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Research Article

Keywords: CO2 emissions, Technology innovation, Panel NARDL

Posted Date: February 1st, 2022

DOI: https://doi.org/10.21203/rs.3.rs-833968/v1

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on January 3rd, 2022. See the published version at https://doi.org/10.1007/s11356-021-18067-0.

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Abstract
Technological innovation positively contributes to economic development in BRICS countries; their environmental consequences cannot be ignored. Thus, it is imperious to explore the impact of technological shocks on environmental quality. We used ARDL and NARDL models to draw empirical consensus on the data set from 1990 to 2019 for BRICS economies. The results of ARDL model reveal that technological shocks positively affect carbon emissions in the long-run and short-run. The findings of NARDL model reveal that positive shocks in technology positively affect carbon emissions in the long-run and short-run, implying that an increase in technological development triggers an increase in carbon emissions. However, the negative shocks in technology have a negative impact on carbon emissions in the long-run, inferring that a reduction in technological development leads to a decrease in carbon emissions. The negative shock in technology has no significant impact on carbon emissions in the short-run. The findings emphasize the importance of environmental-friendly technology to achieving sustainable development goals.

Keywords: CO2 emissions. Technology innovation. Panel NARDL

Introduction

To pursue the goal of economic development, regional cooperation and amalgamation have almost become a norm of new economic order. The countries from all the continents and regions have formed economic blocs that would enable them to work together for a common goal of growth and development. The latest example of such integration is BRICS, where five different economies viz. Brazil, Russia, India, China, and South Africa, from different regions, have joined hands together and formed an economic alliance (Zhao et al. 2021). This is not a regional bloc but an alliance between five emerging economies from four different continents, for the economic prosperity of almost 40% of the World's population living in these countries, that are collectively producing almost 20% of the total world's GDP and covered about 30% of earth's surface. These statistics are sufficient to convince anyone about the significant role that the BRICS economies are playing in the economic and political affairs of the world (Tian, 2015; Santra, 2017; Zhao et al. 2021).

In the 21st century, the most important challenge for world leaders is, how to reduce the harmful environmental effects attached to economic activities performed by humans (Usman et al. 2021). BRICS economies are an important part of every discussion on climate change held at the global stage, as they contribute about 41% of the total world's carbon emissions in 2017 (Mahalik et al. 2021). The environmental policies are very strict in developed and advanced economies and the environmental concerns in the developing economies are also on the rise due to the shifting of production units from developed to developing countries, particularly, the BRICS economies. Against this backdrop, the leadership and policymakers in the BRICS economies are not only keeping an eye on the target of high economic growth rate for the member countries but also trying to address the growing concerns of the international community about global warming and degrading environmental quality.

During the sixth meeting of BRICS countries in 2014 under the motto of 'inclusive growth: sustainable solution', the leaders from these countries concentrated on social inclusion and sustainable development (Fabbri and Ninni 2014). During this summit, they decided to build a new bank with the name of New Development Bank (NDB) which would provide financial assistance to the developing economies for achieving the target of sustainable development. Previously, in 2010, during the meeting of the United Nations Framework Climate Change Convention (UNFCCC) the member countries developed a fund called Green Climate Fund (GCF) and many countries pledged to support the fund. The development of NBD by BRICS economies is part of the commitment their leadership made in 2014 at the UNFCCC's summit in Bonn (Fabbri and Ninni 2014; Pao and Tsai 2011). Since then a major portion of the GCF has been utilized, in the promotion of low-emission and climate-friendly technology and also, in the financial support of the developing economies in the global fight against climate change (Lantz and Feng 2006; Tian 2015).

One of the largest sources of carbon emissions is the increased use of energy consumption due to rising growth activities (Aslam et al. 2021). BRICS countries are collectively consuming one-third of the total world's energy consumption and, by 2040, their consumption will reach more than 40% (BRICS Energy Report, 2020). One way of tackling the rising emissions of greenhouse gasses is through technological innovations. Technological innovation will not only help to reduce CO_2 emissions by conversing energy but also help to speed up the process of growth (Ullah et al. 2021). With the improved technology, the production activities become much more efficient which helps in the reduction of energy consumption because of the use of energy-efficient products during the manufacturing process (Usman et al. 2021). Similarly, on the demand side, as the prices of environment-friendly electronic appliances go down with the positive technology shock the domestic consumer also prefers more advanced and sophisticated appliances that conserve more energy and a lesser threat to the environment (Mensah et al. 2018; Usman et al. 2020; and Ahmad et al. 2021). Though there are studies available that dubbed innovations or investment in R&D crucial in the fight against CO_2 emissions (Jones, 1998) but the researchers lack in answering the question: whether the innovation is pro or countercyclical? According to Barlevy (2004), firms generally participate in R&D to attain momentary paybacks from the fruitful invention, in that, such liking for temporary returns activates R&D contribution in the time of booms and contracts in slumps. Similarly, Artuç and Pourpourides (2012) found that there is a positive relationship between rising capital stock and innovations. Whereas, Wälde and Woitek (2004) argued that innovation activities flourish during economic recessions. Although the previous studies to some extent have explained the procyclical innovations not many studies are available to explain the countercyclical conduct of innovation. Hence, the upward and downward trends in innovation not only affect the overall pace of the economy but it has many implications for the environmental quality of the globe as well.

A bulk of literature is highlighting the association between technological innovation and quality of environment for numerous regions and employed various out-of-dated regression techniques. For example, several studies have adopted symmetric estimation approaches to explore the impacts of technological innovation and ICT development on CO2 emissions (Zhang and Liu, 2015; Danish and Ulucak, 2020; Ulucak et al., 2020; Baloch et al., 2021; and Liu et al., 2021). However, none of the existing studies have investigated the asymmetric impact of technological innovation on CO2 emissions in BRICS economies. Technological innovations influence the quality of the environment asymmetrically through various aspects, such as financial, political, economic, and social. Thus, it provides asymmetric (positive or negative) variations in technological innovations that symmetric techniques are unable to capture. Previous stock of literature overlooks the asymmetric aspects of technological innovation on environmental quality that deliver biased findings. In keeping with this shortcoming of existing studies, this research employed nonlinear autoregressive distributed lag (NARDL) approach of Shin et al. (2014) to build literature on asymmetric impact of technological innovation on CO2 emissions in BRICS countries. Both empirically and theoretically, this research will contribute significantly in green growth research and theory given that no study has yet explored the asymmetric impact of technological innovation shocks on CO2 emissions to this date, especially in the case of BRICS.

Therefore, in this study, our primary goal is to see how the carbon emissions in BRICS countries respond to technology shocks. The selection of BRICS economies is not random rather based on their role as key players in today's world in almost all fields. To the best of our knowledge, this is the first-ever study that has picked the BRICS countries and tried to examine the technology-CO_2 nexus in these countries. To strengthen our analysis we have taken recourse to the non-linear Panel ARDL-PMG technique which gives us the extra to separately capture the impact of positive and negative shocks in technology on CO_2 emissions. As previously described, technological innovations are more prone to positive and negative shocks, hence, it becomes pertinent in the context of emerging economies like BRICS to see the implications of technology shock for the environmental quality of these countries.

The composition of this study is based on different sections. The second section will present information about data and estimation techniques. The results will be discussed in the third section. Last but not least, we will provide the conclusion in section fourth of the study.

Model and methods

Following the literature, we have developed model (1) to investigate the relationship between carbon emissions and technology shocks in BRICS economies.

$$\mathrm{CO}_{2,it} = \varphi_0 + \varphi_1 \mathrm{Tech}_{it} + \varphi_2 \mathrm{Education}_{it} + \varphi_3 \mathrm{GDP}_{it} + \varphi_4 \mathrm{POP}_{it} + \varphi_5 \mathrm{RD}_{it} + \varepsilon_{it} \qquad (1)$$

Where the carbon emission (CO_2) is a function of technology innovation (tech), average year of schooling (education), GDP per capita (GDP), population (POP), and research and development (RD), and random-error term (ε_{it}). This model is a long-run model and produces results in the long-run only. To get the short-run estimates as well, we have decided to apply the panel ARDL-PMG model. To that end, equation (1) needs to be described in a format known as error-correction as shown below:

$$\begin{aligned}\Delta \mathrm{CO}_{2,it} = {} & \omega_0 + \sum_{k=1}^{n} \beta_{1k} \Delta \mathrm{CO}_{2,i,t-k} + \sum_{k=0}^{n} \beta_{2k} \Delta \mathrm{Tech}_{i,t-k} + \sum_{k=0}^{n} \beta_{3k} \Delta \mathrm{Education}_{i,t-k} + \sum_{k=0}^{n} \beta_{4k} \Delta \mathrm{GDP}_{i,t-k} \\ & + \sum_{k=0}^{n} \beta_{5k} \Delta \mathrm{POP}_{i,t-k} + \sum_{k=0}^{n} \beta_{6k} \Delta \mathrm{RD}_{i,t-k} + \omega_1 \mathrm{CO}_{2,i,t-1} + \omega_2 \mathrm{Tech}_{i,t-1} + \omega_3 \mathrm{Education}_{i,t-1} \\ & + \omega_4 \mathrm{GDP}_{i,t-1} + \omega_5 \mathrm{POP}_{i,t-1} + \omega_6 \mathrm{RD}_{i,t-1} + \varepsilon_t \qquad (2)\end{aligned}$$

The equation (2) can now be called panel ARDL-PMG (1999 and 2001). This method has few advantages as compared to other methods. Firstly, it gives us both the short and long-run estimates simultaneously. In equation (2) the variables connected with the first difference indicator Δ provide the short-run results and the long-run results can be collected by estimating the coefficients $\omega_2 - \omega_6$ normalized on ω_1. The validity of the long-run results rests on the significant and negative value of the error correction term (Bahmani-Oskooee et al. 2020 and Yin et al. 2021). By using the normalized long-run estimates from equation (1) we generate a series of residuals. We call this series as ECM and replace the lagged value of ECM in place of the linear relationship of lagged-level variables in equation (2) and estimate this new equation with the same number of lags. The estimate attached to ECM_{t-1} represents the speed of adjustment towards long-run equilibrium and its value should be negative and significant to prove the co-integration among long-run estimates. Secondly, the major advantage of using this method is that it can estimate the model efficiently even if the model contains the variables that are I(0), I(1), or blend of both due to the power of this method for accounting for the integrating properties of the variables (Ullah & Ozturk 2020 and Ullah et al. 2021). In order to get the asymmetric estimates, which is the main purpose of this study, we will split the main variable i.e. technology into two components viz. the positive shocks in technology and negative shock in technology by applying the partial sum technique of Shin et al. (2014) and the equational form of the procedure is given underneath:

$$Tech^{+}_{it} = \sum_{n=1}^{t} \Delta Tech^{+}_{it} = \sum_{n=1}^{t} \max\ (\Delta Tech^{+}_{it}, 0) \qquad (3a)$$

$$Tech^{-}_{it} = \sum_{n=1}^{t} \Delta Tech^{-}_{it} = \sum_{n=1}^{t} \min\ (\Delta Tech^{-}_{it}, 0) \qquad (3b)$$

Where $Tech^{+}_{it}$ represents the rising trend or shocks and $Tech^{-}_{it}$ represents the decreasing trend or shock in the above equations (3a & 3b). Next, these positive and negative series should be substituted in place of the original series and the new equation will look like as follows:

$$\begin{aligned}\Delta CO_{2,it} = {} & \alpha_0 + \sum_{k=1}^{n} \beta_{1k} \Delta CO_{2,it-k} + \sum_{k=0}^{n} \beta_{2k}\, \Delta Tech^{+}_{it-k} + \sum_{k=0}^{n} \delta_{3k}\, \Delta Tech^{-}_{it-k} \sum_{k=0}^{n} \beta_{4k}\, \Delta Education_{it-k} \\ & + \sum_{k=0}^{n} \beta_{5k}\, GDP_{it-k} + \sum_{k=0}^{n} \beta_{6k}\, POP_{it-k} + \sum_{k=0}^{n} \beta_{7k}\, RD_{it-k} + \omega_1 CO_{2,it-1} + \omega_2 Tech^{+}_{it-1} \\ & + \omega_3 Tech^{-}_{it-1} + \omega_4 Education_{it-1} + \omega_5 GDP_{it-1} + \omega_6 POP_{it-1} + \omega_7 RD_{it-1} + \varepsilon_{it} \qquad (4)\end{aligned}$$

Specification (4) has taken the shape of non-linear panel ARDL-PMG and the procedure of estimating this equation is similar to the linear panel ARDL-PMG. Moreover, as this is an extension to the linear model, hence, it is subject to the same test of co-integration and diagnostic tests.

Data

In order to inspect the link between technological shocks and CO2 emissions, this analysis employed panel data from 1990 to 2019. The BRICS economies are one of the most influential players because BRICS economies consume 40% of the world's energy consumption and are massive contributors to carbon emissions. The dependent variable is CO2 emissions and the independent variable is technology innovation which is used as a proxy of total patent applications. Also, Mensah et al. (2018) consider this factor as a proxy of technological innovation. Moreover, our analysis has used the average year of schooling, population, GDP per capita, and research and development as control variables. All data employed in this analysis are extracted from the World Bank, while a year of schooling is obtained from Barro-Lee. While CO2, technology innovation, population, GDP per capita variables are transformed into a natural log to improve the coefficient estimates of the model. The detailed data and sources information are given in Table 1.

Table 1: Definitions and sources

Variables	Abbreviations	Definitions	Sources
Carbon dioxide emissions	CO2	Carbon dioxide emissions (kilotons)	World Bank
Technology innovation	Tech	Patent applications, total (residents and non-residents)	World Bank
Year of schooling	Education	Average year of schooling	Barro-Lee
Population	POP	Population, total	World Bank
GDP per capita	GDP	GDP per capita (constant 2010 US$)	World Bank

Research and development	RD	Research and development expenditure (% of GDP)	World Bank

Results and discussion

Before the application of the Panel ARDL model, we will perform some panel unit root tests to confirm that all the variables included in the analysis become stationary even after differencing once. To that end, three different panel unit root tests are applied viz. Levin, Lu and Chin (LLC), Im, Pesaran, and Shin (IPS), and Fisher-ADF. In table 2, the results of these tests are presented which confirm that all the variables included in the model are either I(0) and I(1). Therefore, the pre-condition for the application of the ARDL method is fulfilled and we can now start our formal discussion on the estimates of the variables. The estimates of both the linear and non-linear models, calculated values of the co-integration test, and related diagnostic statistics are provided in table 3. The long-run results are judged absurd if there is proof of co-integration between them is not found. The estimates attached to ECM_{t-1} (a test of co-integration) are negatively significant in both models implying the fact that a valid long-run relationship exists between CO_2, Tech, Education, GDP, RD, and POP. The negative and significant estimates of ECM_{t-1} reject the null hypothesis of no co-integration in both the linear and non-linear models.

Table 2: Panel unit root testing

	LLC			IPS			ADF		
	I(0)	**I(1)**	**Decision**	**I(0)**	**I(1)**	**Decision**	**I(0)**	**I(1)**	**Decision**
CO2	0.232	-1.372*	I(1)	-1.310	-3.632***	I(1)	-1.735**		I(0)
Tech	-1.911**		I(0)	-1.504	-3.640***	I(1)	-0.528	-9.448***	I(1)
Education	1.084	-3.516***	I(1)	-0.452	-2.966***	I(1)	-0.701	-5.670***	I(1)
GDP	-3.594***		I(0)	-2.166**		I(0)	-2.438***		I(0)
RD	-1.741*		I(0)	-1.928*		I(0)	-1.676**		I(0)
POP	-2.089*		I(0)	-1.106	-3.933***	I(1)	-0.220	-11.67***	I(1)

Note: * p-value < 0.10 ** p-value < 0.05 *** p-value < 0.01

From Table 3, we collect that the carbon emissions in BRICS economies are positively affected by technological improvement. More specifically, as the number of patent applications (TECH) increases by 1% the CO_2 emissions rise by 0.281%. The BRICS economies fall in the category of emerging economies that use technological innovations to promote their economic growth and the energy mix used by these countries is dominated by fossil fuels e.g. China the largest economy of BRICS, China fulfill 87% of its energy demand via fossil fuels (Petroleum, 2019) and the technology innovations in fossil energy boost the carbon emissions (Wang and Zhu, 2020). According to Dauda et al. (2019), the positive effects of innovation on environmental quality is largely dependent on whether the innovation is happening in the developed or developing economy. The innovations in the developed economies are more energy-efficient and environment-oriented, hence, reduce CO_2 emissions. Whereas, innovations in emerging and developing economies increase CO_2 emissions because the environment-related rules and regulations are not strict and do not force the firms to involve in eco-innovations and renewable-energy innovations. Ganda (2019) and Koçak and Ulucak (2019) observed similar type of findings in the context of OECD countries and China respectively.

Now we will see how the CO_2 emissions respond to asymmetric changes in technology innovations. The estimated coefficient of Tech_POS is positive and significant conferring that CO_2 emissions increase by 0.050% with every percentage point increase in patent applications in the BRICS economies. Conversely, a negative shock in technology i.e. a 1% fall in the number of patent applicants reduces the CO_2 emissions by 0.214 %. This result fortifies the finding of our symmetric model because the asymmetric findings are also conveying the same message that positive shock in innovations in emerging economies is not environment-oriented rather growth-oriented, hence, the negative shock in innovation will prove environment friendly. However, the impact of negative change is much stronger as compared to the positive which is a sign of long-run asymmetric effects between positive and negative change on CO_2 emissions also confirmed by the significant estimate of Wald test represented by Wald-LR illustrated in table 3.

Alongside the main variable of innovation, we have included some control variables such as Education, GDP, RD, and POP. The symmetric estimate attached to Education suggests that every extra year of schooling decreases the CO_2 emissions by 0.135% in BRICS economies. According to endogenous growth theory, knowledge can serve as an input in the production function and contribute to the sustainable growth of the economy (Ang and Madsen, 2011; Benos and Zotou, 2014). During the process of economic growth, investment in human capital i.e. education is helpful to shift the economy to more energy-efficient production methods that will improve the environmental quality (Li and Lin, 2016 and Li & Ullah 2021). Moreover, energy and knowledge can substitute each other in the production process and more knowledge-oriented production techniques drive the economy towards more eco-friendly methods of productions (Arbex and Perobelli, 2010). Similarly, in the non-linear analysis, the estimated coefficient (0.120) is negative and significant inferring that Education proves to be environment friendly in BRICS economies.

Table 3: Panel ARDL and NARDL estimates of CO2 emissions

	ARDL				NARDL			
Variable	**Coefficient**	**Std. Error**	**t-Stat**	**Prob.***	**Coefficient**	**Std. Error**	**t-Stat**	**Prob.***
Long-run								
TECH	0.281***	0.036	7.801	0.000				
TECH_POS					0.050*	0.030	1.666	0.100
TECH_NEG					0.214*	0.113	1.891	0.063
EDUCATION	-0.135***	0.035	3.831	0.000	-0.120***	0.008	15.71	0.000
GDP	0.008	0.018	0.437	0.664	0.033***	0.007	4.471	0.000
RD	-0.510***	0.144	3.549	0.001	-0.270***	0.053	5.108	0.000
POP	0.130	0.243	0.536	0.593	1.481***	0.238	6.221	0.000
Short-run								
D(TECH)	0.001	0.051	0.006	0.995				
D(TECH(-1))	-0.019	0.058	0.336	0.738				
D(TECH_POS)					0.098*	0.051	1.904	0.060
D(TECH_POS(-1))					0.038	0.076	0.502	0.617
D(TECH_NEG)					-0.247	0.651	0.379	0.706

D(TECH_NEG(-1))					0.008	0.444	0.018	0.986
D(EDUCATION)	0.003	0.018	0.142	0.887	0.004	0.012	0.297	0.768
D(EDUCATION(-1))	0.029	0.027	1.058	0.293	0.044	0.030	1.444	0.154
D(GDP)	0.036*	0.022	1.660	0.100	0.021*	0.013	1.687	0.095
D(GDP(-1))	-0.005	0.005	1.110	0.270	-0.005	0.011	0.415	0.679
D(RD)	-0.221*	0.123	1.803	0.074	-0.139**	0.065	2.145	0.034
D(RD(-1))	-0.177	0.227	0.779	0.438	0.075	0.200	0.373	0.710
D(POP)	-0.272	0.307	0.887	0.378	-0.826	0.704	1.173	0.245
D(POP(-1))	0.626*	0.366	1.711	0.091	0.018	0.495	0.036	0.971
C	1.369	1.154	1.186	0.239	-8.112	6.247	1.299	0.199
Diagnostic								
ECM (-1)	-0.299**	0.147	2.029	0.045	-0.274**	0.135	2.031	0.045
Log-likelihood	297.1				291.1			
Wald-LR					3.386**			
Wald-SR					1.254			
Kao-Cointegration	4.658***				5.017***			

Note: * p-value < 0.10 ** p-value < 0.05 *** p-value < 0.01

The variable of GDP does not have any noticeable impact on CO_2 emissions in the linear model, whereas, a 1% rise in GDP per capita in BRICS economies increases the CO_2 emissions by 0.033% suggesting that economic activity in the BRICS economies is contaminating the environment. On the other side, a 1% increase in research and development expenditures decreases the CO_2 emissions by 0.510% in the linear model and 0.270% in the non-linear model. From this result, we can deduce that the RD expenditures in the BRICS economies help control environmental degradation due to the development of more energy-efficient production techniques and consumer appliances consuming less energy (Mensah et al. 2018 and Ahmad et al. 2021). Lastly, the estimated coefficient of the population (POP) is insignificant in the linear analysis, whereas, a 1% rise in the population increases the carbon emissions by 1.481%. The size of the estimate is quite large which confirms the fact that population is a key source in polluting the environment.

The short-run results are also provided in table 3. The symmetric estimates attached to ΔGDP and ΔPOP are positive and significant, whereas, the estimate attached to ΔRD is negatively significant. The asymmetric estimates of ΔTech and ΔGDP are positively significant, while, negatively significant in the case of ΔRD. Lastly, the causality results are reported in table 4. From the estimates, illustrated in Table 4, we can say that there is bidirectional symmetric causality existed between Tech and CO_2. Similarly, in the asymmetric causal analysis, we find support for bidirectional causality between Tech_POS and CO_2, alongside, Tech_NEG and CO_2.

Table 4: Panel symmetric and asymmetric causality

Symmetric causality				**Asymmetric causality**			
Null Hypothesis:	**W-Stat.**	**Zbar-Stat.**	**Prob.**	**Null Hypothesis:**	**W-Stat.**	**Zbar-Stat.**	**Prob.**
TECH →CO2	5.486	3.021	0.003	TECH_POS →CO2	6.861	4.233	0.000
CO2 →TECH	7.820	5.167	0.000	CO2 →TECH_POS	1.826	-0.350	0.726
EDUCATION →CO2	6.750	4.183	0.000	TECH_NEG →CO2	2.110	-	0.927

						0.092	
CO2 →EDUCATION	5.239	2.794	0.005	CO2 →TECH_NEG	4.232	1.840	0.066
GDP →CO2	2.232	0.030	0.976	EDUCATION →CO2	6.750	4.183	0.000
CO2 →GDP	4.241	1.877	0.061	CO2 →EDUCATION	5.239	2.794	0.005
RD →CO2	4.522	2.135	0.033	GDP →CO2	2.232	0.030	0.976
CO2 →RD	3.126	0.852	0.394	CO2 →GDP	4.241	1.877	0.061
POP →CO2	4.817	2.406	0.016	RD →CO2	4.522	2.135	0.033
CO2 →POP	3.040	0.772	0.440	CO2 →RD	3.126	0.852	0.394
EDUCATION →TECH	2.646	0.410	0.682	POP →CO2	4.817	2.406	0.016
TECH →EDUCATION	3.390	1.094	0.274	CO2 →POP	3.040	0.772	0.440
GDP →TECH	3.270	0.983	0.326	TECH_NEG →TECH_POS	32.50	27.56	0.000
TECH →GDP	2.430	0.212	0.832	TECH_POS →TECH_NEG	2.828	0.562	0.574
RD →TECH	7.022	4.433	0.000	EDUCATION →TECH_POS	0.212	-1.819	0.069
TECH →RD	2.229	0.026	0.979	TECH_POS →EDUCATION	4.530	2.111	0.035
POP →TECH	5.659	3.180	0.002	GDP →TECH_POS	3.328	1.017	0.309
TECH →POP	5.947	3.445	0.001	TECH_POS →GDP	2.304	0.085	0.932
GDP →EDUCATION	3.387	1.091	0.275	RD →TECH_POS	4.135	1.751	0.080
EDUCATION →GDP	2.264	0.058	0.953	TECH_POS →RD	3.035	0.750	0.453
RD →EDUCATION	6.245	3.719	0.000	POP →TECH_POS	1.221	-0.901	0.368
EDUCATION →RD	3.536	1.229	0.219	TECH_POS →POP	6.686	4.073	0.000
POP →EDUCATION	2.285	0.078	0.938	EDUCATION →TECH_NEG	6.667	4.056	0.000
EDUCATION →POP	2.504	0.279	0.780	TECH_NEG →EDUCATION	3.279	0.972	0.331
RD →GDP	4.161	1.803	0.071	GDP →TECH_NEG	2.352	0.129	0.897
GDP →RD	1.671	-0.486	0.627	TECH_NEG →GDP	3.454	1.132	0.258
POP →GDP	2.148	-0.048	0.962	RD →TECH_NEG	4.728	2.292	0.022
GDP →POP	2.933	0.674	0.500	TECH_NEG →RD	2.469	0.235	0.814
POP →RD	3.572	1.261	0.207	POP →TECH_NEG	3.805	1.451	0.147
RD →POP	4.660	2.261	0.024	TECH_NEG →POP	2.196	-0.013	0.990
				GDP →EDUCATION	3.387	1.091	0.275
				EDUCATION →GDP	2.264	0.058	0.953
				RD →EDUCATION	6.245	3.719	0.000
				EDUCATION →RD	3.536	1.229	0.219
				POP →EDUCATION	2.285	0.078	0.938
				EDUCATION →POP	2.504	0.279	0.780
				RD →GDP	4.161	1.803	0.071
				GDP →RD	1.671	-0.486	0.627
				POP →GDP	2.148	-0.048	0.962
				GDP →POP	2.933	0.674	0.500
				POP →RD	3.572	1.261	0.207
				RD →POP	4.660	2.261	0.024

Note: * p-value < 0.10 ** p-value < 0.05 *** p-value < 0.01

Conclusion and implications

During the previous few years, the technology sector in BRICS economies has documented enormous development. The governments of these economies are still making efforts to converge themselves into digital economies. This study investigates the renowned effect of technological shocks on environmental quality in BRICS economies. The study adopted panel ARDL and NARDL models for empirical inspection with year-wise data over the period of 1990-2019. The findings of the study indicate that the emergence of technological innovation in daily life contributes significantly to increasing pollution emissions. The results of ARDL model demonstrate that technology innovation has a significant positive impact on carbon emissions in the long-run, however, the effect is statistically insignificant in the short-run. The results of the panel NARDL model reveal that positive shock has a significant positive impact on pollution emissions in the long-run. In a more simplified manner, these findings reveal that positive components of technology innovations disrupt environmental quality by increasing pollution emissions, and negative components of technology innovation improve environmental quality by reducing pollution emissions in the long run. The outcomes NARDL model also reveals that positive shocks in technology innovations result in increasing carbon emissions in the short-run. Finally, the outcomes of asymmetric causality suggest that any positive shock in technology innovation has a positive causal effect on pollution emission in BRICS countries.

Based on these findings, our analysis also forwarded some policy implications. The first and foremost is that the non-linear analysis provides an opportunity to measure the direction and magnitude of the effects of positive and negative shocks in technology on the environmental quality of BRICS economies. Hence, policymakers and environmentalists should devise their strategies by keeping in mind the impacts of both positive and negative shocks. Moreover, BRICS economies should promote the trademark and patent policies for those products and innovations that conserve more energy and are environmentally friendly. In this context, the governments could implement the pollution tax on the technologies that are damaging for the ecosystem and could increase the fees on the registration of such technologies, so that the overall wellbeing of the society is not compromised at the expense of few. The BRICS economies should pay more attention to environmental protection and energy-saving innovation in the industry. BRICS economies should adopt policies that support technological innovation for environmental sustainability.

Although, this study has some limitations. Our study has explored the influence of technology innovations on CO2 emissions, while the causal relationship between environmental technology innovations and CO2 has not been demonstrated asymmetrically. Future empirical research can explore the relationships between environmental technology innovation and CO2 emissions for BRICS economies. In further, authors should be extended research by considering other advanced estimation approaches based on a panel as well time-series models for regional and country-wise analysis.

Ethical Approval: Not applicable

Consent to Participate: I am free to contact any of the people involved in the research to seek further clarification and information

Consent to Publish: Not applicable

Authors Contributions: This idea was given by Jingjing Chen. Jingjing Chen, Fuwei Yang, Yicen Liu, and Ahmed Usman analyzed the data and wrote the complete paper. While, Ahmed Usman read and approved the final version.

Funding: Not applicable.

Competing interests: The authors declare that they have no conflict of interest.

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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