Economic Dialogue: International Journal of Policy & Practice 01 (2026) 57-85

Contents lists available at

Economic Dialogue: International Journal of Policy & Practice

Journal Homepage: https://journal.vu.edu.pk/EDJ

Evaluating the Role of Green Technology Diffusion on Environmental Quality: PMG-ARDL Evidence from BRICS Economies

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ARTICLE INFORMATION

Keywords:
Green Technology Diffusions, Green Growth, Second Generation Technique, PMG-ARDL, Granger Causality

ABSTRACT

The BRICS countries rank among the top emitters of CO2 and are important contributors to global economic growth. Achieving climate targets while preserving sustainable development requires speeding up the adoption of green technologies due to mounting environmental concerns. Thus, this article scrutinizes the empirical consequences of green technological diffusion on environmental quality in BRICS economies, by employing panel data for the period from 1990 to 2023. Pooled Mean Group ARDL (PMG-ARDL), a 2nd generation panel technique, is utilized to analyze the long plus short-term influence of selected factors of interest on environmental quality. The Granger causality test has been utilized to determine causation among the variables. Empirical evidence confirms that green technology diffusion reduces CO2 emissions significantly in the long run. Further, FDI and Energy prices also help to reduce CO2 emissions and improve environmental quality. Further, Fossil fuels, and industrialization have significantly and positively promoted CO2 emissions in these countries. A collaborative fund should be established by the government to promote research and development in green technologies, including energy-efficient manufacturing, carbon capture and storage (CCS), electric transportation, and renewable energy, according to the study.

1. Introduction

Environmental deterioration has been a major global problem since the 1990s. To motivate economic actors to consider environmental problems, it is imperative that sustainability be incorporated into the economic model. Environmental issues including catastrophic weather events that jeopardize agricultural output levels, biodiversity loss, and the depletion of global resources are all results of the production model that is built on the pursuit of limitless development (Abdulqadir, 2023; Fakher et al., 2023; Abdulqadir, 2022; Asongu et al., 2020; Alam et al., 2007). Significant action on the adoption and usage of new information and communication technologies is a promising way to address this sustainability challenge and guarantee environmental preservation (Ko et al., 2021; Adebayo & Kirikkaleli, 2021). Information and communication technologies

(ICTs) can have a significant impact on environmental protection through a variety of mediating channels. One of them is their ability to drastically change production methods or modes into clean ones through energy savings. Furthermore, it contributes to the enhancement of renewable energy sources, which in turn helps to level the quantity of renewable energy required for future uses. Nevertheless, a significant number of empirical studies challenge this conclusion despite the negative effects of ICTs on carbon emissions (Adebayo & Kirikkaleli, 2021; Raheem et al., 2020; Majeed & Svendsen, 2018; Asongu, 2018; Salahuddin et al., 2016; Lee & Brahmasrene, 2014). In this regard, the creation and dissemination of green technologies serve as a catalyst for social, economic, and environmental pillars and are crucial to accomplishing the 2030 Sustainable Development Goals (SDGs). Green technology adoption necessitates adjustments to the productive structure, which must be backed by financial incentives and socioeconomically relevant governmental measures.

Green technologies include the development and application of equipment, processes, and byproducts that are used to protect the environment. Technology, emission reduction, energy efficiency, and renewable energy technologies are all regarded as components of energy-efficient technology (Du et al., 2019; Hottenrott et al., 2016). The growth requirements of nations should be satisfied by these technologies in a way that allows for gradual transition without necessarily depleting natural resources. Therefore, green technologies are a crucial instrument for attaining sustainable growth, and they also offer a growth opportunity insofar as they ensure that the requirements of current and future generations are met. Green technologies include fewer harmful processes and products, effective use of resources, reusable waste and products, and proper residual waste management (Traore et al., 2023; Traoré, & Asongu, 2023). Innovation in green technologies can lower energy use, lower emissions of pollutants, enhance environmental quality, and encourage the growth of a more environmentally friendly economy (Wang et al., 2021). Green technology encompasses a wide range of industries, including solid waste management, biofuels, eco-forestry, and renewable energy. However, implementing all green technology without considering the institutional framework unique to each nation is neither feasible nor required. Additionally, there is a direct connection between institutions and ICT. The latter is characterized as a collection of customs, shared game rules, norms, or laws that impact interactions and relationships between individuals and groups. They make it possible to put into operation efficient environmental regulations that lower greenhouse gas emissions. Institutions can also help put environmental protection policies that lower carbon emissions into action (Teng et al., 2021; Ibrahiem, 2020).

With their big populations, fast economic growth, and substantial contributions to global emissions and resource consumption, the BRICS countries Brazil, Russia, India, China, and South Africa—are at the forefront of the global environmental agenda. To achieve sustainable development and enhance environmental quality, green technology adoption and dissemination are essential as these economies grow and the environmental challenges they confront increase. The adoption and distribution of eco-friendly technologies, such as sustainable resource management techniques, energy-efficient procedures, renewable energy, and pollution control systems, is referred to as "green technology diffusion." Decoupling economic growth from environmental deterioration is a major problem for emerging economies such as those in the BRICS group, and this diffusion is essential to achieving this goal (Geng et al., 2023). Reduced carbon emissions and improved sustainability are regularly associated with the use of renewable energy technology. While non-renewable energy use worsens environmental impact, renewable energy and green technologies have been shown to improve environmental quality (Shahbaz et al., 2021). Although the development of new green technologies, or technological innovation, generally improves environmental quality, the diffusion or broad use of both green and non-green technologies can have conflicting results. According to some research, if non-renewable or inefficient technologies predominate, technological diffusion may initially worsen environmental consequences unless it is accompanied by robust policy support for green alternatives. Green technology diffusion effectiveness is highly impacted by institutional governance and quality. The beneficial effects of green technology on environmental quality are increased by robust institutions, efficient environmental legislation, and focused expenditures in green R&D (Zia, et al., 2023). Green technology frequently offers non-linear environmental advantages. Significant improvements in environmental metrics like CO_2 emissions and ecological footprint are only observed in BRICS nations when they have passed a specific adoption threshold.

1.1 Problem Statement and Research Gap

The BRICS nations Brazil, Russia, India, China, and South Africa—continue to face serious environmental issues, such as growing pollution, rising greenhouse gas emissions, and ecological degradation, despite their fast industrialization and economic expansion (Zubair, et al 2024; Geng et al, 2023; Rout et al, 2022). Although the spread and adoption of environmentally friendly innovations and practices, or "green technology diffusion," has the potential to lessen these adverse effects, little is known about how effective and widespread it will be in enhancing environmental quality throughout the BRICS region (Zia, et al., 2023; Miranda, et al., 2021). Research already conducted shows that, depending on the type and extent of adoption, the energy mix, and the underlying institutional framework, technological innovation and dissemination can have both positive and negative effects on environmental outcomes. Nonetheless, there are significant gaps in the empirical data about: The precise processes by which the spread of green technologies influences carbon emissions and environmental quality metrics in the BRICS nations. Thus, the primary issue is the dearth of thorough, comparative, and mechanism-focused studies on the ways in which the spread of green technologies affects the BRICS region's environmental quality. Closing this gap is essential to creating investment plans and regulations that can promote environmental preservation and sustainable development in these significantly growing economies. The remainder of the research is structured as follows: Section 2 provides an overview of the literature, the mechanisms underlying the spread of green technologies, and their relationship with institutions; Section 3 explains the data and methodology; Section 4 discusses the findings and debate; and Section 5 concludes the study and offers policy recommendations based on the findings.

2. Literature Reviews

A literature review is a critical evaluation and synthesis of the body of knowledge previously available on a particular topic or research issue in empirical research. It entails gathering, evaluating, and comprehending the key theories, concepts, models, empirical findings, and research methodologies that have been used by previous academics to study the subject at hand. By encouraging resource efficiency, lowering greenhouse gas emissions, and supporting sustainable practices, the spread of green technology is essential to enhancing environmental quality. There is a wealth of literature on this subject that includes case studies, empirical research, and theoretical frameworks from a variety of industries and geographical areas. Sustainable development techniques, which are typically linked to reducing environmental degradation, depend heavily on green environmental technologies. The spread of green technology is impacted by several variables, including market structures, organizational networks, information flow, and behavioral attitudes (Allan, et al. 2014). Serener et al., (2022) and Pei et al., (2019), investigated technological innovation in developed industrialized countries to support the claim that technological advances are crucial to easing ecological pressure in the face of a swift industrial and economic transition. According to Huang et al. (2022), by monitoring major industrial pollutants in China's industrial sector, advancements in green technology infrastructure have helped alleviate ecological problems. Rout et al. (2022) investigated how technological innovations may be applied to urban environment concerns in the BRICS region in order to propose that intelligent and sustainable equipment minimize ecological and environmental problems. Several studies attest to the fact that implementing green technologies, especially those related to waste management, renewable energy, and sustainable transportation, significantly lowers CO2 emissions and other pollutants (Islam, et al., 2024; Traoré, & Asongu, 2023). More use of digital and green technologies is associated with decreased CO2 emissions in Sub-Saharan Africa, according to empirical research employing panel VAR modeling, particularly when backed by robust institutional frameworks (Traoré, & Asongu, 2023). Sulfur dioxide (SO2) and nitrogen oxide levels (NOx) are lower in nations that use more green power and technology (Zhou et al., 2023). Shi et al. (2021) also revealed a direct correlation between GET adoption and lower carbon emissions, while Gao et al. (2022) focused on GET's role in reducing fog-haze pollution. On the other hand, several studies show that while technology advancements boost productivity, they may also inadvertently result in higher energy consumption and environmental harm (Yang et al., 2019). Schmidt & Sewerin (2019) demonstrated that technical developments do not necessarily result in cleaner output and that environmental contamination might rise over time despite them. The adoption of green technology undoubtedly has an impact on the environment and energy use, whether positively or negatively.

H_1 = Green Technology Diffusion significantly reduce CO_2 Emissions and Improve Environmental Quality

3. Theoretical Background

The process by which environmentally friendly innovations are embraced and dispersed throughout many sectors, businesses, and nations is known as "green technology diffusion." With an emphasis on the effects on the environment and the function of institutions and policy, the theoretical underpinnings of this subject are drawn from the larger literature on technology diffusion, environmental economics, and innovation systems. Green technologies include inventions like pollution-control devices, energy-efficient appliances, and renewable energy systems that are intended to help the environment. Numerous factors, including technological advancements, socioeconomic circumstances, and environmental regulations, impact the spread of these technologies. According to studies, countries with better socioeconomic conditions and greater technological advancements likely to see faster adoption of green technologies, which improves environmental consequences (Agan, & Balcilar, 2022). According to the Innovation Diffusion Theory, perceived benefits, compatibility with current systems, and simplicity of use are some of the elements that determine the predictable pattern of new technology adoption. According to the EKC, there is an inverse U-shaped link between environmental degradation and economic development. This means that countries may invest more in environmental protection at greater income levels, which would encourage the use of green technologies. Technology spillover models encourage the spread of green technology across industries by demonstrating how achievements in one field can inspire breakthroughs in others. The dissemination of green technologies, which improve environmental quality, is greatly influenced by aspects including technological accomplishments, income levels, education, and environmental performance, according to a study that examined data from 58 countries. Green technology innovation has been shown to effectively reduce atmospheric pollution in China, with notable spatial spillover effects. This suggests that improvements in one location can have a favorable impact on nearby areas. The importance of strict environmental rules in encouraging the adoption of cleaner energy technologies and improving environmental quality was brought to light by an analysis of environmental policies and global technology diffusion (Zhou, et al., 2023; Verdolini, & Bosetti, 2017). One of the most important factors in improving environmental quality is the spread of green technologies. Societies can hasten the adoption of green technologies and achieve sustainable environmental results by comprehending the factors that affect this dissemination and putting supportive policies into place.

3. Methodological Framework and Data

3.1 Conceptual Framework

The present study offers a conceptual framework based on the foregoing debate in previous literature reviews and theoretical background. Both primary and control variables are included in this approach. Reviews of previous research and theoretical underpinnings serve as the foundation for this approach.

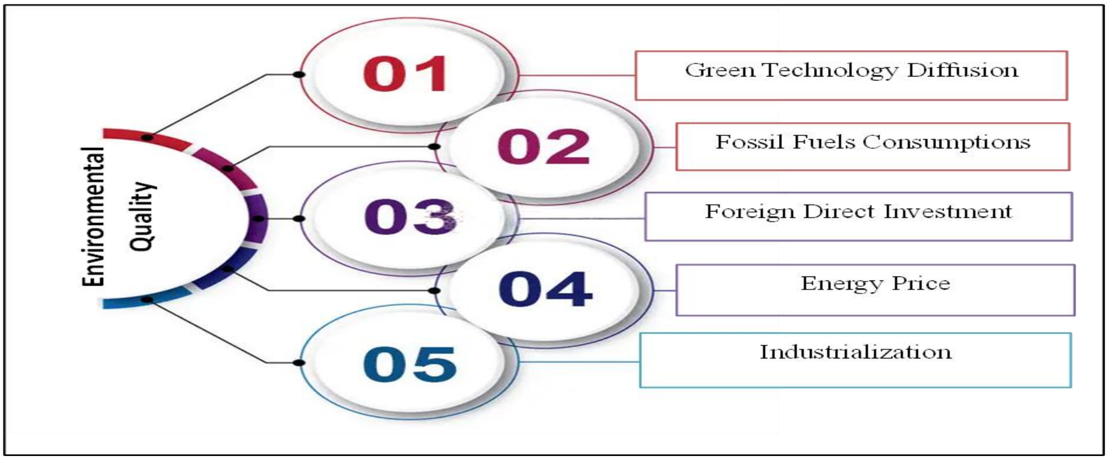

Fig. 1: The Conceptual Framework

3.2 Econometric Model Data Type & Econometric Model

In a panel of BRICS nations from 1990 to 2023, we investigate the long-term relationships between environmental quality and green technology diffusion with other control variables. The research on sustainable environmental issues has found that factors such as national economic growth, financial development, trade openness, energy consumption, and urbanization all have an impact on environmental quality. Previous research has shown that GTI has a major impact on environmental quality. Based on the theoretical and empirical underpinnings, the relationship between environmental quality, the dissemination of green technologies, and other control factors may be stated as follows:

$$LEQ_{it} = f(LGTD_{it}, LFF_{it}, LFDI_{it}, LEP_{it}, LIND_{it}) \quad (1)$$

Where LEQ indicates the log of environmental quality, LGTD is log of green technology diffusion, LFF is the log of fossil fuels, LFDI stand for log of FDI, LEP is log of energy price and LIND is log of industrialization. The model with a logarithmic basis may be expressed in a cross-sectional manner as follows:

$$LEQ_{it} = \beta_0 + \beta_1 LGTD_{it} + \beta_2 LFF_{it} + \beta_3 LFDI_{it} + \beta_4 LEP_{it} + \beta_5 LIND_{it} + € _{it} \quad (2)$$

In the equation, "it" is donated as Time Period and countries, β_0 is constant and β_1,β_2,β_3,β_4, and β_5 are elastic coefficients of each variable. In the last, "€" is Error Term. In order to evaluating the effect of green technology diffusion on environmental quality in case of BRICS countries namely Brazil, Russia, India, China and South Africa., the present study utilized Panel Data from 1990 to 2023. The study compiles data from different sources including Official Website of Worldwide

Development Indicator (WDI) and OECD Database. The data extracted from different secondary sources as mentioned in Table 1 below.

Table 1: Descriptions Variables

Sr. #	Variables	Descriptions	Measurements Unit	Source
1	LEQ	Log of Environmental Quality	CO2 Emissions / Capita	WDI
2	LGTD	Log of Green Technology Diffusion	No. of environmental related technologies	OECD
3	LFF	Log of Fossil Fuels	% of Final Consumption	WDI
4	LFDI	Log of Foreign Direct Investment	Inflow, % of GDP	WDI
5	LEP	Log of Energy Price	Consumer Price Index	WDI
6	LIND	Log of Industrialization	Value Added, % of GDP	WDI

Sources: WDI (2024) and OECD (2024)

The reason of selecting these nations is because of their rapid economic growth and extensive developmental initiatives. The rate of development, expansion, and general socioeconomic change also includes environmental risks such increasing CO_2 emissions among others, endangering the sustainability of the environment and potentially causing health problems, social unrest, and ecological imbalance.

3.3 Empirical Methods of Estimations

The current study also included a number of methods to determine the association between the parameters. To determine if the data was steady, the study used a unit root analysis in the first phase. To ascertain if CSD existed in a panel of BRICS countries, the study also employed the Pesaran Scaled LM and Pesaran CSD tests. Due to the presence of CSD and a combination of mixed order of integration, the study will be able to estimate the long-run panel cointegration link among the selected variables in the model using the second-generation PMG-ARDL econometric approach (Zakari et al., 2021). Additionally, the PMG-ARDL estimator is proven to be successful even with a small sample size, thanks to the ARDL-PMG econometric approach presented by Pesaran et al. (1999). Furthermore, the long-term characteristics align with the standard F-tests and t-distribution (Pesaran et al., 1999). Both short-term and long-term relationships may be found using the ARDL model, which is categorized as an error correction model. This approach is relevant because it may assess any long-term correlations regardless of the integration order of the variables, whether they are I(1) or mutually integrated (I(0) and I(1)), with the caveat that the dependent variable can only be I(1). On the other hand, this approach does not work when the series are integrated of order 2 (I(2)). Additionally, this method eliminates the problems brought on by endogeneity and offers accurate and efficient estimators by including lag time for both endogenous and exogenous variables. According to (Pesaran et al. 1999), the long-term link between variables is included in the ARDL (p, q) model, which looks like this:

$$\Delta Y_{1,it} = \alpha_{1i} + \gamma_{1i} Y_{1it-1} + \sum_{l=2}^{k} \gamma_{1i} X_{1it-1} + \sum_{j=1}^{p-1} \delta_{1ij} \Delta Y_{1it-j} + \sum_{j=0}^{q-1} \sum_{l=2}^{k} \delta_{1ij} \Delta_{1it-j} + \varepsilon_{1it} \quad (3)$$

Where, the DV is Y_l and exogenous variables are denoted as Xl, with l=1, 2, 3, 4, 5. ε_{it} is error term or residual, and "Δ" is the operator of 1st difference. In our model, the PMG-ARDL is prepared as follows:

$$\Delta LEQ_{it} = \alpha_{1it} + \gamma_{1i} LEQ_{it-1} + \gamma_{2i} LGTD_{it-1} + \gamma_{3i} LFF_{it-1} + \gamma_{4i} LFDI_{it-1} + \gamma_{5i} LEP_{it-1} + \gamma_{6i} LLIND_{it-1}$$

$$+ \sum_{j=1}^{p} \delta_{1i} \Delta LEQ_{it-j} + \sum_{j=1}^{p} \delta_{2i} \Delta LGTD_{it-j} + \sum_{j=1}^{p} \delta_{3i} \Delta LFF_{it-j} + \sum_{j=1}^{p} \delta_{4i} \Delta LFDI_{it-j} +$$

$$\sum_{j=1}^{p} \delta_{5i} \Delta LEP_{it-j} + \sum_{j=1}^{p} \delta_{6i} \Delta LIND_{it-j} + \varepsilon_{1it} \quad (4)$$

The AIC and SBC are used to determine the lagged variable to use. Sequentially to testify the survival of long phrase association among selected variables, the use of conventional co-integration tests where variables I(0) plus I(1) are present, as executed by (Pedroni, 2004, 1999, 1995); (Bai & Ng,2001), leftovers inexcusable. The third step involves estimating an error correction method (ECM) in order to determine the short-term dynamic affiliation. The following is the definition of the ECM:

$$\Delta Y_{1it} = \alpha_{1i} + \sum_{j=1}^{p-1} \beta_{1ij} \Delta Y_{1it-j} + \sum_{j=0}^{q-1} \sum_{1=2}^{k} \beta_{1ij} \Delta X_{1it-j} + \mu_{1i} ECT_{1it-1} + \varepsilon_{1it} \quad (5)$$

Where, residuals are independent ϵ_{it} ($l = \{1,2,3,4,5,\}$) and distributed normally with variance constantly and mean is zero and ECTit-1 is the Error Correction Term specifies the relationship in long term. The rate of alteration to the level of equilibrium is indicated by the parameter μ_{it}. In our model of study, the ECM model is structured as follows:

$$\Delta LEQ_{it} = a_{it} + \sum_{j=1}^{p-1} \beta_{1ij} \Delta LQ_{it-j} + \sum_{i=0}^{p-1} \beta_{2ij} \Delta LGTD_{it-j} \sum_{i=0}^{p-1} \beta_{3ij} \Delta LFF_{it-j}$$

$$+\sum_{i=0}^{p-1} \beta_{4ij}\, \Delta LFDI_{it-j} + \sum_{i=0}^{p-1} \beta_{5ij}\, \Delta LEP_{it-j} + \sum_{i=0}^{p-1} \beta_{6ij}\, \Delta LIND_{it-j} + \mu_{it} ECT_{it-1} + \varepsilon_{it} \quad (6)$$

Consistent with (Pesaran et al.,1999), the PMG technique is used to obtain the ARDL estimators and all parameters. Because it takes into consideration individual features and offers a better assessment of the long-term relationship, this estimating process supported on the maximum likelihood technique is thought to be the most reliable. According to (Pesaran et al.,1999), the resulting PMG estimators are asymptotically and normally distributed. Granger causality tests can be used to identify causal relationships (Engle & Granger 1987).

4. Empirical Analysis and Findings

The study starts by running the test of descriptive statistics, which identifies the fundamental characteristics of key variables utilized in the investigation. The outcomes are specified in Table 2 below:

Table 2: Fundamental Characteristics of Variables

	LEQ	LGTD	LFF	LFDI	LEP	LIND
Mean	1.411566	7.298230	4.338274	1.504695	4.271225	3.404967
Median	1.707231	7.229110	4.442593	1.500728	4.452997	3.372056
Maximum	2.801213	13.18714	4.539564	2.519042	5.394260	3.861937
Minimum	-0.364620	1.098612	3.898938	2.00E-06	0.240345	2.900790
Std. Dev	0.909149	1.995498	0.204180	0.331462	0.956666	0.247019
Skewness	-0.230432	0.518044	-0.780370	0.263243	-1.981088	0.317383
Kurtosis	1.663881	4.099290	2.114542	4.447292	7.465267	2.244353
JB Stat	14.14974	16.16359	22.80793	16.80054	252.4319	6.898677
Prob:	0.000846	0.000309	0.000011	0.000225	0.000000	0.031767
Obs.	170	170	170	170	170	170

Source: Author Calculation

The Table 1 depicts the fundamental characteristics of key variables and indicates that LGTD is the highest value of mean with the value of 7.298230 and lowest mean value is 1.411566 of LEQ, and highest median value is 7.229110 of LGTD and lowest median value is 1.500728 of LFDI. Further, table shows the maximum and minimum values of the data and Std.Dev is also given in the table, LGTD is the highest with value of 1.995498 and 0.247019 is lowest of LIND. LEQ, LFF and LFP are negatively skewed because their mean value is less than their median values and LGTD, LFDI and LIND are skewed positively because their mean value is greater than their median. The kurtosis value of LGTD, LFDI and LEP are greater than 3 making them leptokurtic or more peaked and LEQ, LFF and LIND are less than 3 making them platykurtic or flatter. The Jarque-Bera (JB Statistic) test evaluates the Normal Distribution.

4.1 Cross – Sectional Dependence Test

The current study employed the cross-sectional dependence test to determine whether there is cross-sectional reliance among the variables in a panel data set. This test is important in panel data analysis since it can impact the overall efficacy of panel estimate. The table 3 below depicts the findings.

Table 3: Findings of CSD Test

Test	Stat:	d.f	Prob.
Breusch-Pagan LM:	89.80408	10	0.0000
Pesaran Scaled LM:	16.72670		0.0000
Pesaran CD:	-3.405854		0.0198

Source: Author Calculation

Note: Significance Level, *1%, **5% and ***10%

Based on the results in the above table, the study is unable to accept the Null (H0) Hypothesis, which states that there is no CSD, or reject the Alternative (H1) Hypothesis, which states that CSD exists in the E7 economies at various significance levels, such as the 1%, 5%, and 10% levels.

4.2 Unit Root Analysis

To confirm the stationary nature and stability of the variables in panel data, the current study uses the Phillips-Perron (PP) and Augmented Dickey-Fuller (ADF) tests for unit root. The findings are shown in table 4 below.

Table 4: Findings of ADF and PP Unit Root Test

Variables	ADF – Fisher Chi-Square				PP – Fisher Chi-Square				Outcomes
	At Level		1st Difference		At Level		1st Difference		
	Intercept	T&I	Intercept	T&I	Intercept	T&I	Intercept	T&I	
LEQ:	10.436 (0.4031)	10.228 (0.4207)	31.160* (0.00028)	26.813* (0.0006)	8.3757 (0.5922)	4.8384 (0.9017)	67.615* (0.0000)	60.382* (0.0000)	**I(1)**
LGTD:	20.024** (0.0290)	20.646** (0.0237)	63.885* (0.0000)	51.925* (0.0000)	26.954* (0.0026)	22.457** (0.0129)	120.424* (0.0000)	121.556* (0.0000)	**I(0)**
LFF:	16.335	4.7691	46.395*	41.515*	13.834	5.3580	88.095*	97.582*	**I(1)**

	(0.9061)	(0.9041)	(0.0000)	(0.0000)	(0.1807)	(0.8660)	(0.0000)	(0.0000)	
LFDI:	17.632**	22.604**	61.272*	52.178*	28.713*	25.378*	109.155*	460.395*	**I(0)**
	(0.0115)	(0.0123)	(0.0000)	(0.0000)	(0.0014)	(0.0047)	(0.0000)	(0.0000)	
LEP:	29.111*	31.359*	37.962*	42.174*	57.004*	70.343*	41.067*	33.983*	**I(0)**
	(0.0012)	(0.0005)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0002)	
LIND:	17.096	8.4268	53.987*	53.163*	22.979	4.0328	79.955*	101.249*	**I(1)**
	(0.7523)	(0.5872)	(0.0000)	(0.0000)	(0.8108)	(0.9459)	(0.0000)	(0.0000)	

Source: Author Calculation
Note: Significance Level, *1%,**5% and***10%
T&I: Trend & Intercept

The findings of panel unit root tests can be found in the table below. As summarized in the results below. LGTD, LFDI and LEP are stationary at level and intercept because at this point the probability function of these variables is less than (0.05) or 5% and the data are stationary at this point. These data are integrated in the form of I(0). LEQ, LFF and LIND are stationary at 1st difference and intercept because at this point the probability function of these variables is less than (0.05) or 5% and the data are stationary at this point. These results can be seen as follows. Null Hypothesis is rejected, and Alternative Hypothesis is accepted and here we can see that panel data does not have unit root (meaning these variables are stationary). The data are stationary both at I(0) and I(1) and for this reason the data are ideal for the Panel ARDL estimator and co-integration.

4.3 Long and Short Run Empirical Findings of PMG-ARDL

An econometric method called the PMG-ARDL is utilized to verify the long-term associations and short-term dynamics of predictors, Pesaran et al. (1999) created this technique. Their long and short run findings are given in the following table 5. The manuscript utilized the PMG-ARDL test after determining whether a cointegration relationship existed, (Zakari et al., 2021) and findings are indicated in Table above. In this table below, environmental quality which is measured by CO_2 emission is dependent variable which is calculated by per capita. According to the outcomes coefficient value of green technology diffusion (GTD) is (*Coeff. = -0.353168*) shows negatively and statistically significant (*t-stat: = -5.937958; Prob. = 0.0000*) effect on dependent variable, environmental quality. It indicates that green technology diffusion reduce CO_2 emission by negative impact. It implies that one unit increase in green technology diffusion will guide to decrease (-0.353168) percent in ecological CO_2 emission which lead to increase environmental quality. By encouraging cleaner, more effective alternatives to conventional carbon-intensive activities in the fields of energy, industry, transportation, and agriculture, green technology diffusion lowers CO_2 emissions. The main sources of CO2 emissions worldwide are fossil fuels (coal, oil, and gas), which are replaced by green technologies such as solar panels, wind turbines, hydroelectric power, and geothermal systems. Carbon capture and storage (CCS) technologies, clean manufacturing techniques, and energy-efficient equipment are all examples of green dissemination. Reliance on petroleum and diesel is decreased by implementing electric vehicles (EVs), hybrid automobiles, and clean public transportation. Heat pumps, LED lighting, insulation, and smart appliances are some of the energy-saving features found in green buildings. GHGs from land-based activities are decreased by technologies including methane capture systems, biofertilizers, and precision farming. This finding is in-line with Obobisa & Ahakwa (2024); Bilgili et al., (2024); Zeng et al., (2024); Traoré & Asongu (2023); Obobisa et al., (2022); Agan, & Balcilar (2022); Zeng et al., (2022); Bilal et al., (2021); Du et al., (2019).

Next, the coefficient value of fossil fuels (FF) is (*Coeff. = 0.517347*) shows positively and statistically significant (*t-stat: = 4.135547; Prob. = 0.0001*) effect on dependent variable, CO_2 emission. It indicates that consumption of fossil fuels increases CO_2 emission by positive impact. It specifies that one unit augment in fossil fuels consumption will lead to boost (0.517347) percent in CO_2 emission which leads to decrease environmental quality. The carbon-rich energy sources known as fossil fuels—coal, oil, and natural gas—were created from prehistoric organic matter. They emit carbon dioxide (CO_2), a greenhouse gas that traps heat in the Earth's atmosphere, when they are burned for energy. In addition to CO_2, burning fossil fuels releases harmful air pollutants such sulfur dioxide, nitrogen oxides, and particulate matter. Greenhouse gases, primarily CO_2 and methane, are released when fossil fuels are burned, trapping heat in the atmosphere. Water is contaminated by fossil fuels while they are being extracted, processed, and transported. There is a growing need to comprehend and solve the environmental implications of fossil fuel consumption as the consequences such as rising sea levels, extreme weather events, and health issues linked to pollution become more apparent. This conversation examines the various ways that using fossil fuels harms the environment and emphasizes how critical it is to switch to cleaner, sustainable energy sources. The outcomes are in-line with Bucak et al., (2024); Eweade et al.,(2024); Iyke-Ofoedu et al., (2023); Onifade, (2023); Usman, et al., (2022); Hadj, T. B. (2021); Akalin et al., (2021); Ibrahiem, & Hanafy, (2020) and Solarin (2020).

Table 5: Empirical Findings of PMG-ARDL Technique

PMG-ARDL Technique Dependent Variable is Environmental Quality (CO_2 Emissions / Capita)			
Variables	**Coefficient**	**t-stat**	**Prob.**
Long Run Co-integration			

LGTD:	-0.353168	-5.937958	0.0000*
LFF:	0.517347	4.135547	0.0001*
LFDI:	-0.459573	-2.370538	0.0116*
LEP:	-0.379053	-3.251442	0.0015*
LIND:	0.652182	1.476927	0.0421**
Short Run Estimations (ECM)			
COINTEQ01:	-0.625708	-2.013882	0.0125**
D(GTD):	-0.125496	-2.643188	0.0212**
D(LFF):	0.406383	3.516589	0.0006*
D(LFDI):	0.003915	2.220757	0.0256**
D(LEP):	-0.064676	-1.965630	0.0152**
D(LIND):	0.200203	1.324903	0.0575***
C:	-0.759902	-0.991783	0.0231*

Source: Author Calculation

Note: Significance Level, *1%, **5% and ***10%

Next, coefficient value of foreign direct investment (LFDI) is (Coeff. = -0.459573) shows negatively and statistically significant (t-stat: = -2.370538; Prob. = 0.0116) effect on dependent variable, CO_2 emission. It indicates that, foreign direct investment decrease CO_2 emissions due by negative impact. It proves that one unit raise in FDI will guide to reduce (-0.459573) percent in CO_2 emission which lead to increase environmental quality. In a world that is becoming more interconnected by the day, foreign direct investment, or FDI, is essential for both economic growth and environmental sustainability. Green technology transfer, environmental innovation, and the international spread of low-carbon practices can all be facilitated by foreign direct investment (FDI), which is the capital invested by foreign companies in domestic industry. Stricter environmental regulations, energy-efficient technologies, and cleaner production methods are frequently introduced by multinational firms when they invest in host nations. Carbon dioxide (CO_2) emissions can be significantly reduced as a result, particularly in underdeveloped nations where access to cutting-edge technologies may be limited. Furthermore, via competition and knowledge sharing, FDI might encourage local businesses to embrace greener practices. The outcomes are in-line with Kim & Seok (2023); Balsalobre-Lorente, et al., (2022); Rahaman et al., (2022); Islam et al., (2021); Xie et al., (2020); Solarin et al., (2018); Sung et al., (2018); Zhang & Zhou (2016); Tang & Tan (2015), Shaari et al., (2014).

Next, coefficient value of energy price (LEP) is (*Coeff. = -0.379053*) shows negatively and statistically significant (*t-stat: = -3.251442; Prob. = 0.0015*) effect on dependent variable, CO_2 emission. It indicates that energy price decrease CO_2 emission by negative impact. It proves that one unit raise in energy price will guide to reduce (-0.379053) percent in CO_2 emission which lead to increase environmental quality. Energy prices have a significant impact on how people consume, how businesses operate, and how the environment turns out. Both consumers and producers are motivated to lower their energy consumption, boost efficiency, and switch to cleaner alternatives as the cost of energy rises, particularly from fossil fuels like coal, oil, and natural gas. This economic mechanism has emerged as a crucial tool in the fight against climate change and to cut carbon dioxide (CO_2) emissions. Carbon-intensive operations become more costly when energy costs rise, whether because of market forces or legislative measures like carbon taxes or changes to fossil fuel subsidies. Governments may hasten the switch to renewable energy sources, companies may invest in energy-efficient technologies, and families may reduce their electricity usage as a result. Over time, these structural and behavioral changes have the potential to significantly lower greenhouse gas emissions. The premise that energy price reforms can promote sustainable energy use and lower CO_2 emissions without compromising long-term economic growth is becoming increasingly supported by empirical data, particularly when combined with robust environmental regulations. Energy prices are therefore an essential weapon in the worldwide battle against climate change. The outcomes are in-line with Naimoğlu (2022); Wu et al., (2022); Li et al., (2020); Antonietti & Fontini, (2019); Zaghdoudi (2017); Lee & Chong (2016); Hammoudeh et al., (2015); Hammoudeh et al., (2014a); Hammoudeh et al., (2014b); Sadorsky (2009).

Next, the coefficient value of industrialization (LIND) is (*Coeff. = 0.652182*) also shows positively and statistically significant (*t-stat: = 1.476927; Prob. = 0.0421*) effect on dependent variable, CO_2 emission. It indicates that industrialization increases CO_2 emission by positive impact. It specifies that one unit raise in industrialization will guide to boost (0.317677) percent in CO_2 emission which lead to decrease environmental quality. A key component of economic development, industrialization has changed societies via improvements in infrastructure, technology, and industry. However, the environment has suffered greatly because of this quick industrial expansion, especially in the form of higher carbon dioxide (CO_2) emissions. Countries become more dependent on fossil fuels like coal, oil, and natural gas to power manufacturing, transportation, and electricity generation as their energy needs increase dramatically as they become more industrialized. Because of its extensive use of energy for heavy machinery, production processes, and chemical synthesis, the industrial sector is one of the biggest contributors to world CO_2 emissions. In many underdeveloped countries, industrialization frequently takes a high-emission route because cleaner technology is less available or inexpensive. This worsens regional environmental issues including air pollution and ecosystem degradation in addition to hastening climate change. Industrialization presents significant obstacles to environmental sustainability even if it is necessary for economic growth and the fight against poverty. To create policies that support low-carbon industrial strategies and allow countries to thrive economically while reducing their environmental impact, it is essential to comprehend the relationship between industrial growth and CO_2 emissions. The outcomes are in-line with Mentel et al., (2022); Sikder et al., (2022); Sarkodie et al., (2020); Mahmood et al., (2020); Dong et al., (2019); Liu & Bae (2018); Ahmad & Zhao (2018); Raheem & Ogebe (2017); Xu et al., (2015); Shahbaz et al., (2014). In this work, the Error Correction Model is used to obtain short-term results. At the 1% or 0.01 level of significance, CointEQ01's coefficient in the preceding table is negative (*Coeff. = -0.625708*) and statistically significant (t-Statistic = -2.013882; Prob. = 0.0125). It is necessary for the ECT term to be statistically significant and negative. Our results show that when transferring from the short-run to the long-run equilibrium, 62.57% of errors are corrected.

4.4 Co-integration Tests

A cointegrating relationship in research indicates a statistical connection between two or more time series variables that remain consistent over an extended period. The Pedroni Residual Cointegration Test is used in the paper to determine whether such a link exists. To determine if there is a long-term equilibrium between several time series, the (Pedroni, 2004) test is useful. This test is frequently used by researchers to examine panel data. In panel data situations, it looks for a cointegrating link between two or more time series. The following table 6 lists the results of these tests.

Table 6: Empirical Findings of Co-integrations Test

Pedroni Residual Cointegration Test				
	Stat:	**Prob.**	**W. Stat:**	**Prob.**
Panel v-Stat:	0.123464	0.4509	0.004655	0.4981
Panel rho-Stat:	2.513211	0.0349	2.514613	0.0351
Panel PP-Stat:	1.992794	0.0266	2.340848	0.0334
Panel ADF-Stat:	2.465150	0.0486	2.200658	0.0595

	Stat:	**Prob.**
Group rho-Stat:	2.550032	0.0442
Group PP-Stat:	1.122080	0.0692
Group ADF-Stat:	1.496064	0.0601

Source: Author Calculation

Note: Significance Level, *1%, **5% and ***10%

If p-value for the test statistic falls below the significance level (5% or 0.05), researchers can reject the H_0 of no co – integration, this points to proof of a co - integrating affiliation. On the other hand, if p-value surpasses the chosen significance level, you don't reject the H_0. This indicates a lack of cointegration. The outcomes of the Pedroni panel co-integration test disprove the idea that there's no co-integration in the study with the evidence that 8 out of 11 significantly reject the null hypothesis.

4.5 Granger Causality Test

The Granger Causality Test is a statistical hypothesis test that is used for formative whether one time series can predict (or "cause") changes in another time series. Developed by economist Clive Granger in the 1960s, it is a common method for examining the occurrence of a causal association among two variables and to analyze their relationships in time series analysis. Granger Causality test for the causal link among variables has been applied. Table 8 below gives the results of the Granger Causality test.

Table 8: Findings of Granger Causality test

Granger Causality Test (Optimal Lag 2)					
Null Hypothesis: (H_0)	**Obs.**	**F-Stat**	**Prob.**	**Results**	**Conclusion**
LGTD does not Granger Cause LEQ	160	4.27470	0.0156**	Rejected	Bidirectional
LEQ does not Granger Cause LGTD		0.57932	0.0415**	Rejected	
LFF does not Granger Cause LEQ	160	3.32943	0.0384**	Rejected	Bidirectional
LEQ does not Granger Cause LFF		4.61641	0.0113**	Rejected	
LFDI does not Granger Cause LEQ	160	0.87575	0.0186**	Rejected	Bidirectional
LEQ does not Granger Cause LFDI		1.02583	0.0609***	Rejected	
LEP does not Granger Cause LEQ	160	1.18056	0.3099	Rejected	Unidirectional
LEQ does not Granger Cause LEP		0.01192	0.0881***	Accepted	
LIND does not Granger Cause LEQ	160	5.68005	0.0042*	Rejected	Unidirectional
LEQ does not Granger Cause LIND		0.34685	0.0075*	Rejected	

Source: Author Calculation
Note: Significance Level, *1%, **5% and ***10%

Green Technological Diffusion is Granger Cause environmental quality at the 1%, 5%, and 10% levels of significance, according to the Granger Causality test results shown in the above table. It suggests that there are two-way causal links between variables as well as bidirectional causation. However, LEP, LIND, LFF, and LFDI are Granger causes of ecological footprint. Between variables, there is both unidirectional and bidirectional causality.

4.6 Diagnostic Analysis

One of the methods utilized in statistical research is the use of diagnostic testing. They can be used to determine a model's strength and appropriateness or to confirm that the data are appropriate for the analysis's type of study. Therefore, by doing diagnostic tests, researchers can determine whether their findings are accurate and unaffected by assumptions that aren't correct. The essential checks for figuring out the results of statistical and economic techniques are diagnostic tests. To detect and diagnose the issues of multicollinearity, heteroscedasticity, autocorrelation or serial correlation, and specification errors, the current study additionally used a variety of tests and instruments. Table 9 below presents their findings.

Table 9: Pair – Wise Correlation Matrix

	LEQ	LGTD	LFF	LFDI	LEP	LIND
LEQ:	1.000000					
LGTD:	-0.394012	1.000000				
LFF:	0.785792	0.189386	1.000000			
LFDI:	-0.077812	0.411535	-0.129436	1.000000		
LEP:	-0.011456	0.327226	0.076684	0.347969	1.000000	
LIND:	0.279020	0.347060	0.489984	0.040862	-0.311229	1.000000

Source: Author Calculation

Initially, the research unveils the presence of multicollinearity in the dataset. Multicollinearity refers to a multiple linear regression situation in which two or more predictor variables in a model are intercorrelated (positively or negatively) with each other. Checking the correlation among the explanatory and dependent variables is a necessary measure. Large numbers show a high degree of similarity and correlations. As in the table above, LGTD, LFDI, and LEP are negatively correlated with LEQ and LFF and LIND are optimistically correlated with LEQ. So, the values of correlations are below 0.9 of all parameters with each other which indicates that there is absence of multicollinearity in the panel data set. The study also testifies the problem of autocorrelation, Heteroskedasticity and specifications errors. Their findings are given in Table 10 below.

Table 10: Empirical Findings of Diagnostic Tests

Diagnostic Test:				
Sr. #	**Tests**	**F-Stat**	**Prob.**	**Conclusion**
1	Serial Correlation LM Test	0.128047	0.8799	No Serial Correlation
2	Breusch Pagan-Godfrey Test	7.684613	0.7681	No Heteroskedasticity

	Ramsey RESET Test	Values	d.f	Prob.	
3	t-statistic:	0.616650	163	0.5383	The Estimated Model is free from Specification Errors and Model is Well Specified
	F-statistic:	0.380258	(1,163)	0.5383	
	Likelihood Ratio:	0.396126	1	0.5291	

Source: Author Calculation
Note: Significance Level, *1%, **5% and ***10%

The table above provides the results of several instruments and methods for evaluating diagnostic tests. Autocorrelation and heteroskedasticity are shown to have the following results: (*F-Stat: = 0.128047; Prob. = 0.8799*) and (*F-Stat: = 7.684613; Prob. = 0.7681*), respectively. These results demonstrate that the study cannot reject the null hypothesis (H0) and accept the alternative hypothesis (H1) in either scenario. They also verify that the residuals are homoscedastic and equal and that the model does not contain heteroskedasticity or autocorrelation. Additionally, the results of the Ramsey RESET Test show that the estimated model is accurately specified and devoid of specification mistakes.

5. Conclusion & Policy Implications

As countries struggle with the dual issues of environmental sustainability and economic development, environmental quality has emerged as a critical global concern. Historically, the pursuit of economic expansion has been linked to a rise in environmental deterioration, which has shown up as pollution, resource depletion, and climate change. The emergence of green technological innovation, however, presents viable avenues for reducing these negative effects and advancing sustainable development. Thus, this article scrutinizes the empirical consequences of green technological diffusion on environmental quality in BRICS economies, by employing panel data for the period from 1990 to 2023. Pooled Mean Group ARDL (PMG-ARDL), a 2^{nd} generation panel technique, is utilized to analyze the long plus short-term influence of selected factors of interest on environmental quality. The Granger causality test has been utilized to determine causation among the variables. Empirical evidence confirms that green technology diffusion reduces CO_2 emissions significantly in the long run. Further, FDI and Energy prices also help to reduce CO_2 emissions and improve environmental quality. Further, Fossil Fuels, and Industrialization have significantly and positively promoted CO_2 emissions in these countries.

Based on our findings, our study presented essential policy recommendations for the BRICS economies. Governments should foster an atmosphere that encourages cooperation among the private and public sectors by offering encouragement to businesses that invest in green technology like electric vehicles (EVs), renewable energy, and energy-efficient infrastructure. Support the exploitation of clean production technology, low-carbon infrastructure, and renewable energy by implementing specific tax breaks or subsidies. These could include modifying industrial processes to increase energy efficiency or offering financial incentives for the adoption of biofuel, wind, and solar technologies. Develop national green growth policies that integrate environmental objectives into development plans, emphasizing areas such as water conservation, waste management, forestry, agriculture, and renewable energy. To reduce energy use, carbon emissions, and the depletion of natural resources, governments should establish specific targets. Adopt the principles of the circular economy, which prioritize waste reduction, recycling, and material reuse, throughout all sectors of the economy. These policies include infrastructure spending for recycling, eco-design criteria, and extended producer responsibility (EPR). Companies who use circular methods could be given tax breaks or low-interest loans as incentives.

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