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Unlocking Climate Mitigation in BRICS: The Role of Economic and Technological Drivers

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A R T I C L E I N F O

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A B S T R A C T

The study employed Autoregressive Distributed Lag (ARDL) modeling to examine the dynamic relationship between carbon emissions and various economic and environmental factors. It assessed short- and long-term environmental impacts through variables such as agriculture, energy consumption, financial development, forestry, economic growth, and information and communication technology (ICT). The analysis utilized a panel data set covering the period from 1991 to 2022 for BRICS economies. The findings revealed a strong persistence of emissions and significant short-term adjustments toward a long-run equilibrium. Energy consumption is identified as the primary driver of environmental degradation in both time frames, highlighting a structural reliance on energy-intensive manufacturing processes. In the short term, agriculture and forestry contribute to reducing emissions, whereas financial development increases environmental pressure. Economic growth and ICT appeared to have minimal direct effects. Long-term analyses indicated that while agriculture and energy consumption contribute to rising emissions, forestry conservation and technological advancements positively impact the environment. The long-term effects of financial development and GDP are found to be negligible. The error correction process confirmed a gradual convergence toward equilibrium, albeit with a slow adjustment rate. Diagnostics indicated model stability, despite issues such as heteroscedasticity and non-normal residuals. To effectively reduce emissions and stabilize the climate, a combination of economic and environmental strategies is essential.

Introduction

Changes in the climate around the world can't be ignored or left out. The fact is that climate change is happening, and we will be ready for the bad effects of big changes in the climate because these changes are making natural disasters happen more often. Global warming, changing weather patterns, heavy monsoons, sudden rain, fast urbanization, pollution, and industrialization, food losses due to drought, and rising water levels in rivers caused by melting glaciers are all examples of climate change. Flash floods are one of the effects of climate change. Climate change affects both human society and the natural environment. According to IPCC (2007) climate change is weather changes. Climate changes are not suitable for humanity as well as other living things on the earth. (Adams et al., 1990, Adams et al., 1993). Long-term changes in temperature and weather patterns are also referred to as climate change. While these changes may occur naturally, human activity has been the primary cause since the 1800s, mostly as a result of the combustion of fossil fuels. (Takle & Hofstrand, 2008).

The "United Nations Framework Convention on Climate Change" (2007) said that the most important changes in the climate are due to global warming (warming of the Earth's normal temperature), which causes heat waves, wild fires, high temperatures, and droughts. As glaciers melt, the water level in rivers rises. Storms happen with more force at most of the times. It also seen that the oceans are getting warmer and more acidic due to constantly taking in Carbon dioxide (CO_2) and heat from the air. As a climate change effect, air pollution is dangerous and not good for humanity. In in emerging economies most of the environmental and social problems have been correlated with Carbon Emission. These problems are also including rapid population growth, heavy traffic, and the burning of fuel and energy. These are the main causes of air pollution and noise pollution. Polluted air can cut a person's life by about five years. (Shafiq et al 2014).

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The effects of climate change, which are becoming more and more perceptible, are very clear. The frequency and intensity of major natural disasters have increased. Due to this, global temperature is still rising. Long-term effects of climate change will be felt by society and the economy. Individual businesses and people have persisted in their economic endeavors without giving the effects of greenhouse gas emissions on climate change more importance. As a result, both society and the economy are emitting too much greenhouse gases. (IFF, 2021).

The term "climate finance" describes the financial mechanisms and resources utilized to support climate change action. Due to the significant financial outlays required to move towards a low-Carbon global economy and to support societal resilience and adaptation to climate change's effects. Climate finance is essential to combating the issue of climate change. There are various sources of climate funding, including public and private, national and international, bilateral and multilateral. It may use a variety of tools, including gifts and grants, green bonds, stocks, debt swaps, guarantees, and loans with favorable terms. Additionally, it can be applied to a variety of tasks, such as resilience-building, adaptation, and mitigation.

We live in a time of great technological change. Technology is making life better in almost every area. Technologies improve the abilities and functions of the things we do every day, helping people in the best way possible. We use the newest technology in many areas of our daily lives, such as buying, school, healthcare, sports, banking, the stock market, public services, travel, supplies, and even managing crises and emergencies. Our phones have the same amount of computing power that was used to send Neil Armstrong to the moon. Annika S (2013) said that many technologies that help people, computers and telecommunications are the most common and widely used ones in these days. These tools are included computers, the Internet, e-mail, cell phones, and fax machines. ICT is a new technology that is quickly becoming the most famous, fastest-growing, and widely used in almost every aspect of human life (Ogbomo and Ogbomo, 2008). It's importance not to forget how quickly Information and Communication Technology (ICT) and Mobile Technology (MT) are changing and growing. Faster uptake of MT is opening up chances to offer a wide range of useful services through mobile devices. (Sheng et al., 2005).

A significant determinant of agricultural production is the climate. The importance of agriculture to human wellbeing is vital, and many organizations, as well as others, have voiced worry about the possible consequences of climate change on agricultural output. Over the past ten years, a significant amount of research on agriculture and climate change has been driven by interest in this topic. Climate change is predicted to affect input supply, hydrologic balances, livestock and agricultural productivity, and other aspects of agricultural systems.

This study contributes to the existing literature in following three impacts. Firstly, the past researchers left this area and focused on higher economies. There is not much detailed data from expanding economies like BRICS, where fast industrialization and structural change have a big impact on the relationship between the economy and the environment. Secondly previous studies often analyze discrete relationships such as ICT–energy, finance–environment, or agriculture–emissions rather than synthesizing these essential economic, technical, and environmental factors into a cohesive analytical framework. Lastly, methodological constraints persist, since several research depend on static or single-equation models that do not adequately represent dynamic changes and long-term equilibrium connections. Consequently, this work fills these gaps by using a panel ARDL methodology to concurrently examine the short- and long-term impacts of economic, technical, and environmental variables on carbon emissions among BRICS countries.

Review of Literature

A lot of study has been done on how agriculture can adjust to climate change. The main topics of discussion are how farmers see climate change (Apata, Samuel, & Adeola, 2009; Deressa, Hassan, & Ringler, 2011; Mertz, Mbow, Reenberg, & Diouf, 2009; Vedwan, 2006), how to measure the effects of climate change (Benhin, 2008; Kurukulasuriya & Rosenthal, 2013; Misra, 2013), how to adapt to climate change (Binternagel et al., 2010; Conway & Schipper, 2011; Esham & Garforth, 2013; Moradi, Koocheki, Mahallati, & Mansoori, 2013), and what makes it hard for farmers to adapt (Below et al., 2012; Bryan, Deressa, Gbetibouo, & Ringler, 2009; Hassan & Nhemachena, 2008). There are different ways that each theme adds to the study on how to adjust to climate change, but their main goal is to share what they know about climate change and adaptation with other researchers and come up with useful and effective ways for farmers to adapt.

Many studies have been done on these important topics, especially on the factors that help and hurt farmers' ability to adapt in various settings and regions, mainly in developing nations (Arbuckle, Morton, & Hobbs, 2013; Below et al., 2012; Dang, Li, Nuberg, & Bruwer, 2014; Deressa et al., 2011; Esham & Garforth, 2013; Hisali, Birungi, & Buyinza, 2011). Many things were said to be stopping farmers from adapting and affecting their ability to do so. Ones that can cause this are farmers' ideas about climate change (Gbetibouo, 2009; Patt & Schröter, 2008; Vedwan & Rhoades, 2001); racial and socioeconomic factors (Deressa et al., 2009;

Hisali et al., 2011); lack of resources and information (Bryan et al., 2009; Vincent, 2007; Wall & Marzall, 2006); faith in the reality of climate change (Blennow & Persson, 2009; Heath & Gifford, 2006); changes in the economy and the market (Adger, 1999); and psychological factors (Grothmann & Patt, 2005; Grothmann & Reusswig, 2006; Osberghaus, Finkel, & Pohl, 2010). Related empirical studies may be categorized into two research strands. The first strand examines the nexus between ICT adoption, energy/electricity consumption, and economic growth. Perspectives adopted based on empirical studies regarding ICT-energy issues differ. It is believed that ICT investment will raise productivity, boost economic growth, and reduce energy intensity (Coroama et al. 2013; Moyer and Hughes 2012; Erdmann and Hilty 2010).

Those studies argued that ICT does not hurt the environment and further urged that ICT can even moderate global climate change. Shahiduzzaman and Alam (2014), Coroama et al. (2013), Ishida (2015) among others found that ICT upgrades production technology and reduces energy intensity. Those studies approved of ICT usage and investment help to save energy and reduce CO2 emissions. Such evidence supports policies where governments invest in ICT. However, some studies found that ICT leads to heavy pressure on electrical demands or energy consumption. The opposite results can be found for the ICT–energy nexus (Sadorsky 2012; Hamdi et al. 2014). The second strand of research examines the ICT, energy consumption, economic growth, CO2 emissions, and the other important explanatory variables. Moreover, ICT use may increase energy consumption and economic growth simultaneously (Lee and Brahmasrene 2014; Sadorsky 2012). The second strand focuses on the disadvantages of ICT usage. This perspective is concerned that increased ICT usage could reduce the demand for labor and raise labor productivity, while also increasing energy demand and consumption. The previous empirical results still remained mixed, likely derived from different countries (regions), different time periods, and econometric methods. The econometric methods used for traditional research is based on the environmental (Kuznets) hypothesis, whereas different time-series techniques such as the error correction model (ECM), autoregressive Distributive lag (ARDL), panel cointegration, and Granger causality may be used to test whether a hypothesis holds or not. Salahuddin et al. (2016b) considered putting financial development

The literature on the relationship between the environment and the economy is complicated and sometimes contradictory, therefore it needs a more unified way of looking at things. The Environmental Kuznets Curve (EKC) theory says that emissions go up as wealth goes up, but they go down after a certain point. This idea is the basis for a lot of study. Grossman and Krueger (1995) endorse the EKC hypothesis; nevertheless, subsequent research remains inconclusive, particularly in emerging nations where structural transformation and energy dependence alter this relationship. Previous studies on financial development provide inconsistent findings. Acheampong (2019) and Shahbaz et al. (2016) asserted that financial development might exacerbate environmental degradation by facilitating industrial growth and energy use. Other studies suggest that advanced financial systems might enhance green investment and technology, therefore benefiting the environment. This difference shows how important it is to separate short-term and long-term effects, which earlier research had not done.

The importance of ICT in environmental sustainability remains ambiguous both empirically and philosophically. According to Coroama et al. (2013) and Malmodin & Lundén (2018), ICT makes things more efficient, decreases transaction costs, and uses less energy. But digitization might lead to more power demand and pollution (Sadorsky, 2012). These conflicting perspectives illustrate the effects of scale, methodology, and composition, which are essential to environmental economic theory but insufficiently reflected in empirical models. The links between agriculture and the environment show how complicated this is. Using fertilizers, machines, and changing how land is used all add to greenhouse gas emissions (Pant, 2009). However, carbon confiscation and sustainable land management may help lower these emissions. A lot of research treats agriculture as a static thing, yet it really changes from low- to high-intensity production systems. There are not many studies that look at the connections between economic growth, energy use, financial development, ICT, agriculture, and forestry. Dynamic modeling techniques that distinguish between short-term fluctuations and long-term structural connections have garnered little attention. By including many factors into a panel ARDL framework, this study provides a more comprehensive and theoretically grounded analysis of climate mitigation in BRICS nations.

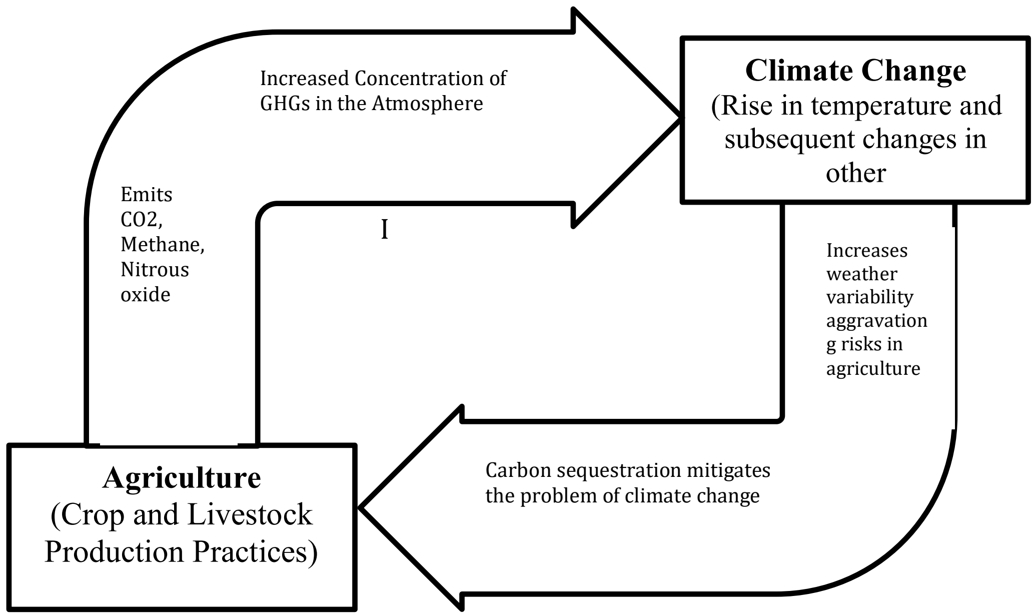
Material and Method

Conceptual Framework

Agriculture releases greenhouse gases (GHGs) and may also hold them in. Carbon dioxide, methane, and nitrous oxide are the main gases that come from farming. The number of places where these gasses come from and go to depends on how land is used and how soils, crops, manures, animals, and energy are managed. Most of the Carbon dioxide that farms release comes from using fuel to heat buildings and equipment, heavy tillage, and summer fallow when the organic matter in the soil is breaking down. The main sources of methane emissions on farms include enteric fermentation from ruminant animals like cows, sheep, and goats, anaerobic respiration of organisms in riparian environments, and manure storage systems such stored solid or liquid storage (Takle and Hofstrand, 2008). The main causes of nitrous oxide emissions on farms include also things like managing nitrogen in the soil, such as by using moist soils with nitrogen-fixing plants like alfalfa or pulses, and applying manure and nitrogenous fertilizers.

Agriculture makes climate change worse by releasing various greenhouse gases, but it is also impacted by climate change. On the other side, it provides a means for sequestering these gases from the atmosphere, so partially alleviating the issue of climate change.

Figure 1: Inter-linkages between agriculture and climate change (Pant, K,P, 2009)



Empirical Model

In this study we tried to explore the impact of economic growth (GDP), Information and Communication Technology (ICT), Foreign Direct Investment (Finance), Energy Consumption (EC), Agriculture and Forestry over the Carbon Emission (CO_2) that is proxy variable for climate change mitigation and environmental sustainability in BRICS region (Sadorsky, 2010; Shahbaz et al., 2016).

The following is functional for of the said relationships:

$$CO_2 = f\,(GDP, HEG, HCE, FIN, IEI, ICT, Fer, For) \qquad (1)$$

Whereas,

CO_2 = Carbon Emission GDP = Gross Domestic Production

FIN = Foreign Direct Investment EC = Energy Consumption

ICT = Information and Communication Technology Fer = Use of Fertilizer in Agriculture Sector

For = Forest Area of total Land of the Country

The Empirical model is:

$$CO_2t = \beta 0 + \beta_1 GDPt + \beta_2 FINt + \beta_3 ECt + \beta_4 ICTt + \beta_5 FERt + \beta_6 FORt + \in t$$

The Panel Autoregressive Distributive Lag model incorporates both lagged dependent and independent variables to capture dynamic relationships across time and cross-sections (Pesaran et al., 2001; Engle & Granger, 1987).

$$CO2_{i,t} = \alpha_i + \sum_{j=1}^{p} \lambda_j\, CO2_{i,t-j} + \sum_{j=0}^{q_1} \beta_{1j}\, GDP_{i,t-j} + \sum_{j=0}^{q_2} \beta_{2j}\, FIN_{i,t-j} + \sum_{j=0}^{q_3} \beta_{3j}\, EC_{i,t-j} + \sum_{j=0}^{q_4} \beta_{4j}\, ICT_{i,t-j} + \sum_{j=0}^{q_5} \beta_{5j}\, FER_{i,t-j} + \sum_{j=0}^{q_6} \beta_{6j}\, FOR_{i,t-j} + \varepsilon_{i,t} \qquad (2)$$

Whereas,

- i= cross-section (countries)
- p= lag of dependent variable
- α_i= country-specific fixed effects
- t= time period
- $q_1 \ldots q_6$= lags of regressors

Panel ARDL Error Correction Representation (ECM Form)

The Error Correction Model captures both short-run dynamics and long-run equilibrium (Banerjee et al., 1998).

$$\Delta CO2_{i,t} = \phi_i(CO2_{i,t-1} - \theta_1 GDP_{i,t-1} - \theta_2 FIN_{i,t-1} - \theta_3 EC_{i,t-1} - \theta_4 ICT_{i,t-1} - \theta_5 FER_{i,t-1} - \theta_6 FOR_{i,t-1}) \quad (3)$$

$$+\sum_{j=1}^{p-1}\gamma_j\,\Delta CO2_{i,t-j} + \sum_{j=0}^{q_1-1}\delta_{1j}\,\Delta GDP_{i,t-j} + \sum_{j=0}^{q_2-1}\delta_{2j}\,\Delta FIN_{i,t-j} + \sum_{j=0}^{q_3-1}\delta_{3j}\,\Delta EC_{i,t-j} \quad (4)$$

$$+\sum_{j=0}^{q_4-1}\delta_{4j}\,\Delta ICT_{i,t-j} + \sum_{j=0}^{q_5-1}\delta_{5j}\,\Delta FER_{i,t-j} + \sum_{j=0}^{q_6-1}\delta_{6j}\,\Delta FOR_{i,t-j} + \mu_{i,t} \quad (5)$$

Data

We used data from 1991 to 2022 for the empirical study. CO_2 emissions per capita (CO2), Internet users per 100 population (ICT), GDP per capita (GDP), the financial development index (FDI) (World Bank, 2023), and energy consumption (EC) are taken from the World Bank's development indicators. CO2 emissions per capita (CO_2) was calculated to be one million tons of Carbon dioxide per capita. The Internet index is computed by means of a weight average of fixed-telephone (landline) subscriptions per 100 inhabitants, Internet users per 100 population, and mobile cellular subscriptions per 100 population (ITU, 2019). GDP per capita (GDP) is measured using per capita real GDP data in constant 2000 U.S. dollars.

Results and Analysis

This section presents and discusses the empirical findings of the study on Unlocking Climate Mitigation in BRICS: The Role of Economic and Technological Drivers. It provides a detailed interpretation of the econometric results in relation to the study's objectives and underlying theoretical framework. The analysis focuses on examining both short-run and long-run relationships among the selected economic, technological, and environmental variables influencing climate mitigation outcomes in BRICS economies. The discussion further connects the statistical evidence with existing literature, highlighting consistencies, deviations, and possible explanations for the observed relationships. Overall, this section aims to provide a comprehensive understanding of how economic growth, technological advancement, and policy-related factors contribute to climate mitigation efforts within the BRICS bloc.

Table: 1 Panel Unit Root Test

Variable	Levin, Lin & Chu	ADF - Fisher Chi-square	PP - Fisher Chi-square	Stationarity Level
Carbon Emission	-7.0913 (0.000)	80.891 (0.000)	80.5130 (0.000)	I (1)
Energy Consumption	-3.8218 (0.000)	48.8674 (0.000)	65.5216 (0.000)	I (1)
Finance	-1.5613 (0.573)	19.9545 (0.029)	21.2817 (0.019)	I (0)
Forestry	0.1846 (0.573)	270.288 (0.000)	270.308 (0.000)	I (1)
Gross Domestic Production	-2.9776 (0.0015)	35.1375 (0.000)	35.1488 (0.000)	I (0)
Information and Communication Technology	-2.8433 (0.0022)	26.0458 (0.0037)	65.4650 (0.000)	I (1)
Agriculture	0.7813 (0.7827)	17.8481 (0.057)	33.1652 (0.000)	I (0)

Panel Unit Root Test

Stationarity of all variables are showed in table 1 using panel unit root tests to assure panel data estimate reliability. Non-stationary series may yield false regression results, therefore understanding the sequence of integration before model estimate is crucial. Levin, Lin & Chu (LLC) (Levin et al., 2002; Im et al., 2003), ADF–Fisher Chi-square, and PP–Fisher Chi-square tests were used for panel unit root. Fisher-type tests aggregate individual unit root statistics and accept panel member heterogeneity, whereas the LLC test assumes a consistent unit root process across cross-sections. A 5% significance threshold was used. The coefficient values of all test are shown in above table.

After differentiating, Carbon emissions become stagnant. Significant p-values ($p < 0.01$) in all three tests indicate that the variable is integrated of order one, I(1). Energy consumption shows first-difference stationarity with substantial statistical significance across LLC, ADF–Fisher, and PP–Fisher tests. LLC tests provide mixed evidence for finance, which is statistically insignificant. However, both Fisher-type tests show 5% significance. In heterogeneous panels, Fisher tests are more flexible, thus finance is stationary at level and integrated of order zero, I(0).

Forestry is insignificant in the LLC test but significant in both Fisher tests. Non-stationarity at level with stationarity after initial differencing supports order one integration.

All three level form tests show statistical significance for GDP, indicating its stationary status. Thus, it is I(0). Information & Communication Technology shows statistically significant results in all tests, demonstrating stationarity following order one differencing and integration. Agriculture has minor LLC and moderate ADF–Fisher findings, while the PP–Fisher statistic is very significant. The variable is stationary at level and integrated of order zero based on the evidence. Overall, the panel has I(0) and I(1) variables. Finance, GDP, and agriculture are level-stationary, but Carbon emissions, energy consumption, forestry, and ICT become stationary after differencing. A prerequisite for advanced panel estimation is that no variable is incorporated of order two.

Mixtures of integration orders justify panel ARDL modeling and panel cointegration, which include both I(0) and I(1) variables in a single estimating framework.

Table 2: Autoregressive Distributed Lag (ARDL) Estimation Results

Regressor	Coefficient	Standard Error	T-Ratio	Probability
CO_2 (-1)	0.9767	0.02442	39.996	[0.000]
Agriculture	0.0021	0.542E-3	3.829	[0.000]
Agriculture (-1)	0.0023	0.547E-3	4.224	[0.000]
Energy Consumption	0.0024	0.813E-2	29.103	[0.000]
EC (-1)	-0.0023	0.109E	20.993	[0.000]
Finance	0.0273	0.0140	1.943	[0.005]
Forestry	-0.068	0.0138	-4.883	[0.000]
For (-1)	0.0642	-0.014	4.572	[0.000]
GDP	0.0040	0.004	0.926	[0.356]
ICT	-0.4915	0.355E-3	-1.383	[0.169]
R-Squar	**0.96**	**Adjusted R^2**	**0.95**	
DW-Stat	**2.23**			

Autoregressive Distributive Lag Estimation

Table 2 illustrated the result of short turn of Autoregressive Distributive lag Model. It showed that Agriculture, Energy consumption, financial supports, Forestry is highly significant on Carbon emission proxy of climate change mitigation for BRICS economies. We use Fertilizer usage in agriculture sector. It means that an increase in fertilizer usage in agriculture sector results increase in Carbon emission. 1 percent increase in fertilizer will increase 0.0021 percent increase in Carbon emission. (Pant, KP, 2009). In the same way Energy consumption has also positive impact on CO_2 emission which meant that when the consumption of energy enhanced. The financial support has positive and significant impact on Carbon emission as increase in finance in industrial sector may cause high emission rate (Acheampong, 2019.

Forestry has negative impact on Carbon emission. When the area of forestry increase it reduces the level GHSs, and Carbon dioxide in the atmosphere. One percent increase in forestry may decrease 0.068 percent in Carbon emission. GDP (Pan et al., 2011). and ICT have 0.0042 and -0.4915 percent impact on Carbon emission. The R square has very value 0.96 and adjusted R Square 0.95. which means that 95% effect had been capture in this model.

The Autoregressive Distributive Lag (ARDL) short-run estimate shows how Carbon emissions (CO_2) change over time and how they are related to important factors like GDP, ICT, farmland, energy use, finance, forests, and energy usage. The lagged dependent variable $CO_2(-1)$ has a value of 0.9767, which is very high and shows that emissions have stayed high over time. This means that past levels of Carbon emissions have a big effect on current levels, and that changes that bring things back into balance happen slowly.

In the short term, agriculture has a mixed effect on pollution. The current-period index is negative and statistically significant, which means that farming originally lowers CO2 emissions. The lagged agriculture term, on the other hand, is positive and important, which suggests that the growth of agriculture may lead to higher emissions after a certain amount of time. This trend might show the environmental trade-off between environmentally friendly methods and actions that produce a lot of pollution, like using machines, applying fertilizer, and changing the use of land. In the short term, using more energy has a strong and statistically significant positive effect. This means that using more energy causes more Carbon pollution. The lag energy term is negative and important, which points to a way for some corrections to happen over time. This finding shows that fossil fuels are still the most common source of energy, even though energy economy has been slowly getting better over time.

The index for financial development is positive and large, which means that growth in the financial industry raises pollution in the short term. This connection might happen because improving finances leads to more manufacturing, building of infrastructure, and energy needs. In the short term, forestry is good for the environment because its present coefficient is negative and important, which means it reduces emissions by storing corban. The lagging forestry term, on the other hand, is positive and important, which means that cycles of destruction or using forest resources for profit may undo gains over time.

The fact that GDP has a positive but statistically insignificant value means that economic growth does not have a big effect on emissions in the short term. In the same way, ICT has a negative but not very important coefficient, which means that digitization and technology progress do not immediately help the environment in the short term.

An R-squared of 0.96 and an adjusted R-squared of 0.95 showed that the model is very good in explaining the determinants of Carbon Emission. The Durbin–Watson test showed value of 2.23 employed that there isn't any major autocorrelation, which means that the values are accurate.

Table 3 Diagnostic Test

	Test Applicable	CHSQ	Prob
Serial Correlation	Langrage Multiplier	2.7492	[0.109]
Functional Form	Ramsay's RESET	0.2559	[0.626]
Normality	Test of Skewness & Kurtosis	215.022	[0.000]
Heteroscedasticity	White Test	8.0447	[0.005]

Diagnostic tests show in table 3 that the predicted model is reliable and good enough. The Breusch–Godfrey Lagrange Multiplier test for serial correlation returns an insignificant chance value. This means that there is no evidence of autocorrelation in the residuals, which means that the mistakes are independent. Ramsey's RESET test for functional form also gives an insignificant chance value, which means the model is properly set up and doesn't have any missing variable bias (White, 1980; Gujarati & Porter, 2009).

The normality test using skewness and kurtosis, on the other hand, shows that the residuals are not Distributive normally. This problem might happen because of errors or changes in the structure of the information, but it doesn't lead to bias in large groups. The White test for heteroscedasticity gives a significant chance value, which proves that error variance is not constant. This shows that heteroscedasticity is present and that strong standard errors are needed to make sure that reasoning works well (White, 1980; Gujarati & Porter, 2009).

Table 4 Estimated Long Run Coefficient, Using the ARDL Approach

Variable	Coefficient	Standard Error	Probabilities
Agriculture	0.010194	.013503	[0.045]
Energy Consumption	0.0033067	.0011179	[0.004]
Finance	1.1729	1.3054	[0.370]
Forestry	-0.15335	.14380	[0.028]
GDP	0.17022	.21118	[0.421]
ICT	-0.021086	.028881	[0.046]

The equilibrium relationships among the variables are revealed by the long-term ARDL results (table 4). The coefficient of agriculture is statistically significant and positive, suggesting that the long-term increase in Carbon emissions is due to agricultural expansion. This implies that environmental quality is subjected to sustained pressure as a result of structural agricultural growth. Energy consumption also exhibits a positive and highly significant long-term impact on emissions, thereby affirming that the continued reliance on fossil-fuel energy is a significant contributor to environmental degradation. The coefficient of financial development is positive, but it is statistically insignificant, suggesting that finance does not independently influence long-term emission levels. The significance of forest conservation and afforestation in mitigating emissions is underscored by the negative and substantial long-run coefficient of forestry. The coefficient of GDP is positive but insignificant, indicating that environmental quality is not inherently deteriorated by economic growth alone. ICT exhibits a statistically significant negative coefficient, suggesting that technological advancements lead to increased energy efficiency and a decrease in Carbon intensity over time.

Table 5 Estimated Error Correction Mechanism, Using the ARDL Approach

Variable	Coefficient	Standard Error	Probabilities
dAgriculture	-0.0020765	0.5423E-3	[0.000]
dEnergy Consumption	0.0023677	0.8136E-4	[0.000]
dFinance	0.027339	0.014075	[0.054]
dForestry	-0.067860	0.013898	[0.000]
dGDP	0.0039677	0.004282	[0.356]
dICT	-.4915E-3	0.3554E-3	[0.169]
Ecm (-1)	-.023309	0.024420	[0.341]

The Error Correction Model elucidates the short-term adjustments that are made in order to achieve long-term equilibrium (table 5). The short-term environmental benefits are confirmed by the negative and significant impact of changes in agriculture on emissions. The energy-environment nexus is reinforced by the positive and significant increase in emissions that results from changes in energy consumption. Financial development exhibits a positive and marginally significant short-term impact, indicating that financial expansion contributes to environmental pressure. (Engle & Granger, 1987)

The environmental function of forestry is reaffirmed by the substantial reduction in emissions that results from changes in forestry. The short-term growth–emissions link is limited, as GDP changes are insignificant. Additionally, the insignificance of ICT changes implies that digital transformation generates progressive environmental advantages rather than immediate ones. The error correction term is negative, suggesting that the system is approaching long-term equilibrium. Nevertheless, its statistical insignificance implies a delayed rate of adjustment, indicating that deviations from equilibrium are corrected gradually.

Conclusions and Implications

The study examined the dynamic interaction between environmental quality and its principal variables using the ARDL and Error Correction modeling methodology. The results validate the existence of significant short-term adaptations in conjunction with long-term equilibrium connections. Short-term findings suggest that agricultural practices enhance environmental quality, however energy use continues to be a primary factor in emissions, hence strengthening the energy-environment relationship. Financial development imposes short-term upward pressure on emissions, reflecting the environmental costs associated with investment-driven economic growth. Conversely, forestry serves a crucial mitigating function, underscoring the need of forest protection and sustainable land-use management.

The long-term estimates indicate that structural determinants influence environmental outcomes variably over time. Ongoing dependence on energy-intensive manufacturing exacerbates emissions, whereas forestry and technological innovation promote environmental sustainability. Economic growth alone does not seem to be a critical factor influencing emissions, indicating that the kind and quality of growth are more significant than its magnitude. ICT-induced efficiency improvements illustrate that digital transformation fosters sustainable industrial systems over the long run.

The negative sign of the error correction term indicates convergence to equilibrium; nonetheless, the gradual and statistically insignificant adjustment speed implies that environmental stability requires enduring policy commitment. Diagnostic tests confirm the model's overall strength; nonetheless, heteroscedasticity and non-normality underscore the need for robust estimate methods. The findings highlight the significance of cohesive environmental plans that amalgamate clean energy transition, sustainable farming practices, financial sector greening, forestry conservation, and digital transformation. Coordinated policy frameworks are crucial for attaining long-term emission reduction and sustainable development goals.

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Appendix

Table: 1 Panel Unit Root Test

Variable	Levin, Lin & Chu	ADF - Fisher Chi-square	PP - Fisher Chi-square	Stationarity Level
Carbon Emission	-7.0913 (0.000)	80.891 (0.000)	80.5130 (0.000)	I (1)
Energy Consumption	-3.8218 (0.000)	48.8674 (0.000)	65.5216 (0.000)	I (1)
Finance	-1.5613 (0.573)	19.9545 (0.029)	21.2817 (0.019)	I (0)
Forestry	0.1846 (0.573)	270.288 (0.000)	270.308 (0.000)	I (1)
Gross Domestic Production	-2.9776 (0.0015)	35.1375 (0.000)	35.1488 (0.000)	I (0)
Information and Communication Technology	-2.8433 (0.0022)	26.0458 (0.0037)	65.4650 (0.000)	I (1)
Agriculture	0.7813 (0.7827)	17.8481 (0.057)	33.1652 (0.000)	I (0)

Table 2: Autoregressive Distributed Lag (ARDL) Estimation Results

Regressor	Coefficient	Standard Error	T-Ratio	Probability
CO_2 (-1)	0.9767	0.02442	39.996	[0.000]
Agriculture	0.0021	0.542E-3	3.829	[0.000]
Agriculture (-1)	0.0023	0.547E-3	4.224	[0.000]
Energy Consumption	0.0024	0.813E-2	29.103	[0.000]
EC (-1)	-0.0023	0.109E	20.993	[0.000]
Finance	0.0273	0.0140	1.943	[0.005]
Forestry	-0.068	0.0138	-4.883	[0.000]
For (-1)	0.0642	-0.014	4.572	[0.000]
GDP	0.0040	0.004	0.926	[0.356]
ICT	-0.4915	0.355E-3	-1.383	[0.169]
R-Squar	**0.96**	**Adjusted R^2**	**0.95**	
DW-Stat	**2.23**			

Table 3 Diagnostic Test

	Test Applicable	CHSQ	Prob
Serial Correlation	Langrage Multiplier	2.7492	[0.109]
Functional Form	Ramsay's RESET	0.2559	[0.626]
Normality	Test of Skewness & Kurtosis	215.022	[0.000]
Heteroscedasticity	White Test	8.0447	[0.005]

Table 4 Estimated Long Run Coefficient, Using the ARDL Approach

Variable	Coefficient	Standard Error	Probabilities
Agriculture	0.010194	.013503	[0.045]
Energy Consumption	0.0033067	.0011179	[0.004]
Finance	1.1729	1.3054	[0.370]
Forestry	-0.15335	.14380	[0.028]
GDP	0.17022	.21118	[0.421]
ICT	-0.021086	.028881	[0.046]

Table 5 Estimated Error Correction Mechanism, Using the ARDL Approach

Variable	Coefficient	Standard Error	Probabilities
dAgriculture	-0.0020765	0.5423E-3	[0.000]
dEnergy Consumption	0.0023677	0.8136E-4	[0.000]
dFinance	0.027339	0.014075	[0.054]
dForestry	-0.067860	0.013898	[0.000]
dGDP	0.0039677	0.004282	[0.356]
dICT	-.4915E-3	0.3554E-3	[0.169]
Ecm (-1)	-.023309	0.024420	[0.341]