 emissions in China's industrial sector. Additionally, Ochieng et al. (2024) have developed an approach that employs robots to monitor and reduce CO2 emissions. Some other authors like Shiam et al.(2024a), Rana et al.(2024), Ferdous et al.(2023), Shiam et al.(2024b), Arif et al.(2024),also concluded similar findings. The system predicts emissions, offers methods for cutting them, and detects pollution using drones and other ecologically conscious sensors. Liu et al. (2023) demonstrated the influence of AI on carbon footprint between 2005 and 2016, leveraging the STIRPAT model. The study's findings reveal that the use of AI significantly mitigates CO_2 releases, as evidenced by several scientific articles regarding AI and robotics in this sector.

Renewable Energy Use and CO2 Emission Nexus

Currently, multiple scholars are investigating the urgent connection between the usage of renewable energy (REN) and the release of CO_2. In order to lower emissions and improve the surroundings, it is crucial to promote alternative power sources for example- sunlight, biogas, geothermal energy, wind energy, and hydroelectric (Jabeen et al., 2020; Atasoy et al.,2022b; Onwe et al.,2024; Raihan et al.,2024e). Ahmad et al. (2024a) made use of the ARDL bound test to assess China's carbon neutrality. They showed that a 1% consumption in REN application should causes to a 0.03% decline in CO_2 pollution over time. Byaro et al. (2023) conducted an evaluation of the association between REN consumption and environmental harm in 48 sub-Saharan African states. For their analysis, they used categorized panel quantile regression. Research has demonstrated that using renewable energies reduces environmental harm on several levels. Additionally, Rahman and Alam (2022) look to see if using renewable energy can lower Bangladesh's CO_2 emissions. The study used the PMG and NARDL approaches, and its conclusions illustrate that harnessing sustainable power helps Bangladesh reduce its CO_2 emissions. Similarly, Raihan et al. (2022a) in China, Isik et al. (2024) in 27 OECD countries, and Kwilinski et al. (2024) in the EU transportation sector expressed the same conclusion. However, Rehman et al. (2023) researched the worldwide influence of nuclear power and REN on CO_2 emissions from 1985 to 2020. The outcomes demonstrate that the adoption of REN does not have the ability to alter the levels of CO_2 emissions either in the long run or in the short run. Shang et al. (2024) found a U-shaped link between environment friendly energy and pollutions when examining China's REN and CO_2 pollutions from 1995 to 2020.

Literature Gap

The work observes that no prior research has looked at the BRICS countries in extensive detail. However, a limited number of studies have explored the connection among GDP expansion, the utilization of green power, and CO_2 emissions. By adding new distinct variables, such as financial inclusion, geopolitical risk, and AI innovation, this analysis adds to the body of expertise. We found that the majority of earlier studies had difficulty drawing meaningful results. Furthermore, there is a dearth of research on environmental damage, especially concerning the sophisticated variables of AI innovation and financial inclusion, which have the potential to foster green development and reduce carbon pollution. As a result, this study examines the most recent data for the BRICS states, providing a longer time frame and comprehensive insights into past carbon emissions patterns among the countries. By concentrating on these important factors, this study ultimately seeks to improve understanding of how the BRICS nations contribute to their economic success and ecosystem health.

Methodology

Data and Variables

The inquiry used sophisticated statistical approaches to understand the complex correlation between the selected factors. The study's dependent variable, CO_2, came from the reliable WDI. The WDI (2022) also provided data for GDP and renewable energy utilization, while reputable sources such as Our World in Data, the GPR Index, and Global Financial Development provided information on AI innovation, geopolitical risk, and financial inclusion. Table 1 provides a thorough summary of all the variables examined, along with definitions, sources, and units of measurement.

Table 1. Variable and sources of data

Variables	Description	Logarithmic Form	Unit of Measurement	Source
CO_2	CO_2 Emission	LCO_2	CO_2 Emission (kt)	WDI
GDP	Gross Domestic Product	LGDP	GDP per capita (current US$)	WDI
GPR	Geopolitical Risk	LGPR	Geopolitical Risk Index	GPR Index
FNI	Financial Inclusion	LFNI	Automated teller machines (ATMs) (per 100,000 adults)	Global Financial Development
AI	AI Innovation	LAI	Annual patent applications related to AI	Our World in Data
REN	Renewable Energy Use	LREN	Renewable Energy Consumption (% of total final energy consumption)	WDI

Theoretical Framework

Cobb and Douglas (1928) statistically examined the Cobb-Douglas production function, commonly adopted to illustrate the association concerning input and output components. The primary goal is to conduct a deeper analysis of the complicated relationship between the utilization of clean energy, GDP growth, financial inclusion, geopolitical risk, and AI advancements, and their impact on CO2 pollutions in BRICS area. Equation (1) depicts the structure of the Cobb-Douglas production function.

$Y_t = f(K_t, L_t)$ …………………………………..(1)

Here, Y_t indicates the GDP at time t. On the other hand, K_t represents capital at t time and L_t means effective labor at t time. Nowadays, ecological economics makes use of this function (Nicolle et al.,2023). Economic progress has been linked to CO2 emissions in the past (Mensah et al. 2019; Aye and Edoja, 2017). From here on out, the creation function can look like this:

$CO_{2t} = f(GDP_t)$ …………………………………..(2)

Disruptions in energy supply due to global conflicts can push nations to depend more on carbon-intensive energy sources. Additionally, increasing access to finance can drive modernization and GDP growth in emerging nations, both of which can lead to higher carbon emissions. Now, the function can be present like-

$CO_{2t} = f(GDP_t; GPR_t; FNI_t)$ …………………………………..(3)

In contrast, although growing use of green power promptly reduces the release of CO2 by substituting fossil fuels with alternative sources such as wind and solar energy, AI has a varied impact on pollution levels.

$CO_{2t} = f(GDP_t; GPR_t; FNI_t; AI_t; REN_t)$ …………………………………..(4)

The equation (5) represents the economic model and is clarified as the actual context in the next way:

$CO_{2t} = Z_0 + \partial_1 GDP_t + \partial_2 GPR_t + \partial_3 FNI_t + \partial_4 AI_t + \partial_5 REN_t + \mu_t$ …………………………………..(5)

In this case , $\partial_1, \partial_2, \partial_3, \partial_4, \partial_5, \partial_6$used as the coefficients whereas, Z_0 and μ_t illustrate the intercept and error terms. Moreover, the logarithmic version of equation (5) can be presented like:

L$CO_{2t} = Z_0 + \partial_1 LGDP_t + \partial_2 LGPR_t + \partial_3 LFNI_t + \partial_4 LAI_t + \partial_5 LREN_t + \mu_t$ …………………………………..(6)

Because the coefficient indicates the elasticity, this formulation is more beneficial and eliminates the problem of multicollinearity (Akther et al.,2024; Sohail et al.,2018b).

Empirical Methodology

The cross-sectional hyperlink and panel data features point to a chance that the BRICS countries are dealing with a stationary mixed-order problem. Therefore, we employ the slope homogeneity test and CSD. In this endeavor, we need to validate the CSD and SH issues through cointegration analysis and first and second-generation panel unit root tests. We carefully considered each of these factors and selected the ARDL method. The research analyzed the estimations of DKSE, AMG, and CCEMG to assess robustness. This part provides a clear and brief description of the research findings, their interpretation, and any possible repercussions for the study.

Cross Sectional Dependence Test

If researchers ignore this issue and handle the cross-sections as isolated, CSD can result in distorted, deceptive, and contradicting results (Hoyos et al., 2006). The optimum test to utilize is the CSD test, even if a standard unit roots testing shows cross-sectional independence (Sahoo & Sethi, 2021). In order to investigate CSD, this study uses Pesaran's (2015) technique with full panel data and weakly exogenous components.

$$CSD = \sqrt{\frac{2T}{N(N-1)N}\left(\sum_{i=1}^{N-1}\sum_{m=i+1}^{N}\widehat{Corr_{\iota,t}}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (7)$$

Slope Homogeneity Test

Slope heterogeneity (SH) must be considered when evaluating panel data (Voumik and Mimi, 2023; Mithun et al.,2023). Because cross-sections usually show similar features, panel data typically have consistent slopes so addressing slope uniformity is essential (Ayad and Djedaiet, 2022). Following that, we apply in our work the SH test developed by Pesaran and Yamagata (2008). The SH is shown by Equation (8) as follows:

1. $\breve{\Delta} = \sqrt{N}\left(\frac{N^{-1}S\%-k}{\sqrt{2k}}\right)$ and $\breve{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}S\%-k}{\sqrt{\frac{2k(T-k-1)}{T+1}}}\right)$…………………. (8)

Panel Unit Root Test

According to the scientific community, it is widely accepted that identifying the integration order of the series is a vital prerequisite for exploring any connections between variables (Voumik et al., 2023b; Ahmad et al.,2024b). Im et al. (2003) developed the initial IPS test, while Pesaran (2007) created the subsequent version of the CIPS test and the CADF unit root examinations. The IPS test can be represented in the following way:

$$\Delta y_{it} = \alpha_i + \beta_i t + \gamma y_{it-1} + \delta_i \Delta y_{it-1} + \varepsilon_{it} \ldots\ldots\ldots\ldots \text{(9)}$$

The first generation of panel unit root testing overlooks heterogeneity, CSD implications, and over-rejection of null hypotheses (Choi, 2001). The purpose of the CIPS analysis is to take into consideration the possibility of CSD in the panel data, which, if left unchecked, could result in inaccurate inference (Polcyn et al.,2023). The CIPS test is conducted using Equation (10):

$$CIPS = \frac{1}{N}\sum_{t=1}^{N} t_1(N,T) \ldots\ldots\ldots\ldots \text{(10)}$$

The CADF test has a strong relationship with the CIPS test and the equation is given below:

$$\Delta Yi_t = \varphi_i + \rho i Y i_{t-1} + \varphi i \bar{Y}_{t-1} + \sum_{j=1}^{m} \varphi_{ij} \bar{Y}_{t-1} + \sum_{j=1}^{m} \gamma_{ij}\, \Delta Y_{i,t-1} + \varepsilon_{it} \ldots\ldots\ldots (11)$$

Panel Cointegration Test

The authors administer the cointegration test after completing the unit root assessments. In this investigation, we applied the second-generation panel cointegration approach to determine the cointegration relationships between the relevant variables (Westerlund, 2007). We generate statistics from the four-panel cointegration test.

$$G_a = \frac{1}{n}\sum_{i=1}^{N} \frac{\acute{a}_i}{SE(\acute{a}_i)} \ldots\ldots\ldots\ldots \text{(12)}$$

$$G_t = \frac{1}{n}\sum_{i=1}^{N} \frac{T\acute{a}_i}{a_i\acute{}(1)} \ldots\ldots\ldots\ldots \text{(13)}$$

$$P_t = \frac{\acute{a}}{SE(\acute{a})} \ldots\ldots\ldots\ldots \text{(14)}$$

$$P_a = T\acute{a} \ldots\ldots\ldots\ldots \text{(15)}$$

In this case, mean group statistics are represented by Gt and Ga, and cointegration is symbolized by Pt and Pa.

Panel ARDL Framework

Pesaran et al. (2001) proposed the panel autoregressive distributed lag (ARDL) technique, which was adopted in this study due to its ability to handle variables that are either I(0), I(1), or a combination of both (Raihan et al., 2024e; Sohail et al., 2018a). The ARDL model is advantageous over models like OLS, VECM, and VAR because of its flexibility in defining lag lengths and its effectiveness in both short- and long-term estimations (Voumik and Ridwan, 2023). Although it operates differently from traditional cointegration methods, the ARDL model offers several advantages, such as its ability to address endogeneity by incorporating variable lag periods (Pesaran et al., 2001; Abir, 2024). A key strength of the model is its robustness in estimating systems with mixed levels of integration (Ullah et al., 2021; Ridzuan et al., 2023; Raihan et al., 2024f), enabling it to account for the integration properties of variables. This feature enhances the model's ability to reflect real-world dynamics and effectively capture complex temporal relationships, as noted by Raihan et al. (2024b).

$$\Delta LCO_{2it} = \beta_{1i} + \gamma_{1i}LCO_{2i,t-1} + \gamma_{2i}LGDP_{i,t-1} + \gamma_{3i}LGPR_{i,t-1} + \gamma_{4i}LFNI_{i,t-1} + \gamma_{5i}LAI_{i,t-1} + \gamma_{6i}LREN_{i,t-1} + + \sum_{j=1}^{p}\lambda_{1i}\Delta LCO2_{i,t-j} + \sum_{i=0}^{q}\lambda_{2i}\Delta LGDP_{i,t-j} + \sum_{i=0}^{q}\lambda_{3i}\Delta LGPR_{i,t-j} + \sum_{i=0}^{q}\lambda_{4i}\Delta LFNI_{i,t-j} + \sum_{i=0}^{q}\lambda_{5i}\Delta LAI_{i,t-j} + \sum_{i=0}^{q}\lambda_{6i}\Delta LREN_{i,t-j} + \varepsilon_{1i,t} \quad (16)$$

Furthermore, this paradigm is useful in any situation where investigative series integration is involved (Voumik et al., 2023c). When series variables are cointegrated, we can evaluate the short-run effects of GDP, AI innovation, GPR, FNI, and REN on CO2 emissions using an error-correcting mechanism (ECM). The ECM, defined as Eq. (17), used for long-term link between each factor.

$$\Delta LCO2_{it} = \sum_{j=1}^{p-1}\alpha_{1ij}\Delta LCO2_{i,t-j} + \sum_{i=0}^{q-1}\alpha_{2ij}\Delta LGDP_{i,t-j} + \sum_{i=0}^{q-1}\alpha_{3i}j\Delta LGPR_{i,t-j} + \sum_{i=0}^{q-1}\alpha_{4i}j\Delta LFNI_{i,t-j} + \sum_{i=0}^{q-1}\alpha_{5ij}\Delta LAI_{i,t-j} + \sum_{i=0}^{q-1}\alpha_{6ij}\Delta LREN_{i,t-j} + \mu_{1i}ECT_{1,it-1} + \varepsilon_{1i,t} \quad (17)$$

Robustness Check

We found out how stable the model was by comparing the effects of time-dependent parts on the environment using the DKSE created by Driscoll and Kraay (1998), the AMG (Bond & Eberhardt ,2009), and the CCEMG created by Pesaran (2006) in our study. We use DKSE in CSD problems because it is heteroscedastic, autocorrelation-consistent, and resistant to typical forms of CSD (Hoechle, 2007). Due to their consideration of the correlation among panel members, the AMG and CCEMG estimators are both resistant to CSD (Ng et al., 2020). Furthermore, according to Kapetianos et al. (2011), the CCEMG approach is resilient to structural fractures and non-stationary prevalent elements that go unnoticed.

Results and Discussion

Based on a dataset encompassing the BRICS countries from 1996 to 2019, Table 1 showcases the statistical findings for several normality metrics, such as skewness, probability, kurtosis, and the Jarque-Bera test. Each variable has 100 observations. Highlighted are the descriptive statistics for the following seven variables: LCO2, LGDP, LGPR, LFNI, LAI, and LREN. The table indicates that all variables have positive means, except LGPR. In addition, almost all of the parameters have relatively low standard deviations, suggesting that the data points are somewhat shifting over time and clustered around the mean. Most variables show positive skewness, except for LCO2, which is positively skewed. Furthermore, the Jarque-Bera test was utilized to verify the level of normality of each factor in this investigation. This type of test is suitable as it takes into account inconsistencies related to both skewness and kurtosis.

Table 2. Summary statistics of variables

Statistic	LCO2	LGDP	LGPR	LFNI	LAI	LREN
Mean	14.01781	8.744605	-1.829589	3.868414	3.054113	2.772809
Median	14.25714	8.808211	-1.534152	4.028851	3.113269	2.685356
Maximum	16.19161	9.22577	0.14121	5.222552	3.89182	3.890186
Minimum	12.55836	7.693433	-3.912023	2.581988	1.791759	1.156881
Std. Dev.	1.114343	0.391927	1.202445	0.800042	0.500842	0.952693
Skewness	0.475347	-1.100278	-0.176032	-0.011587	-0.405564	-0.454151
Kurtosis	2.113849	3.526287	1.548373	1.502311	2.437028	1.90319
Jarque-Bera	7.037847	21.33094	9.296546	9.348368	4.061935	8.450011
Probability	0.029631	0.000023	0.009578	0.009333	0.131209	0.014625
Sum	1401.781	874.4605	-182.9589	386.8414	305.4113	277.2809
Sum Sq. Dev.	122.9343	15.20711	143.1416	63.36673	24.83345	89.85468
Observations	100	100	100	100	100	100

Cross Sectional Dependence test

In Table 3, at the 1% level, all CSD statistic values are highly significant, and the p-value for each variable is less than 0.05. These findings reject the null hypothesis, which asserts no cross-sectional dependence between nations, for all factors. It indicates that an unforeseen incident in one of the chosen countries might have consequences for the other nations as well.

Table 3. Results of CSD test

Variables	CD-Statistics	P-Value
LCO_2	10.13***	0.000
LGDP	13.26***	0.000
LGPR	7.68***	0.000
LFNI	11.62***	0.000
LAI	2.15**	0.025
LREN	4.17***	0.000

Table 4 summarizes the outcomes of the slope heterogeneity experiment. The calculated p-values of 0.000 reject the null hypothesis, stating that the slope coefficients are homogeneous, at the 1% significance level. The p-values reject the homogeneity hypothesis, demonstrating that multiple variables have distinct coefficients.

Table 4. Results of Slope Homogeneity test

SH tests	Δ statistic	P-value
$\breve{\Delta}$ test	4.065***	0.000
$\breve{\Delta}_{adj}$ test	5.062***	0.000

Note: "Null Hypothesis: Slope of the coefficients are homogenous"

Table 05 provides the unit root analysis conclusions. At the 1% significance threshold, the IPS test confirms that only LGPR and LAI are stationary at the level form I(0), whereas the other variables appear to exhibit significant and stationary patterns at the first difference I(1). The results of the CIPS test demonstrate that LAI is stationary at the 1% level and LGPR is stationary at the I(0) level at the 5% significance threshold. At the 1% significance level, the remaining factors are stationary at the initial difference, I(1). Similar to this, the CADF unit root examination finds that, at the 1% significance level, only LGPR and LAI are stationary at the level form I(0), but all the others start to become stationary at the first difference I(1). Furthermore, following the first difference, everything else is significant in the 1% range. Our results rule out the notion of a unit root problem by indicating that the variables reflect strong cointegration.

Table 5. Results of panel Unit root test

Variables	IPS		CIPS		CADF		Decision
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	
LCO2	-1.554	-3.950***	-2.183	-2.842***	-1.029	-3.053***	I(1)
LGDP	-0.018	-3.041***	-2.045	-3.651***	-0.764	-3.201***	I(1)
LGPR	-4.098***	-6.383***	-2.524**	-5.296***	-3.021***	-5.064***	I(0)
LFNI	-0.121	-3.132***	-2.225	-3.707***	-1.552	-3.881***	I(1)
LAI	-3.933***	-7.003***	-3.071***	-5.323***	-2.980***	-3.871***	I(0)
LREN	-1.535	-4.031***	-1.750	-3.226***	-0.780	-4.586***	I(1)

The Westerlund (2007) cointegration assessment evaluates long-term relationships between variables in Table 06 using four test statistics (Gt, Ga, Pt, and Pa). P-values less than 0.05 for the Gt and Pt test statistics partially confirm the null hypothesis, suggesting cointegration and a consistent, persistent connection between the variables in the panel dataset.

Table 6. Results of panel Cointegration test

Statistics	G_t	G_a	P_t	P_a
Value	-3.761***	-6.570**	-4.904**	-3.877***
Z-Value	-1.872	1.901	2.087	1.704
P-Value	0.001	0.017	0.043	0.001

The Panel ARDL model's results, presented in Table 07, demonstrate the intricate dynamics influencing the BRICS region's carbon pollution. In terms of LGDP, the short-term coefficient is 0.3017 while the long-run coefficient is -0.4131, and both are statistically significant at conventional levels. This suggests that economic expansion alone contributes to environmental degradation in this setting. Our implications are agreed by Addai et al. (2023) in Eastern Europe, Syed et al. (2022) in BRICST, Ridwan et al.(2024d) within USA, Gessesse and He (2020) in China, Rahman et al.(2022) in Bangladesh, Raihan et al.(2024h) within Bangladesh, Raihan et al.(2024d) in Indonesia and Kongkuah (2021) in OECD economies. Furthermore, Minh et al. (2023) demonstrate a link within GDP development and CO2 emissions, which declines in Vietnam beyond a specific threshold. Similarly, LGPR has a positive association with LCO2 in both periods. In the short run, the coefficient has a positive value of 0.0206, and in the long run, the value is 0.1362. The variable is significant because its p value is less than the conventional level for both periods. Our results align with Dun and Wang (2023) in China, Adedoyin et al. (2020) in EU countries, and Gyamfi et al. (2021) in E-7 zones. In contrast, in the short and long terms, there is a negative link between LFNI and LCO2. The short-term is insignificant as the p value is 0.0993, and the long-term results are significant as the p value is 0.0006. These findings demonstrate that financial accessibility has a positive effect on the BRICS ecosystem. For every 1% increase in LFNI, LCO2 reduces by 0.0472% in the near term and 0.1061% in the long term. Usman et al. (2021) found support for this conclusion in the 15 highest emitting countries, Saqib et al. (2023) in emerging economies, Raihan et al.(2022b) within USA and Tamazian and Rao (2010) in transitional countries. But Musah (2021) found that financial inclusion causes more carbon emissions in Ghana.

Similarly, there is an obvious connection between AI innovation and the environment, as evidenced by the beneficial relationship observed between LCO2 and LAI across both short and long periods. Specifically, a 1% expansion of LAI will cut LCO2 by 0.0094% in the short term and by 0.1221% in the long term. These results imply that utilization of modern AI technology could boost ecological conditions in both terms, and the results are significant in long terms and insignificant in short terms. This result is supported by Ridwan et al.(2024b) in USA, Ridwan et al.(2024c) in G-7 countries Akther et al.(2024) in USA, Bala et al. (2024) in G-7 countries, Abir et al.(2024) in USA, Shiam et al.(2024c) in Nordic area and Hossain et al.(2024) within Nordic region. Mor et al. (2021) studied in the Indian agricultural sector is consistent with these findings. Chen et al. (2022) discovered that the use of industrial robots in a variety of industries can minimize the ecological impact, particularly across 72 nations. By using artificial intelligence (AI), humans can better manage climate change and achieve sustainability while using natural assets (Habila et al., 2023; Faruk et al.,2023). In both the short and long term, the table demonstrates an inverse relationship between LREN and LCO2.

Table 7. Results of Panel ARDL test

Variable	Coefficient	Std. Error	t-Statistic	Prob.*
Long-run Estimation				
LGDP	0.4131	0.0734	5.6323	0.0000
LGPR	0.1362	0.0581	2.3438	0.0227
LFNI	-0.1061	0.0291	-3.6655	0.0006
LAI	-0.1221	0.0445	-2.7411	0.0082
LREN	-0.8690	0.1056	-8.2326	0.0000
Short-run Estimation				
COINTEQ01	-0.1535	0.0807	-2.9021	0.0624
D(LCO2(-1))	-0.0050	0.0670	-1.0751	0.0404
D(LGDP)	0.3017	0.1345	2.2433	0.0289
D(LGPR)	0.0206	0.0082	2.5010	0.0154
D(LFNI))	-0.0472	0.0894	-1.5284	0.0993
D(LAI)	-0.0094	0.0054	-1.7437	0.0868
D(LREN)	-0.5075	0.3068	-3.6540	0.0038
C				

The long-term and short-term results reveal statistical significance, as the p value is less than the conventional thresholds. Over time, there will be a 0.8690% reduction in LCO2, and in a short time, there will be a reduction of 0.5075% for every 1% increase in LREN. In particular, the effect indicates that consumption of green energy reduces emissions. The findings of Aziz et al. (2021) for MINT countries, Raihan et al.,(2024f), Islam et al.(2024) in top nuclear energy consuming area, Atasoy et al.(2022a) within USA, Raihan et al. (2024g), Mahmood et al. (2019) for Pakistan, and Attiaoui et al. (2017) for Africa align with our findings.

Table 8 uses three different estimate approaches (DKSE, AMG, and CCEMG) to establish the consistency of the ARDL results. For each method, the estimated LGDP coefficients are 0.472, 0.456, and 0.174, respectively, and all estimators' exhibit significance at the 1% level. These findings are consistent with the short- and long-term outcomes of the ARDL paradigm, indicating that economic growth has had a detrimental influence on natural health in the BRICS countries. In a similar vein, the LGPR coefficient indicates negative correlations in the AMG approach but positive correlations in the DKSE and CCEMG calculations. In particular, LCO2 increases by 0.820% in DKSE and 0.034% in CCEMG for each percent rise in risk related to geopolitics, but AMG forecasts a 0.923% drop in carbon emissions.

Table 8. Results of Robustness check

VARIABLES	(1) DKSE	(2) AMG	(3) CCEMG
LGDP	0.174***	0.456***	0.472***
	(0.263)	(0.099)	(0.158)
LGPR	0.820***	-0.923***	0.034**
	(0.038)	(0.013)	(0.059)
LFNI	-0.108***	-0.116***	-0.178**
	(0.107)	(0.038)	(0.094)
LAI	-0.116***	-0.034**	-0.027**
	(0.156)	(0.078)	(0.047)
LREN	-0.196**	-0.469***	-0.292
	(0.085)	(0.090)	(0.213)
Constant	14.22***	11.79***	9.670***
	(2.632)	(1.325)	(2.021)
Observations	100	100	100
Number of groups	5	5	5
R-squared	0.971	0.988	0.864

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

In DKSE, AMG, and CCEMG, the LGPR factor is statistically significant at the 1% and 5% thresholds, accordingly. On the other hand, the opposite relationship between LFNI and LCO2 suggests that ongoing financial inclusion has no adverse effects on the BRICS atmosphere. In the CCEMG estimation, the LFNI coefficient is significant at the level of 5%, but in other approaches, it is significant at the 1% threshold. All three investigations have found a negative correlation between LCO2 and LAI. In the AMG and CCEMG analyses, the LAI coefficient is significant at the 5% level; in the DKSE test, it is significant at the 1% range. According to such outcomes, a 1% increase in AI innovation cuts LCO2 by 0.116%, 0.034%, and 0.027%, respectively, implying that higher AI innovation contributes to the BRICS ecosystems. Similarly, favorable interactions between LCO2 and LREN illustrate that greater utilization of clean energy has an excellent consequence for biodiversity in the regions under investigation. In the CCEMG estimation, the LREN variable is not significant, but it is significant at the 1% level in AMG and the 5% level in DKSE. These findings verify the implications of the experiment and reinforce the ARDL model, which was the main estimating approach deployed.

Conclusion and Policy Recommendation

This investigation looked at the complex relationship among CO2 emissions, renewable energy use, geopolitical risk, financial inclusion, AI innovation, and GDP expansion in the BRICS nations between 1996 and 2022. The research sought to determine the key factors changing environmental conditions in this region by utilizing the Cobb-Douglas production function and advanced econometric methodologies. To make sure that there are no unit root problems in the dataset and to tackle all possible empirical difficulties, our study performed both first-generation and second-generation panel unit root examinations. Panel cointegration tests further highlighted the variables' dependency and validated their long-term cointegration. This investigation also utilized the ARDL framework to capture the short- and long-term connection between the selected variables. We fully investigated the correlations between dependent and independent variables using the DKSE, AMG, and CCEMG techniques to validate strong conclusions. The results revealed that while economic expansion and geopolitical risk raise CO2 emissions, financial inclusion, AI innovation, and the use of clean energy had a beneficial effect on the environmental sustainability of the BRICS blocks. Through the use of modern technology and inclusive growth in finances, this evaluation underscored the importance of the diverse elements influencing environmental sustainability in the BRICS region. In order to ensure ecological viability, the paper advocates the adoption of fresh political approaches that support sustainable growth in GDP and AI technology adoption. In the end, this research provides a basis for informed decisions aimed at improving environmental preservation and the implementation of green energy techniques, thereby increasing resilience and prosperity in this region.

This study's findings highlight several policy suggestions for the BRICS countries as they navigate the complicated link between economic growth, geopolitical risks, and environmental sustainability. It is important to recognize the strong association between GDP and CO2 emissions, which highlights the necessity for implementing policies that separate economic growth from carbon emissions. This could include encouraging the adoption of green technologies, enhancing energy efficiency, and advocating for environmental friendly industrial practices. Given the negative effects of geopolitical risks on CO2 emissions, it is critical for BRICS policymakers to prioritize diplomatic engagement and conflict resolution in order to promote geopolitical stability. Additionally, they should focus on implementing domestic policies that address the environmental consequences of these risks. In addition, the research deploys the requirement of AI innovation in addressing carbon emissions. It recommends that BRICS governments focus on investing in AI-driven solutions to optimize energy usage and minimize environmental impact in different industries. Moreover, the significant influence of accessibility in finances on decreasing CO2 pollutions indicates that by increasing access to financial services, more individuals can engage in environmentally conscious investments and embrace sustainable behaviors. This is especially crucial for marginalized communities. Policies that promote financial literacy, microfinance, and digital banking can have a significant impact on fostering an inclusive green economy. The significant decrease in CO2 emissions linked to the use of renewable energy emphasizes the urgency for BRICS nations to foster their shift to sustainable energy resources. This may include the consideration of enhanced subsidies for renewable energy projects, the implementation of more stringent regulations on fossil fuel consumption, and the allocation of resources towards the development of infrastructure that facilitates the seamless integration of renewable energy into national grids. Furthermore, the validation of these findings using rigorous econometric techniques indicates that these policy measures are not only effective, but also able to withstand various economic conditions and political landscapes. By embracing a comprehensive approach that incorporates these valuable insights, BRICS countries have the potential to successfully tackle the intertwined issues of maintaining economic growth and mitigating climate change. This can be used as a model for other nations to emulate on a global scale. It is crucial for BRICS policymakers to work together, think creatively, and put these strategies into action to secure a stable and strong future for their economies and the global environment.

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