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Toward a Green Transition: Unravelling the Impact of Innovation, Urban Dynamics, and Economic Expansion on CO_2 Emissions in BRICS

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ABSTRACT

Environmental degradation from growing carbon dioxide (CO_2) emissions now stands as a significant worldwide issue that impacts regions undergoing quick economic expansion. The BRICS nations, which include Brazil as well as Russia, India, China and South Africa, create 45% of global CO_2 emissions while generating 18% of world GDP, positioning them as key participants in climate discussions at the international level. A statistical analysis evaluates the permanent and temporary relationships between technological innovation and urbanization and economic growth on CO_2 emission levels among BRICS nations using World Development Indicators (WDI) annual data from 1990 to 2023. Results from PMG-ARDL modelling demonstrate that both technological innovation and consumption of renewable sources actively diminish CO_2 emission patterns during extended periods, although economic growth helps reduce emissions when certain limitations arise. The relationship between urbanization and the environment becomes difficult to predict since it worsens emissions and demonstrates the intricate relationship between progress and sustainability. According to these results, future sustainability demands immediate implementation of advanced sustainable technologies and proper urban expansion management strategies.

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1. Introduction

BRICS countries have been actively engaged in the governance activities and established a cooperation pattern for the emerging nations from a long time period. The BRICS countries have distinguished themselves with relatively high economic growth rates. Gross Domestic Product 2019 was 23.5% of the world economy's total. On the other hand, even though the technology level of BRICS countries has dramatically advanced with high-speed economic development, there is lack of the technological innovation, especially in the high-tech industry, has emerged. While observing patent number of the applications, China has only sustained a high growth rate with the number of applications in 2019 being 164.9 % higher than that in 2008, while the numbers have declined significantly in Brazil, Russia and South Africa. Out of the BRICS nations, only China has figured in the global innovation index list among the 50 countries. Still, there are many opportunities to increase the quantity and size of patents in China compared to developed countries. China has moved from 37th to 14th place in the global innovation index within the last decade, from 2009 to 2019. Russia also improved its rank from 68th in 2009 to 46th in 2019. Other BRICS countries, including South Africa's innovative index standing, have experienced a decline: China and Russia are the only two countries to see a rise in their rankings. It decreased from forty-second to fifty-second place. Holding 43rd position before the list has fallen to 63rd, out of which 20 places fall is the maximum slide for South Africa among these five countries. Brazil is at 50th and has dropped to 66th, the second most significant drop except for South Africa.

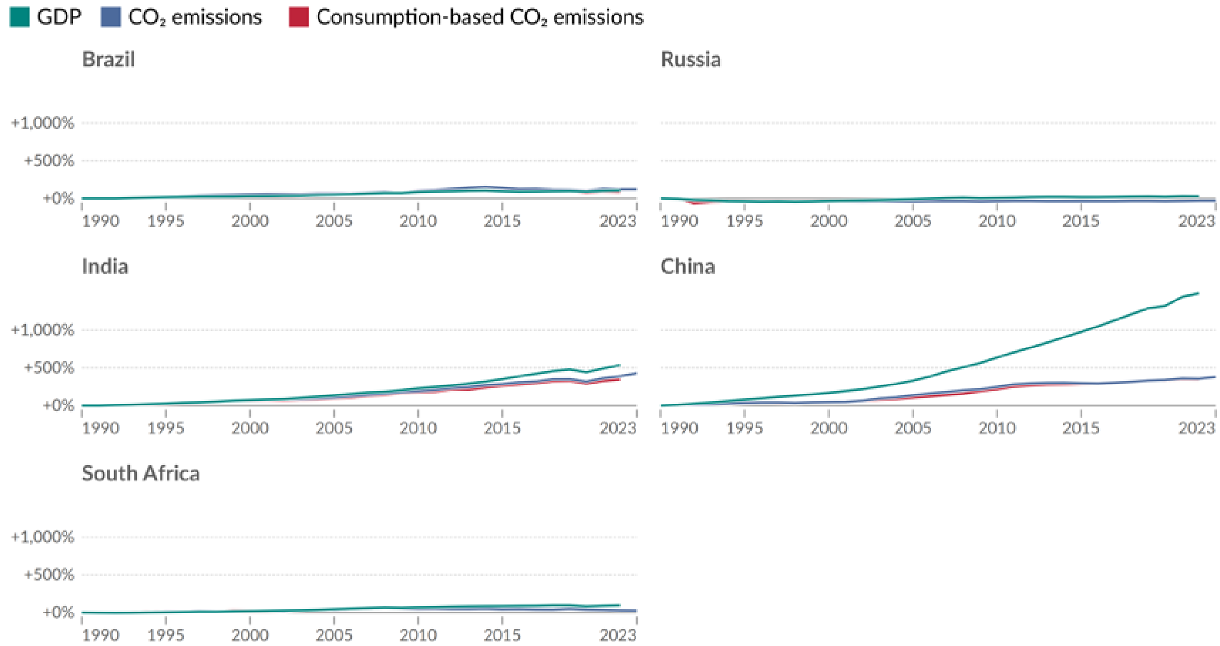

Figure 1: GDP & CO_2 emissions in BRICS countries

Entering the process of global industrialization relatively recently, the countries of BRICS have become truly giants of the world economy. However, it must be stated that because the BRICS countries are in transition, their growth path contains significant dependence on energy consumption. This type of growth mode will worsen energy consumption, raise greenhouse gas emissions, and worsen the ecological circle. Global warming is one of the projects that the world's people are carrying out. Minimizing greenhouse gas emissions is the only possible way to solve this problem. Now, the international community focuses on achieving a carbon peak and neutralization as soon as possible. Around 130 nations worldwide aim to offset their carbon emissions in the mid-21st century, constituting approximately 61 percent of global carbon dioxide emissions (Liu et al., 2022). Carbon neutralization is as simple as no net carbon discharge, meaning that "carbon discharge" and "carbon absorption" are two processes that have been in parallel growth. Carbon peak and carbon neutralization are not only a new path to green development for BRICS countries but also a huge test for the ED of member countries. The process of achieving the peak, neutrality, and decarbonization of carbon and ED has become a scientific question.

BRICS countries are, to a certain extent, enhancing the top design, realizing the carbon peak and carbon neutrality goals, boosting green and low-carbon technological advancements, and adjusting economy and energy structures strictly to restrain new construction of high-emission, high-consumption. For this purpose, the objective of our study is to examine the impact of technological innovation (TIN), urbanization (URN), renewable energy consumption and economic growth (GDPP) in BRICS countries. We used the BRICS countries due to their significant contribution to global CO_2 emissions. Theories in environmental economics and sustainable development underpin TIN, REC, GDPP, URN and CO2 emissions. The Environmental Kuznets Curve (EKC) hypothesis posits that an ED process increases CO_2 emissions because of industrialization and increased demand for energy but decreases the number of CO_2 in later stages of development because of shifts to end-of-pole technologies and energy types (Grossman & Krueger, 1995).

For TIN plays a dual role. Stern (2004) stated that the policy can raise emissions if it encourages a process that uses more inputs, but it can also lower emissions by promoting efficient use of REC sources. REC reduces CO2 emissions by displacing fossil fuel-based energy; it covers the global decarbonization agenda (Chen et al., 2023). URN hence leads to EC and emission despite the former's contribution to better living standards and GDPP (Zafar et al., 2023). However, urbanization can also support sustainability through urban land use planning and centralized energy networks. The relationship between these variables seems to be intricate such that influences and effects not only differ from one country to another and across development levels but are also cyclic; each form seems to influence the others cyclically.

The study on how technological advances offset CO_2 bears specific importance since the BRICS countries, Brazil, Russia, India, China and the Republic of South Africa, are differently positioned economically and environmentally. CO_2 emission in BRICS countries is high because most have passed or are passing through the Industrial Revolution, a growing population, and URN resulting in high EC. Nevertheless, as newcomers to the club of economic powers, these nations can contribute to climate change mitigation by adopting appropriate technology. Technology is a key capacity in facilitating sustainable development. In this way, technological development helps to create the basis for the decoupling of economic growth from the negative impact on the environment through supporting energy efficiency, decreasing fossil use, and encouraging the usage of RE. Estimating its outcome within BRICS countries fits the current context best since they have to foster GDPP while adhering to the Paris Agreement.

2. Literature Review

2.1. EG on CO_2 Emissions

Balsalobre-Lorente et al. (2019) used the cointegration approach in their sample data of 17 industrialized countries from 1990-2012 for RE, GDPP, innovation and environmental pollution. They utilized a study showing that employment of renewable power, GDPP and incorporating new technologies leads to improved environmental standards. Heidari et al. (2015) examined the power use of ED with CO2 by implementing the PSTR model and the fixed effect technology in Thailand, Singapore, the Philippines, Malaysia, and Indonesia. Using power, researchers have found that ASEAN countries emit carbon in equal proportion, based on their research. Mohammed Albiman et al. (2015) examined the empirical relationship between electricity usage, CO_2 and the GDPP rate from 1975 to 2013 in Tanzania. They also used several time series estimations, including variance decomposition, impulse response, and causality tests. According to the authors of the studies in focus, the employment of power resources results in high CO_2. This stated that the research also supports the EKC hypothesis.

Further, Pablo-Romero and De Jesús (2016) posited that ED is inversely proportional to EC concerning ED; both LAC countries have an energy reverse 'U' shaped energy curve. Aruga (2019) pointed out that the hypothesis of EKC occurs only in developed countries in the Asia-Pacific region. Shahbaz et al. (2020) established that out of 30 Chinese provinces, 20 are infected with EKC or Endemic Ebola-like Syndrome. Other studies have also noticed the same (Balsalobre-Lorente et al., 2021; Haseeb et al., 2018). Zaman and Abd-el Moemen (2017) adopted three categories of worldwide incomes to analyze their power use and GDP enhancement impact on CO_2. Thus, the results of EKC simultaneously explain the Pollution Haven Hypothesis (PHH). According to Alvarez-Herranz et al. (2017), to study the impact of GDPP on CO_2, this research only considered the data of 17 developed countries in the OECD.

The conclusion shows that there is a direct relationship between GDPP and CO_2. They have an inverse U-shape EKC curve relationship that forms an N-shaped curve relationship.

Chen and Lei (2018) employed 24 Asian economies to analyze the relationship between CO_2, URN and GDPP through several panel estimation techniques. Consequently, the study established that CO_2 facilitates engagement in clean energy usage and is reciprocally related causal. However, Magazzino (2017) studied 19 APEC member countries from 1960 to 2013 and found that GDPP has no relationship with CO_2. Empirical evidence has been made to pay attention to the effect of CO2 on the ED or EC and other factors in BRICS countries. In some of the previous studies, authors noted that pollution indexes are growing with the extension of globalization (Pata, 2021; (Rahman, 2021 #47). Wu et al. (2015) also proved that the CO_2 of Brazil and Russia decreased with the GDPP in the case of the BRICS countries. Our empirical analysis shows that CO_2 in India, China and South Africa depends positively on GDPP, stating that CO_2 increases with GDPP. The correlation between CO_2 and two components, the urban population and energy use, for all countries that compose the BRICS grouping is positive and statistically meaningful. A few researchers claimed that all the BRICS countries have experienced various types of structural change in the growth-emission nexus (Nawaz et al., 2021).

2.2. Technological Innovation on CO_2 Emissions

Richmond and Kaufmann (2006) and He and Richard (2010) state that there is a positive correlation between TIN and environmental patients. Likewise, Borghesi et al. (2015) stated that as technology changes, the emission reduction technologies as policy would offer learning benefits, meaning mechanized CO_2 reductions are getting cheaper over time. As noted earlier, Acemoglu et al. (2012) also noted that technological improvement either increases or decreases $CO_{2.}$ Balsalobre-Lorente et al. (2021) highlighted that REC reduces $CO_{2,}$ thus creating the opportunity to lower GHG by increasing the use of REC. In another research, Dong et al. (2020) revealed that in 120 countries, a negative relationship between REC and CO_2 indicates that REC improves the ecological environment and CO_2. Accordingly, Bjerregaard (2010) stated that research and development cooperation helps to acquire external knowledge and technology, improve scientific research partnership and information exchange, and achieve regional co-innovation and development. Wang, Gillani, Razzaq, et al. (2024) have proved that technological advances may compel enterprises to eliminate backward actions by using efficient energy management technologies and thus play a role in creating a green industrial value chain and reducing CO_2.

According to Wang et al. (2025), the overall GDPP could perhaps be released from the burden of environmental pressure if R& D investment is put forward. According to Ibrahim and Ajide (2021), energy innovation was a CO_2 abatement activity. The effects of CO_2 are the majority; hence, they affect the environment and global warming. However, the carbon neutrality target begun in 2002 declines the proportion of fossil fuel outputs by 6 per year to remove the carbon environment by 2030 (Erdogan, 2021; Ji et al., 2021). Furthermore, the cessation of fossil fuel production in the year 2030 will enable emission reduction by approximately 45 percent of CO_2 emissions from 2010 and 60 percent relative to 1990. Therefore, for the achievement of the objective of getting to carbon neutrality, it was stated that carbon prices have to be appropriately set, subsidies on fossil fuels have to be abolished, and newly built complex coal-fired power plants should be either restrained or properly regulated (Nazir et al., 2023; Turken et al., 2020; Wang, Gillani, Nazir, et al., 2024). Moreover, since CO_2 equals carbon neutralization, as evidenced by Robalino-Lopez et al. (2014), we may attempt to contain this deficit by simultaneously growing GDP and the clean energy industry. On the one hand, the uses of renewable and nonrenewable energy sources enhance GDPP, but on the other hand, the extraction of nonrenewable energy sources increases carbon levels, which is a challenge to carbon neutrality. On the other hand, clean energy innovation is being exercised to reduce CO_2, which is only helpful for decarbonizing developed countries. Le et al. (2020) and Razzaq et al. (2021) used monthly data to analyze the linkage between green technology innovation and carbon neutrality in BRICS countries.

Ganda (2021) successfully implemented various findings, signaling that innovation bears a high stratosphere nonlinear relationship to the environmental standard. To achieve the goal of modern Australia becoming carbon neutral and to introduce the measures for the complete removal of 80% of CO_2 and other GHG emissions in 2050, as proposed by Wolfram et al. (2016), this paper employs the SC- Hybrid LCA approach to evaluate a change in the carbon intensity of the entire economy based upon the seven compared power generation technologies rather than the share of renewable power sources. They also discovered that carbon neutrality has been attributed to, among other things, renewable energy and renewable electricity. In the case of the different income countries, Jebli et al. (2020) investigated the connection and might check up to 102 countries from 1990 to 2015, employing systematically generalized methods of the moments and distinctly Granger causality. On this account, the evaluation aligns with the concept that clean energy innovation may help meet the carbon neutralization goal. The developed economy cannot generally transition to zero carbon because this is not a simple process. In most studies indices, eco-innovation has been identified as key to reducing carbon emissions Yang, Shafiq, Nazir, et al. (2024) and Zhang et al. (2021).

Furthermore, such a transition will bring issues on which type of development developing countries should adopt and the general switch to new technologies will lead to the disappearance of specific sectors and businesses (Semieniuk et al., 2021). In the following few sections, the previous research works to this study are presented to build the context of this research. Thus, the directing factors towards CO_2 appear to be multiple and all around. This is one of the key considerations that most researchers focus on.

2.3. Renewable Energy Consumption CO_2 Emissions

The consumption of REC plays a pivotal role in mitigating CO_2 and addressing climate change. Bilgili et al. (2021) integrating renewable power like wind, solar, and hydropower has the potential to reduce CO_2 emissions by replacing fossil energy. This co-relationship is highly visible in the Least Developed Countries (LDCs), where governance issues such as the rule of law and bureaucracy also enhance the impact of renewable energy policies. In reality, studies reveal that the countries where the use of renewable energy is increased experience an approximate and significant reduction in emissions, where governance is adequate, and the innovation that occurs in the creation of energy technologies is considered a priority (Szetela et al., 2022). Cross-sectional studies show that REC positively impacts environmental sustainability, but the effects differ according to income and world regions. For instance, developed countries can reduce emissions more effectively because of advanced technological support and policy enforcement, while in developing and least developed countries, factors such as financial crisis and restricted access to such technologies slow development. However, Caldera et al. (2024) stated that GDPP, RE and CO_2 by wavelet coherence analysis provide evidence that the interaction is complex and varies over time, calling for more differentiated, regional policy approaches.

However, there are still problems with extending such a renewable energy structure, solving intermittency problems, and making the whole project economically viable. Investment in innovation and policies for improving subsidies and taxes concerning the emission of clean energy is required (Yang, Shafiq, Sharif, et al., 2024). Subsequent studies should consider other SES, including industrialization and human capital, to analyze the relationship between renewable energy and emissions and have a holistic perspective on its effects (Rai et al., 2025). The above literature synthesis focused on using renewable energy, which negatively affects CO_2 and assessed the effect on 152 countries from 1990–2019. It points out that as the GDDP rises, the emissions increase except when the formal pursuit of the RE exists (Dissanayake et al., 2023).

2.4. Urbanization on CO_2 Emissions

URN is a key driver of increased CO_2 emissions due to the high energy demand associated with urban growth, including transportation, industrialization, and housing infrastructure. Research has established that as much as urbanization increases CO_2 rates, particularly in growing cities in developing nations. For example, densely populated nations like China and India have observed a comparative rise in emission levels because of urban spatial extension from rising ED and EC based on fossil fuels (Xu et al., 2023). Ghosh and Kanjilal (2014) examined the impact of URN on CO_2 in India from 1971 to 2008 using the ARDL. The outcomes suggested that CO_2 emission increases as an increase in the URN.

While using the data of 280 Chinese cities, Xu et al. (2023) concluded a significant and positive relationship between the URB and CO_2 emission by using the spatial spillover effect. They suggested that URB boost the regional coordination's. Further, Das et al. (2024) also analyzed the relationship between URN and CO_2 emission. The findings concluded by the GMM stated that URN significantly enhance the CO_2 comission in the start but significantly reduces with the passage of time. In the long run, URN have a negative impact with CO_2 emission and it also become negative depending on the factors. The results are linear with the EKC hypothesis. Moreover, on conducting research on South Asian countries, Sayal et al. (2024) investigated a relationship between URN and CO_2 with the appliance of machine learning. Their outcomes stated that unplanned URN significantly boost the emission especially most populated cities i.e. Karachi, Delhi, Dhaka. They suggested that URN also reduce the emission and contribute significantly in the EG by using the smart technology and working on the green infrastructure.

In fact, the association between URN and CO_2 has an inverted U-shape form for OECD countries. Emergent urbanization is associated with a rise in emission rates; however, more developed URNs bring a decrease, conditioned by innovations and the use of environmentally friendly energy sources. This is also described by the phenomenon known as the EKC and is also influenced by, for example, governance and regulatory efficiency, which are instrumental in shaping sustainability (Chen et al., 2022). On the other hand, there are potential solutions on how CO_2 reduction can be achieved in connection with some aspects of URN. Eco-efficient designs combined with high-density structures that characterize compact URN ensure that spaces do not require extensive transport networks to access them, as with sprawling urban structures (Ismael et al., 2019).

Apart from direct emissions from fossil fuel burning, other parts of the carbon cycle characteristic of urban life are emissions from waste disposal, transport, and reduced carbon uptake by urban vegetation (Churkina, 2016). However, even in this context of increased urban greening, certain constraints remain for their ability to help reduce emissions, pointing to the necessity of energy efficiency and rational urban planning (Churkina, 2016). In this light, it is evident that specific preventive and reducing measures need to be developed concerning environmental effects resulting from urbanization, especially in the context of the countries belonging to the developing world that are less equipped with environmentally friendly technologies. Developing green and renewable energy, improving the layouts and performance of the built environment in cities, and implementing robust governance strategies can minimally decrease the carbon fleet of cities (Khan & Su, 2021). However, even now, URN as a correlate is somewhat of a double-edged sword concerning CO_2 emissions. Despite significant improvements implemented by high-income countries in formulating sustainable urban practices, low and middle-income countries encountered profound challenges that cascade into implementation problems such as inadequate financial capacity and weak institutional governance structures (Zoundi, 2017).

No study in the literature examines the impact of technological innovation, urbanization, renewable energy consumption, and economic growth on carbon dioxide emissions in BRICS countries. Second, we used the data till 2023 for the analysis. Third, we used the panel data's novel approach, i.e., pooled mean group. In this way, we filled this gap.

3. Theoretical Framework

The framework of analyzing the factors that influence Technological innovation, renewable energy consumption, economic growth and urbanization on carbon dioxide emission levels employs environmental theory to rationalize variation in emission levels. Herman and Xiang (2019) stated that TIN is an important factor in environmental economics since technological efficiency lowers the amount of fossil energy used on policy-induced innovation for sustainable ED. By replacing carbon-intensive energy forms, REC also lowers CO_2 in support of energy transition theory, which shows how societies transition from traditional energy systems to sustainable ones as the economy grows.

The EKC hypothesis offers the only way of depicting the interaction between GDPP and CO_2: while emissions are strongly related to the former, they follow an inverted U-shaped path at a global level as the degree of environmental consciousness increases with income. Nevertheless, it is short-term because URN raises CO_2, as pointed out by urban environmental theory, owing to the resources required to expand cities and support industries. Prioritizing URN as a means through which they can achieve GDPP and technology transfer, however, it leads to more EC and CO_2 if not well-checked by sustainable aims and policies that consider the URN. These theoretical frameworks collectively form the backdrop for analyzing the complex relationship between GDPP, REC, TIN, URN and CO_2. By combining all these elements, we describe our model as follows:

$$CO_2 = f(TIN, GDPP, URN, REC) \quad (1)$$

In the econometric form, our equation is as follows:

$$CO_{2it} = \alpha_o + \alpha_1 TIN + \alpha_2 GDPP + \alpha_3 URN + \alpha_4 REC + e_{it} \quad (2)$$

In the above equation, TIN represents technological innovation, GDPP shows gross domestic product per capita, REC shows renewable energy consumption, URN shows urbanization, and CO2 shows carbon dioxide emission. Moreover, i show the cross-section, and t is the time period. Further, e_{it} It is the error term. The error term prevents the endogenic model from overfitting the statistical relations under consideration.

4. Data and Methodology

This research aims to analyze the impact of the TIN, URN, GDPP and REC on the CO_2 in the BRCIS (Brazil, Russia, India, China, and South Africa) countries. These countries are chosen due to their high contribution to the global CO_2. The data from 1990-2023 is used in this study and obtained from the world development indicator.

Table 1
Description of Variables

Variable	Symbol	Proxy	Data Source
Carbon Dioxide Emissions	CO_2	Carbon dioxide (CO2) emissions (total) excluding LULUCF (% change from 1990)	WDI
Technological Innovation	TIN	resident patent + non-resident patent	WDI
Urbanization	URN	% of the total population	WDI
Economic Growth	GDPP	GDP per capita (constant 2015 US$)	WDI
Renewable Energy Consumption	REC	% of total final energy consumption	WDI

In Table no.2, summary statistics stated that the mean values of the CO2 emission, TI, URN, REC and GGDP are 87.56, 10.18, 61.01, 24.72 and 58.53, respectively. GGDP shows the highest, while REC shows the lowest variation. All the variables are positively skewed. Moreover, COE, TI, URN, REC and GDPP rejected the null hypothesis of the Jarque Bera test and stated that data deviates from the normal distribution.

Table 2
Descriptive Statistics

	CO_2	TIN	URN	REC	GDP
Mean	87.56	10.18	61.01	24.72	58.53
Median	46.22	10.12	73.37	18.5	64.47
Maximum	428.54	14.27	87.78	53	121.74
Minimum	-33.18	8.05	25.54	3.2	528.8
Std. Dev.	121.00	1.38	20.89	17.33	33.32
Skewness	1.31	1.15	-0.58	0.167	-0.28
Kurtosis	3.66	4.37	1.68	1.42	1.73
Jarque-Bera	52.25	51.51	21.76	18.33	13.75
Probability	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}	0.00^{***}

*For p<0.1, ** for p<0.05, ***for p<0.01

4.1. Methodology

To establish the link between technological innovation, urbanization, GDP per capita and the carbon dioxide emissions equation, we used the Pooled Mean Group Autoregressive Distributed Lag (PMG-ARDL) mode, which Pesaran, Shin, and Smith established. We tested cross-sectional dependency through the test developed by Pesaran, which checks whether panel data present dependencies across sections. Thus, it is still possible to obtain cross-sectional dependence, as the failure results in biased and inconsistent estimators. Afterwards, we conducted the CIPS unit root test to determine whether the variables were stationary. This test is suitable for panel data analysis cross-sectional dependence to test for unit roots within the set variables, ensuring that they are integrated with I (0) or I (1) as required by ARDL models. Lastly, to determine the long-run and short-run cointegrations, we employed the PMG-ARDL model. Specifically, the PMG-ARDL framework enables short-run cross-sectional coefficients to be heterogeneous but forces the long-run coefficients to be identical. The model is specified as:

For the short-run

$$CO_{2_{it}} = \alpha_o + \alpha_1 \Delta CO_{2_{it-1}} + \alpha_2 \Delta TIN_{it-1} + \alpha_3 \Delta GDPP_{it-1} + \alpha_4 \Delta URN_{it-1} + \alpha_5 \Delta REC_{it-1} \quad (3)$$

For the long-run

$$CO_{2_{it}} = \gamma_1 CO_{2_{it}} + \gamma_2 TIN_{it} + \gamma_3 GDPP_{it} + \gamma_4 URN_{it} + \gamma_5 REC_{it} \quad (4)$$

The final equation of the model is as follows:

$$CO_{2_{it}} = \alpha_o + \alpha_1 \Delta CO_{2_{it-1}} + \alpha_2 \Delta TIN_{it-1} + \alpha_3 \Delta GDPP_{it-1} + \alpha_4 \Delta URN_{it-1} + \alpha_5 \Delta REC_{it-1} + \gamma_1 CO_{2_{it}} + \gamma_2 TIN_{it} + \gamma_3 GDPP_{it} + \gamma_4 URN_{it} + \gamma_5 REC_{it} + E_{it} \quad (5)$$

CO2 is our dependent variable in this equation, whereas TIN, GDPP, URN and REC are our independent variables. Further, i show the cross section (countries) while t is the time. Moreover, E_{it} shows the error term.

5. Results and Discussions

Before applying the pooled mean group autoregressive distributed lags model, we check the cross-sectional dependency (CSD) among the variables. Table 3 shows the result of the CSD test. The outcomes from CSD indicate the rejection of the null hypothesis among the variables. We can say that CSD is present in our study. After the CD-test, we apply the CIPS unit root test to determine whether the variable is stationary on I(1) or I(o). CIPS unit root test was developed by the Pesaran in 2007. It helps to check the CSDs in the panel data when another factor influences a cross-section. Further, the CIPS unit root test has the advantage of tackling the integration.

Table 3
CD-Test

Variable	P-value
CO_2	0.00***
TIN	0.00***
URN	0.00***
REC	0.00***
GDP	0.00***

*For p<0.1, ** for p<0.05, ***for p<0.01

Table 4
Unit Root Test

Variable	I (0)	I (1)
CO_2	-3.59	-
TIN	-0.26	-4.11
URN	-1.11	-2.42
GDPP	-2.72	-
REC	-1.99	-3.96

*for p<0.1, ** for p<0.05, ***for p<0.0

Table 5
Long Run & Short Run Outcomes

Variable	Coefficient	Prob.
Long Run Equation		
LOG(TI)	-12.8977	0.06**
URN	8.64254	0.00***
REC	-6.8969	0.00***
GDP	-0.00499	0.00***
Short Run Equation		
COINTEQ01	-0.24042	0.01**
DLOG(TI)	-0.70411	0.57
D(URN)	-16.7982	0.43
REC	-0.99	0.63
GDP	0.05	0.19
C	-76.97	0.24

*For p<0.1, ** for p<0.05, ***for p<0.0

From the long-run estimations, it has been reported from PMG-ARDL that TIN has a negative but significant relationship with CO_2 in the BRICS countries. The outcomes reported that a 1% increase in the TIN results in a decrease of 12.89% in CO_2. This means that TIN significantly reduces the CO_2 in the long run. This reduction is attributed to the contribution of new technologies in the achievement of sustainable objectives in energy conservation. Through TIN, there is the advanced application of better production methods, less dependency on fossil energy and minimal CO_2 release. Advancements in renewable energy technologies like solar and wind have allowed countries to shift to low-carbon economies. Also, industrial automation and digitalization enhance resource management, reducing CO_2.

Regarding the rapid ED of the BRICS countries, an example of significant industrial activity is the use of new environmentally friendly technologies, which can considerably relieve the negative effect of industrious growth on the environment. Moreover, the policies supporting the innovation of clean technologies, including research and development and rising awareness of ecological sustainability, strengthen the positive impact of technological innovation on emissions. The outcomes of our study are familiar with the outcomes of Shafiq and Zafar (2023), Noureen et al. (2024), Li and Yue (2024) and Khan et al. (2024).

Like that, URN has a positive and significant impact on the CO_2. The outcomes stated that a 1% increase in the URN results in an increase of 8.62% in the CO_2. This stated that URN significantly enhances the CO_2 in the BRICS countries. This, in turn, means that the rate of EC, especially from the commercial and industrial sectors, increases to meet the demands of the growing URN, such as housing, transport and industries. The growth of the built environment entails construction, and construction contributes significantly to CO_2 because of cement production and utilization, as well as other construction materials such as steel. Thirdly, the observed tendency toward the concentration of populations in cities results in greater use of private cars and energy-consuming investments that run on fossil fuels. This environmental change is experienced in BRICS countries, whereby the extension of urbanization sooner or later entails the extension of industrialization. To the same extent, insufficient preparation of city expansions and the low utilization of green innovations reinforce emissions. This relation captures the environmental cost regarding the unplanned growth of cities in the emergent DE. The results of our research are familiar with the outcomes of Zhai and Kong (2024), Adebayo and Ullah (2024) and Gyamfi et al. (2024).

The outcomes reported a negative but significant impact of REC on the CO_2. The findings declare that a 1% increase in the REC results in a decrease of 6.89% in the CO_2. This declares that the REC significantly reduces the CO_2 in the BRICS countries. Unlike conventional sources of power like fossil fuels, green energy, solar energy, wind energy, hydropower, and biomass energy generate negligible amounts of CO_2 while in use. Raising the share of renewable energy sources in overall energy consumption reduces dependence on coal, oil, and natural gas, which are responsible for CO2 in BRICS countries. RE technologies reduce direct CO_2, and help make industries and homes more sustainable by providing clean power to make goods, move people and products, and power homes. BRICS countries' use of incentive policies and huge investment by their government has positively contributed towards the shift towards low carbon energy-related facilities. This impact is important in these nations because the electricity demand is increasing due to industrialization and URN. Capping emissions is halted by embracing renewable energy to preserve the environment as it fuels ED. The results from the study of Adebayo (2024), Shah et al. (2024) and Shang et al. (2024) also stated that REC significantly reduces the CO_2.

The findings reported a significant but negative relationship between GDPP and CO_2. The GDP slightly affects the CO_2 in BRICS countries. This is an aspect found in most economies; as economies mature, there is a shift from carbonized sectors, such as manufacturing and mining, to less carbonized sectors, such as ICT services. Moreover, ED makes room for other investments in efficient technologies, clean technologies, and improved types of energy to decrease emissions. However, this reduction is insignificant in the case of BRICS countries because they still rely heavily on fossils and resource consumption industrial activities as significant pillars of their economic systems. This is because the rise of the modern economy and development is coupled almost at the same speed as urbanization and industrialization, thus acting as a buffer to the environment. In addition, while developed nations have already developed policies that strictly regulate environmental pollution, it takes time to achieve population-wide results of innovations in environmentally friendly technologies, which can hinder the separation of GDPP from CO_2. Thus, the above dynamics give way to minimal CO_2 reduction, even with economic growth. The outcomes of our study are similar to the findings of Gershon et al. (2024), Khan et al. (2024) and Ritchie (2021). By analyzing the short-run outcomes, TIN, REC, URN and GDPP have an insignificant impact on the CO_2 in BRICS countries.

6. Conclusion

Since the pace of GDPP and industrialization is high among the BRICS countries, CO_2 has remained a crucial issue. These nations have been dependent on fossil energy sources for many generations for their ED. They have, therefore, released a large amount of CO_2. China, the biggest emitter, saw its emissions grow when it went through its industrialization process at the end of the twentieth and the beginning of the twenty-first century, following the American pattern but heavily relying on coal. Likewise, India has been emitting more GHG because of its increasing energy consumption and its industry development, which remains much below that of developed countries in terms of CO_2. Russia has also remained one of the world's top CO_2 emitters due to its EC and strong oil and gas industry. Since 1988, Brazil has been primarily impacted by the emissions from deforestation of the Amazon forests, apart from the industrial and energy-emitting sectors. South Africa, with the highest levels of industrialization in Africa, is one of the biggest emitters on the continent, primarily due to its reliance on coal for electricity generation. Nonetheless, in recent years, the BRICS countries have, in one way or another, realized the necessity to respond to environmental management. Together, they have vowed to decrease CO_2 through transnational climate change coalitions such as the Paris Agreement, which switched to green energy and technology and shifting policies. This paper discovers the study of CO_2 in this respect as relevant and timely, yet integrating economic progress with environmental responsibilities has remained a significant problem for these nations.

According to the PMG analysis, the study presents several findings defining the relationship of technological innovation, urbanization, GDP per capita and renewable energy consumption on carbon dioxide emission in the context of BRICS countries between 1990 and 2023. An adequate level of TIN leads to curbing of CO_2 in the long run, proving its ability to foster clean technologies and energy efficiency. Conversely, the growth variable has higher and positive coefficients for emissions due to energy-intensive URN processes in the BRICS countries. The results also demonstrate that REC has a significant and strongly negative impact on CO_2 in the given countries, thus supporting the idea of shifting to low-carbon energy sources. Similarly, GDPP also leads to a decrease in emissions, but to a minimal extent. The study implies that the efficiency gains from economic growth in decreasing have not been fully harnessed due to the continued use of fossil energy. The error correction term (COINTEQ01) indicates the presence of a stable long-run relationship between the variables analyzed. However, short-term effects are limited compared to them; TIN, URN, REC and GDPP do not considerably affect emissions. This shows that although these features affect the CO_2 levels in the future, a drastic change in such features in the short term does not have a corresponding effect on the emissions. Consequently, this study demonstrates the need to support RE and TIN in supporting sustainable environmental development and responding to the challenges of URN in BRICS countries.

6.1. Policy Implications

This paper argues that TIN is the main force behind CO_2 reduction as it increases energy intensity and purifies commodities. Governments of the BRICS countries must ensure that they foster innovation through regular promotion of green technology and enhancement of technology importation. Such initiatives will lead to a lasting shift in industries that imply low-carbon economic undertakings and ensure the durability of environmental impact. Promoting REC is critical to decreasing the consumption of fossil energy carriers and, hence, a CO2 reduction. Government grants, tax exemptions, and other incentives for deploying renewable electricity generation resources to the grid should exist. In the long run, the specific activities of the capacity enhancement of renewable energy sources will enhance energy security and mitigate the use of greenhouse gases, together with the development of an efficient comfort energy mix for a more efficient economy. A lot of understanding regarding the environmental sustainability of ED also exists because it is possible to grow the economy and green it to enhance the person and percentage emissions, enhancing the economic prospects. To that end, the government has to incorporate environmental issues as part of the strategy for economic development through the provision of grants to industries with low emission rates, development of carbon assets, carbon trading systems and more environmentally friendly approaches. Lastly, they will lower CO2 levels in the activities required for a new GDPP, create a favorable environment for new technologies, and guarantee welfare and ecological security.

Concerning the CO_2 in relation to the process of URN, there evidently lies its imperative challenges and, potentially, opportunities of sustainable development. The public authorities should stimulate green urban development by subsidizing effective energy utilities, transport and intelligent city solutions. In the long run, these initiatives will produce functional cities with low emission, per capita, and least carbon footprint, to become centers of excellence and innovation for environmentally sustainable development. In the short run, BRICS countries should enhance their strategies to mitigate the CO2 emission without disturbing the economic growth. It should be done due to the technological advancement through subsidies and tax reliefs, energy efficient systems and give subsidies on the renewable energy sources. Further, BRICS countries should also make their own green principles for the sustainable infrastructure. This study also has some limitations. We used data from BRICS countries only. So, the outcomes and policies can not be applied to the other nations. Moreover, some of the control variables are ignored. In the future, researchers can extend this study by adding more variables or changing the methodology approach.

Authors Contribution
Waqar Ahmed: literature search, data collection, data interpretation
Muhammad Munsif: literature search, data analysis, drafting
Rameez Akbar Talani: critical revision, incorporation of intellectual content
Ramez Raja: study design and concept, data interpretation, drafting

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References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The environment and directed technical change. *American economic review*, *102*(1), 131-166. https://doi.org/10.1257/aer.102.1.131
Adebayo, T. S. (2024). Do Uncertainties Moderate the Influence of Renewable Energy Consumption on Electric Power CO2 Emissions? A New Policy Insights. *International Journal of Sustainable Development & World Ecology*, *31*(3), 314-329. https://doi.org/10.1080/13504509.2023.2286487
Adebayo, T. S., & Ullah, S. (2024). Towards a Sustainable Future: The Role of Energy Efficiency, Renewable Energy, and Urbanization in limiting CO2 Emissions in Sweden. *Sustainable Development*, *32*(1), 244-259. https://doi.org/10.1002/sd.2658
Alvarez-Herranz, A., Balsalobre-Lorente, D., Shahbaz, M., & Cantos, J. M. (2017). Energy Innovation and Renewable Energy Consumption in the Correction of Air Pollution Levels. *Energy policy*, *105*, 386-397. https://doi.org/10.1016/j.enpol.2017.03.009
Aruga, K. (2019). Investigating the Energy-Environmental Kuznets Curve Hypothesis for the Asia-Pacific region. *Sustainability*, *11*(8), 2395. https://doi.org/10.3390/su11082395
Balsalobre-Lorente, D., Álvarez-Herranz, A., & Shahbaz, M. (2019). The long-term effect of economic growth, energy innovation, energy use on environmental quality. *Energy and environmental strategies in the era of globalization*, 1-34.
Balsalobre-Lorente, D., Leitão, N. C., & Bekun, F. V. (2021). Fresh Validation of the Low Carbon Development Hypothesis under the EKC Scheme in Portugal, Italy, Greece and Spain. *Energies*, *14*(1), 250. https://doi.org/10.3390/en14010250
Bilgili, F., Lorente, D. B., Kuşkaya, S., Ünlü, F., Gençoğlu, P., & Rosha, P. (2021). The Role of Hydropower Energy in the Level of CO2 Emissions: An Application of Continuous Wavelet Transform. *Renewable Energy*, *178*, 283-294. https://doi.org/10.1016/j.renene.2021.06.015
Bjerregaard, T. (2010). Industry and Academia in Convergence: Micro-Institutional Dimensions of R&D Collaboration. *Technovation*, *30*(2), 100-108. https://doi.org/10.1016/j.technovation.2009.11.002
Borghesi, S., Cainelli, G., & Mazzanti, M. (2015). Linking Emission Trading to Environmental Innovation: Evidence from the Italian Manufacturing Industry. *Research Policy*, *44*(3), 669-683. https://doi.org/10.1016/j.respol.2014.10.014
Chen, F., Liu, A., Lu, X., Zhe, R., Tong, J., & Akram, R. (2022). Evaluation of the Effects of Urbanization on Carbon Emissions: The Transformative Role of Government Effectiveness. *Frontiers in Energy Research*, *10*, 848800. https://doi.org/10.3389/fenrg.2022.848800
Chen, W., & Lei, Y. (2018). The Impacts of Renewable Energy and Technological Innovation on Environment-Energy-Growth Nexus: New Evidence from a Panel Quantile Regression. *Renewable Energy*, *123*, 1-14. https://doi.org/10.1016/j.renene.2018.02.026

Chen, W., Wang, G., Yang, L., Huang, C., Xu, N., Gu, T., & Zeng, J. (2023). Spillover Effects of Urbanization on Carbon Emissions: A Global View from 2000 to 2019. *Environmental Impact Assessment Review*, *102*, 107182. https://doi.org/10.1016/j.eiar.2023.107182

Churkina, G. (2016). The Role of Urbanization in the Global Carbon Cycle. *Frontiers in Ecology and Evolution*, *3*, 144. https://doi.org/10.3389/fevo.2015.00144

Das, S., Choudhury, M. R., Chatterjee, B., Das, P., Bagri, S., Paul, D., . . . Dutta, S. (2024). Unraveling the Urban Climate Crisis: Exploring the Cexus of Urbanization, Climate Change, and their Impacts on the Environment and Human Well-Being–A Global Perspective. *AIMS Public Health*, *11*(3), 963. https://doi.org/

Dissanayake, H., Perera, N., Abeykoon, S., Samson, D., Jayathilaka, R., Jayasinghe, M., & Yapa, S. (2023). Nexus between Carbon Emissions, Energy Consumption, and Economic Growth: Evidence from Global Economies. *Plos one*, *18*(6), e0287579. https://doi.org/10.1371/journal.pone.0287579

Dong, K., Dong, X., & Jiang, Q. (2020). How Renewable Energy Consumption Lower Global CO2 Emissions? Evidence from Countries with different Income Levels. *The World Economy*, *43*(6), 1665-1698. https://doi.org/10.1111/twec.12898

Erdogan, S. (2021). Dynamic Nexus between Technological Innovation and Building Sector Carbon Emissions in the BRICS Countries. *Journal of Environmental Management*, *293*, 112780. https://doi.org/10.1016/j.jenvman.2021.112780

Ganda, F. (2021). The Non-Linear Influence of Ttrade, Foreign Direct Investment, Financial Development, Energy Supply and Human Capital on Carbon Emissions in the BRICS. *Environmental Science and Pollution Research*, *28*(41), 57825-57841. https://doi.org/10.1007/s11356-021-14704-w

Gershon, O., Asafo, J. K., Nyarko-Asomani, A., & Koranteng, E. F. (2024). Investigating the Nexus of Energy Consumption, Economic Growth and Carbon Emissions in selected African Countries. *Energy Strategy Reviews*, *51*, 101269. https://doi.org/10.1016/j.esr.2023.101269

Ghosh, S., & Kanjilal, K. (2014). Long-Term Equilibrium Relationship between Urbanization, Energy Consumption and Economic Activity: Empirical Evidence from India. *Energy*, *66*, 324-331. https://doi.org/10.1016/j.energy.2013.12.052

Grossman, G. M., & Krueger, A. B. (1995). Economic Growth and the Environment. *The quarterly journal of economics*, *110*(2), 353-377. https://doi.org/10.2307/2118443

Gyamfi, B. A., Agozie, D. Q., Bekun, F. V., & Köksal, C. (2024). Beyond the Environmental Kuznets Curve in South Asian Economies: Accounting for the Combined Effect of Information and Communication Technology, Human Development and Urbanization. *Environment, Development and Sustainability*, *26*(5), 11263-11288. https://doi.org/10.1007/s10668-023-03281-2

Haseeb, A., Xia, E., Danish, Baloch, M. A., & Abbas, K. (2018). Financial Development, Globalization, and CO 2 Emission in the Presence of EKC: Evidence from BRICS Countries. *Environmental Science and Pollution Research*, *25*, 31283-31296. https://doi.org/10.1007/s11356-018-3034-7

He, J., & Richard, P. (2010). Environmental Kuznets Curve for CO2 in Canada. *Ecological Economics*, *69*(5), 1083-1093. https://doi.org/10.1016/j.ecolecon.2009.11.030

Heidari, H., Katircioğlu, S. T., & Saeidpour, L. (2015). Economic Growth, CO2 Emissions, and Energy Consumption in the Five ASEAN Countries. *International Journal of Electrical Power & Energy Systems*, *64*, 785-791. https://doi.org/10.1016/j.ijepes.2014.07.081

Herman, K. S., & Xiang, J. (2019). Induced Innovation in Clean Energy Technologies from Foreign Environmental Policy Stringency? *Technological Forecasting and Social Change*, *147*, 198-207. https://doi.org/10.1016/j.techfore.2019.07.006

Ibrahim, R. L., & Ajide, K. B. (2021). The Dynamic Heterogeneous Impacts of Nonrenewable Energy, Trade Openness, Total Natural Resource Rents, Financial Development and Regulatory Quality on Environmental Quality: Evidence from BRICS Economies. *Resources Policy*, *74*, 102251. https://doi.org/10.1016/j.resourpol.2021.102251

Ismael, S. M., Aleem, S. H. A., Abdelaziz, A. Y., & Zobaa, A. F. (2019). State-of-the-art of Hosting Capacity in Modern Power Systems with Distributed Generation. *Renewable Energy*, *130*, 1002-1020. https://doi.org/10.1016/j.renene.2018.07.008

Jebli, M. B., Farhani, S., & Guesmi, K. (2020). Renewable Energy, CO2 Emissions and value Added: Empirical Evidence from Countries with Different Income Levels. *Structural Change and Economic Dynamics*, *53*, 402-410. https://doi.org/10.1016/j.strueco.2019.12.009

Ji, X., Zhang, Y., Mirza, N., Umar, M., & Rizvi, S. K. A. (2021). The Impact of Carbon Neutrality on the Investment Performance: Evidence from the Equity Mutual Funds in BRICS. *Journal of Environmental Management*, *297*, 113228. https://doi.org/10.1016/j.jenvman.2021.113228

Khan, I., Zhong, R., Khan, H., Dong, Y., & Nuţă, F. M. (2024). Examining the Relationship between Technological Innovation, Economic Growth and Carbon Dioxide Emission: Dynamic Panel Data Evidence. *Environment, Development and Sustainability*, *26*(7), 18161-18180. https://doi.org/10.1007/s10668-023-03384-w

Khan, K., & Su, C.-W. (2021). Urbanization and Carbon Emissions: A Panel Threshold Analysis. *Environmental Science and Pollution Research*, *28*, 26073-26081. https://doi.org/10.1007/s11356-021-12443-6

Le, T.-H., Chang, Y., & Park, D. (2020). Renewable and Nonrenewable Energy Consumption, Economic Growth, and Emissions: International Evidence. *The Energy Journal*, *41*(2), 73-92. https://doi.org/10.5547/01956574.41.2.thle

Li, X., & Yue, S. (2024). Blessing or Curse? The Role of Digital Technology Innovation in Carbon Emission Efficiency. *Journal of Environmental Management*, *365*, 121579. https://doi.org/10.1016/j.jenvman.2024.121579

Liu, J., Liu, L., Qian, Y., & Song, S. (2022). The effect of artificial intelligence on carbon intensity: evidence from China's industrial sector. *Socio-Economic Planning Sciences, 83*, *83*(101002). https://doi.org/10.1016/j.seps.2020.101002

Magazzino, C. (2017). The Relationship among Economic Growth, CO2 Emissions, and Energy Use in the APEC Countries: A Panel VAR Approach. *Environment Systems and Decisions*, *37*(3), 353-366. https://doi.org/10.1007/s10669-017-9626-9

Mohammed Albiman, M., Nassor Suleiman, N., & Omar Baka, H. (2015). The Relationship between Energy Consumption, CO2 Emissions and Economic Growth in Tanzania. *International Journal of Energy Sector Management*, *9*(3), 361-375. https://doi.org/10.1108/IJESM-05-2014-0006

Nawaz, M. A., Hussain, M. S., Kamran, H. W., Ehsanullah, S., Maheen, R., & Shair, F. (2021). Trilemma Association of Energy Consumption, Carbon Emission, and Economic Growth of BRICS and OECD Regions: Quantile Regression Estimation. *Environmental Science and Pollution Research*, *28*, 16014-16028. https://doi.org/10.1007/s11356-020-11823-8

Nazir, R., Gillani, S., & Shafiq, M. N. (2023). Realizing direct and indirect impact of environmental regulations on pollution: A path analysis approach to explore the mediating role of green innovation in G7 economies. *Environmental Science and Pollution Research*, *30*(15), 44795-44818. https://doi.org/10.1007/s11356-023-25399-6

Noureen, T., Malik, M. Z., Khuhro, N. A., & Zafar, M. A. (2024). Exploring the Dynamics of CO2 Emissions, FDI, and Technological Innovation on Economic Growth: Evidence from BRICS Nations by Using CS-ARDL. *Pakistan Journal of Humanities and Social Sciences*, *12*(3), 2456-2469. https://doi.org/10.52131/pjhss.2024.v12i3.2448

Pablo-Romero, M. d. P., & De Jesús, J. (2016). Economic Growth and Energy Consumption: The Energy-Environmental Kuznets Curve for Latin America and the Caribbean. *Renewable and Sustainable Energy Reviews*, *60*, 1343-1350. https://doi.org/10.1016/j.rser.2016.03.029

Rai, P., Gupta, P., Saini, N., & Tiwari, A. K. (2025). Assessing the Impact of Renewable Energy and Non-Renewable Energy Use on Carbon Emissions: Evidence from Select Developing and Developed Countries. *Environment, Development and Sustainability*, *27*(2), 3059-3080. https://doi.org/10.1007/s10668-023-04001-6

Razzaq, A., Wang, Y., Chupradit, S., Suksatan, W., & Shahzad, F. (2021). Asymmetric Inter-Linkages between Green Technology Innovation and Consumption-Based Carbon Emissions in BRICS Countries using Quantile-on-Quantile Framework. *Technology in Society*, *66*, 101656. https://doi.org/10.1016/j.techsoc.2021.101656

Richmond, A. K., & Kaufmann, R. K. (2006). Is There a Turning Point in the Relationship between Income and Energy Use and/or Carbon Emissions? *Ecological Economics*, *56*(2), 176-189. https://doi.org/10.1016/j.ecolecon.2005.01.011

Ritchie, H. (2021). Many Countries have Decoupled Economic Growth from CO2 Emissions, even if we take Offshored Production into Account. *Our World in Data*.

Sayal, A., Gupta, A., Jha, J., Gupta, O., & Gupta, V. (2024). Renewable Energy and Sustainable Development: A Green Technology. 2024 1st International Conference on Innovative Sustainable Technologies for Energy, Mechatronics, and Smart Systems (ISTEMS),

Semieniuk, G., Campiglio, E., Mercure, J. F., Volz, U., & Edwards, N. R. (2021). Low-Carbon Transition Risks for Finance. *Wiley Interdisciplinary Reviews: Climate Change*, *12*(1), e678. https://doi.org/10.1002/wcc.678

Shafiq, M. N., & Zafar, M. A. (2023). Unraveling the dynamics of BRICS: a comprehensive analysis of CO2 emissions, energy consumption, and technological innovation. *iRASD Journal of Energy & Environment*, *4*(2), 91-100. https://doi.org/10.52131/jee.2023.0402.0038

Shah, W. U. H., Hao, G., Yan, H., Zhu, N., Yasmeen, R., & Dincă, G. (2024). Role of Renewable, Non-Renewable Energy Consumption and Carbon Emission in Energy Efficiency and Productivity Change: Evidence from G20 Economies. *Geoscience frontiers*, *15*(4), 101631. https://doi.org/10.1016/j.gsf.2023.101631

Shahbaz, M., Shafiullah, M., Khalid, U., & Song, M. (2020). A Nonparametric Analysis of Energy Environmental Kuznets Curve in Chinese Provinces. *Energy Economics*, *89*, 104814. https://doi.org/10.1016/j.eneco.2020.104814

Shang, M., Peng, M. Y.-P., Anser, M. K., Imran, M., Nassani, A. A., Binsaeed, R. H., & Zaman, K. (2024). Evaluating the U-shaped Environmental Kuznets Curve in China: The Impact of High Technology Exports and Renewable Energy Consumption on Carbon Emissions. *Gondwana Research*, *127*, 272-287. https://doi.org/10.1016/j.gr.2023.08.013

Stern, D. I. (2004). The Rise and Fall of the Environmental Kuznets Curve. *World development*, *32*(8), 1419-1439. https://doi.org/10.1016/j.worlddev.2004.03.004

Szetela, B., Majewska, A., Jamroz, P., Djalilov, B., & Salahodjaev, R. (2022). Renewable Energy and CO2 Emissions in Top Natural Resource Rents Depending Countries: the Role of Governance. *Frontiers in Energy Research*, *10*, 872941. https://doi.org/10.3389/fenrg.2022.872941

Turken, N., Carrillo, J., & Verter, V. (2020). Strategic Supply Chain Decisions under Environmental Regulations: When to Invest in End-of-Pipe and Green Technology. *European Journal of Operational Research*, *283*(2), 601-613. https://doi.org/10.1016/j.ejor.2019.11.022

Wang, F., Gillani, S., Balsalobre-Lorente, D., Shafiq, M. N., & Khan, K. D. (2025). Environmental degradation in South Asia: Implications for child health and the role of institutional quality and globalization. *Sustainable Development*, *33*(1), 399-415. https://doi.org/10.1002/sd.3124

Wang, F., Gillani, S., Nazir, R., & Razzaq, A. (2024). Environmental regulations, fiscal decentralization, and health outcomes. *Energy & Environment*, *35*(6), 3038-3064. https://doi.org/10.1177/0958305X2311646

Wang, F., Gillani, S., Razzaq, A., Nazir, R., Shafiq, M. N., & Li, B. (2024). Synergistic impacts of technological advancement and environmental hazards on social change and human well-being in South Asia. *Technological Forecasting and Social Change*, *208*, 123721. https://doi.org/10.1016/j.techfore.2024.123721

Wolfram, P., Wiedmann, T., & Diesendorf, M. (2016). Carbon Footprint Scenarios for Renewable Electricity in Australia. *Journal of Cleaner Production*, *124*, 236-245. https://doi.org/10.1016/j.jclepro.2016.02.080

Xu, J., Wang, J., Li, R., & Yang, X. (2023). Spatio-Temporal Effects of Urbanization on CO2 Emissions: Evidences from 268 Chinese Cities. *Energy policy*, *177*, 113569. https://doi.org/10.1016/j.enpol.2023.113569

Yang, X., Shafiq, M. N., Nazir, R., & Gillani, S. (2024). Unleashing the influence mechanism of technology innovation and human development for ecological sustainability in emerging countries. *Emerging Markets Finance and Trade*, *60*(10), 2276-2299. https://doi.org/10.1080/1540496X.2024.2308180

Yang, X., Shafiq, M. N., Sharif, A., Gillani, S., & Zeng, X. (2024). Balancing progress and preservation: analyzing the role of technological innovation in mitigating environmental degradation caused by energy consumption in China. *Economic Analysis and Policy*, *84*, 391-409. https://doi.org/10.1016/j.eap.2024.09.001

Zafar, M. A., Bhatti, M. A., Nawaz, M. A., & Ahmad, T. I. (2023). Assessing the Influence of Renewable Energy Sources on CO2 Emissions: New Insights from Pakistan. *iRASD Journal of Economics*, *5*(3), 825-844. https://doi.org/10.52131/joe.2023.0503.0164

Zaman, K., & Abd-el Moemen, M. (2017). Energy Consumption, Carbon Dioxide Emissions and Economic Development: Evaluating Alternative and Plausible Environmental Hypothesis for Sustainable Growth. *Renewable and Sustainable Energy Reviews*, *74*, 1119-1130. https://doi.org/10.1016/j.rser.2017.02.072

Zhai, J., & Kong, F. (2024). The Impact of Multi-Dimensional Urbanization on CO2 Emissions: Empirical Evidence from Jiangsu, China, at the County Level. *Sustainability*, *16*(7), 3005. https://doi.org/10.3390/su16073005

Zhang, J., Dai, Y., Su, C.-W., Kirikkaleli, D., & Umar, M. (2021). Intertemporal Change in the Effect of Economic Growth on Carbon Emission in China. *Energy & Environment*, *32*(7), 1207-1225. https://doi.org/10.1177/0958305X211008618

Zoundi, Z. (2017). CO2 Emissions, Renewable Energy and the Environmental Kuznets Curve, A Panel Cointegration Approach. *Renewable and Sustainable Energy Reviews*, *72*, 1067-1075. https://doi.org/10.1016/j.rser.2016.10.018