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Revealing the effectiveness of technological innovation shocks on CO_2 emissions in BRICS: emerging challenges and implications

--Manuscript Draft--

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Corresponding Author:	Nafeesa Mughal Xi'an Jiaotong University Xian, Shaanxi CHINA
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Xi'an Jiaotong University
Corresponding Author's Secondary Institution:	
First Author:	Xiaoqiang Ma
First Author Secondary Information:	
Order of Authors:	Xiaoqiang Ma
	Asma Arif
	Prabjot Kaur
	Vipin Jain
	Laila Rafaina
	Nafeesa Mughal
Order of Authors Secondary Information:	
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Abstract:	The debate on technological innovation shocks and its effect on the environment are of great interest to academicians and environmentalists worldwide. At present, primary focus of this research is to investigate the asymmetric technology shocks and its impact on CO2 emissions for BRICS economies. The linear and non-linear panel ARDL models are applied to compute both short run and long run dynamics of technology shocks and CO2 emissions. Asymmetric estimates confer that a positive shock in patents reduces the CO2 emissions by 0.418%, whereas negative shock increases the CO2 emissions by 0.854%. Contrariwise, the trademark positive shock increases the carbon emissions by 0.416% and vice versa. The non-linear analysis provides an opportunity to measure the direction and magnitude 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 positive and negative shocks.
Response to Reviewers:	"Revealing the effectiveness of technological innovation shocks on CO2 emissions in BRICS: emerging challenges and implications" Dear Editor and Reviewers, We would like to commence by thanking the editor and the two reviewers for their valuable time and constructive comments. Their expert knowledge of the field has helped us to strengthen the manuscript significantly. According to the valuable suggestions provided by the reviewers, we have revised the manuscript. We endeavored to address all the comments and our reflections are now given below point

	by point. Changes to the manuscript are shown in red. Sincerely, The Authors
Additional Information:	
Question	**Response**
§Are you submitting to a Special Issue?	No

Reply to Reviewers Comments for ESPR-D-21-13998

"Revealing the effectiveness of technological innovation shocks on CO2 emissions in BRICS: emerging challenges and implications"

Dear Editor and Reviewers,
We would like to commence by thanking the editor and the two reviewers for their valuable time and constructive comments. Their expert knowledge of the field has helped us to strengthen the manuscript significantly. According to the valuable suggestions provided by the reviewers, we have revised the manuscript. We endeavored to address all the comments and our reflections are now given below point by point. Changes to the manuscript are shown in red.

Sincerely,
The Authors

Reviewer #1
1. The title is incorrect. I assume the authors are revealing the the impacts of technological innovation on CO2 emissions. Hence, it should not be 'Unrevealing.' Rather the authors should either use "Unveiling" or "Revealing."
Response: Agreed. It is corrected as suggested. We have changed the title as: **Revealing the effectiveness of technological innovation stocks on CO2 emissions in BRICS: emerging challenges and implications**

2. The introduction should include a paragraph to discuss the relevance of abating CO2 emissions in light of the Paris Agreement and SDG13. In this regard, the authors should refer the following studies:
Response: To expand the discussion on Paris Agreement and SDG13 in introduction section following studies are added.

3. The literature review is weak. Lots of important studies on determinants of CO2 emissions are missing. The authors should include the following studies (may be in a box literature review form) to improve and update the literature review section:
Response: To expand the literature of paper following studies are also added in early part.

4. I am skeptical regarding the choice of the methods. The authors should conduct the cross-sectional dependency, slope heterogeneity, CADF, CIPS, and Westerlund cointegration analyses because it is well acknowledged in the literature that there are issues of cross-sectional dependency and slope heterogeneity in BRICS data.
Response: Thanks! The rationale behind the selection of the model is added in the revised manuscript. We also added the suggested test in the model section.

5. The discussion on the findings should be more elaborate.
Response: Thank you for your thoughtful comment. The economic meaning of the results has been more explained with prior studies.

6. The policy implications should be improved.

Response: A comprehensive policy recommendation with study limitations is added in the revised manuscript.

7. Please improve the quality of the language used in this study. Consult a professional to address this issue.
Response: Thank you for the valuable suggestions. In this new version, we have carefully revised the language of the manuscript, and believe this new version is typos-free and more readable. We have corrected all sentence structure mistakes in the manuscript from the English editor. Changes to the manuscript are shown in red.

Reviewer #2:

Abstract
1 Why this topic is selected? What's the significance of it? Please show 1-2 sentences in the beginning.
Response: We have added the background and significance of the study are also added in the revised manuscript.

2 What do you mean by "ARDL"? It is better to show the full name of it.
Response: Thanks for correcting us. The full name of ARDL is also added in the abstract.

3 What's the study period?
Response: The study period is also mentioned.

4 Do you have any numbers to further explain your major results?
Response: Thanks for correcting us. The results magnitudes are added in revised manuscript.

Introduction
1 Line 45 to line 47. This is not a good way to express.
Response: Agreed, these lines are corrected in simple way.
These statistics are sufficient to convince anyone about the significant role that the BRICS economies play in the world's economic and political affairs (Santra, 2017 and Tian et al., 2020).

2 Please add the relevant citations for line 56 and line 57.
Response: Thanks! The relevant citations are also added.

3 Why this method is selected? How about others? It's better to give a show literature review.
Response: We have revised the model and methods section, we have added some more explanations regarding the methods. This method is also supported by advanced literature.

Methods
1 It's better to give a brief introduction to the method.
Response: A brief discussion on the method is added in the introduction and model section

References
1 Please improve the information for line 353, line 377, line 382, line 386.
Response: Sorry for these mistakes. All reference typographical errors are corrected.

Revealing the effectiveness of technological innovation shocks on CO_2 emissions in BRICS: emerging challenges and implications

Xiaoqiang Ma

School of Economics and Management, Northwest University, Xi'an, China

Asma Arif

Department of Economics, University of Wah, Wah Cantt 47040, Pakistan

Prabjot Kaur

Department of Mathematics, Birla Institute Of Technology Mesra, Ranchi Jharkhand, India

Vipin Jain

College of Management, Teerthanker Mahaveer University Moradabad, Uttar Pradesh, India

Laila Rafaina

Universitas Lambung Mangkurat, Indonesia

Nafessa Mughal *

***Corresponding Author**

nafeesamughal@stu.xjtu.edu.cn

School of Economics, Xi'an Jiaotong university, Xi'an Shaanxi China

Revealing the effectiveness of technological innovation shocks on CO2 emissions in BRICS: emerging challenges and implications

The debate on technological innovation shocks and its effect on the environment are of great interest to academicians and environmentalists worldwide. At present, primary focus of this research is to investigate the asymmetric technology shocks and its impact on CO2 emissions for BRICS economies. The linear and non-linear panel ARDL models are applied to compute both short run and long run dynamics of technology shocks and CO2 emissions. Asymmetric estimates confer that a positive shock in patents reduces the CO2 emissions by 0.418%, whereas negative shock increases the CO2 emissions by 0.854%. Contrariwise, the trademark positive shock increases the carbon emissions by 0.416% and vice versa. The non-linear analysis provides an opportunity to measure the direction and magnitude 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 positive and negative shocks.

Keywords: Technology shocks; CO2 Emissions; Energy Consumption; Sustainability; BRICS

Introduction

The last few decades have experienced unusual fluctuations in global temperature due to increased economic growth worldwide. Policymakers and empirics widely recognize that anthropogenic emissions of greenhouse gases are primarily responsible for rising global temperature, damaging human health, and the ecological setup of nature(Chen & Lee, 2020). The share of CO2 emissions is the largest among all GHGs emissions, and its ratio has been augmented many times since the 1960s (Bhattacharya et al. 2016). Since then, CO2 emissions have become an essential factor in representing environmental quality. Empirical evidence largely supports this notion that economic activities damage environmental quality in different countries (Wang & Zhang, 2020). Two agreements, the Kyoto protocol, and the latest Parsi Agreement have been signed considering the importance of preserving the environment for this and upcoming generations. The main crux of both agreements is to protect the environment without compromising on environmental quality (Rehman et al. 2020).

In the year 2015, the Paris agreement was signed by international leaders from 195 member states during the 21st Conference of Parties (COP) in Paris (Rehman et al. 2021). The Paris agreement demanded the member states make united efforts in combating the menace of climate (Nathaniel et al.2021). Further, the document of the Paris agreement also provides a future course of action to protect the environment worldwide (UNFCCC 2015). Another binding condition for all the member states is to" hold warming well below 2 °C in global mean temperature (GMT), relative to pre-industrial levels, and to pursue efforts to limit warming to 1.5 °C". Consistent with this view, the United Nations Development Program proposed a complete and comprehensive charter for attaining the sustainable development of the world known as sustainable development goals (SDGs). Goal 13 of the SGDs stresses upon the world to swiftly respond to climate change and its related effects. However, the world is not responding to the call of the UNDP and Paris Agreement, and in 2020 the world's average temperature is 1.2°C higher than the pre-industrial baseline (Murshed et al. 2020 and Li et al. 2021).

Despite the growing universal concerns on the depletion of the environment, due to the rise in economic activities, emerging economies are still preferring economic interests over environmental (Murshed et al. 2021). However, following the footprints of advanced economies, the policymakers in emerging economies are now stressing the need for technological innovations to conserve energy, curb CO_2 emissions, and attain long-term economic growth (Balsalobre-Lorente et al. 2021 and Ullah et al. 2021). It is widely recognized that energy contributes to the rising energy demand that causes environmental degradation by emanating CO_2 emissions. But the conservation of energy through innovation can help the market improve its efficiency and remove an imperfection in the supply chains. For example, advancements in the technological process to build and create environmentally-friendly products cycles and units, deployment of end-to-end pipe technology, creation of technology, and fluctuations in fuel mix have been the driving factors behind rising global market efficiency (Murshed et al. 2020; Wang et al. 2020 ; Usman et al. 2021).

In this regard, many studies are available that confirm that technological innovations and rising expenditures on research and development expenditures (R&D) are vital in the fight against CO_2 emissions (Ullah et al. 2021). Adoption of technology uplift the economy as result CO_2 emissions enrichment (Wu et al. 2022: Wang et al. 2021; Su et al. 2021; Pattnayak et al. 2019; Biswas et al. 2021). Conversely, few studies have highlighted the cyclical nature of technological innovations irrespective of whether the cyclical nature is pro or counter. Barlevy (2004) demonstrated that firms and businesses participate in R&D activities to attain short-term benefits. The firms' effort to achieve short-term profits gives rise to R&D activities in a boom period and a decline in recessions or depressions. Comin and Gertler (2006) observed that there occurs a strong cointegration amid embodied and disembodied innovations and total productivity. The outcome of the analysis posits that factor productivity behaves in a procyclical manner but only for medium-term. Conversely, the R&D activities are procyclical, whereas the relative price of capital (a representative of embodied innovations) movement is countercyclical. It highlighted that a shock in the capital stock forecast unrests in R&D investments (An et al. 2019; Artuç and Pourpourides 2012; Srinivas and Sundarapandian 2019). They further argued that a rise in capital investments causes the innovations to rise during the boom and vice versa during recessions. According to Francois and Lloyd-Ellis (2009) if the innovation activities are procyclical then a positive shock in technological change spur the R&D investments. However, investing in R&D is a long term activity, and the stock of new knowledge experience a diminishing rate of return. Once again, Wälde and Woitek (2004) argued that innovation activities flourished during the depression. Though the previous studies have primarily focused on the innovation actitivites in relation to their procyclical nature; however, very little evidence is available that deals with counter cyclical nature of the innovations. Considering the positive and negative shocks in technological innovations may have long-lasting implications for innovations and the whole economy, particularly the environment.

Therefore, this study is an effort to explain the relationship between positive and negative shocks in technological innovation and CO2 emissions in BRICS economies Brazil, Russia, India, China, and South Africa. The choice of BRICS economies is an interesting one because BRICS economies are among the largest contributors to global CO2 emissions. Further, these economies are the fastest-growing economies and the largest consumers of energy sources. Therefore, these economies provide an ideal case to test this relationship. To the best of our knowledge, this is the first-ever study in the context of BRICS economies that have analyzed the asymmetric linkage between CO2 emissions and technological innovations. Asymmetry assumption gives us an opportunity to measure the impact of positive and negative shocks on the CO2 emissions separately. For empirical analysis, we have relied on the Panel NARDL, which provides short and long-run results simultaneously. Most of the previous studies only focus on the long-run results.

Material and methods

Following the literature and very closely Ullah et al. (2021), we assume that the main determinant of the CO2 emissions is technological innovation shocks. Therefore, we begin with the following long-run models:

$$C0_{2,it} = \varphi_0 + \varphi_1 Patent_{it} + \varphi_2 Trademark_{it} + \varphi_3 GDP_{it} + \varphi_4 FDI_{it} + \varepsilon_{it} \qquad (1)$$

Where the carbon emission (CO_2) is a function of technological shocks that are assessed through patent and trademark, GDP per capita (GDP), foreign direct investment (FDI), and random-error term (ε_{it}). Many researchers consider that technological innovation is helpful to reducing CO2 emissions and improving environmental quality (Chen and Lee, 2020 and Ullah et al. 2021), thus estimates of φ_1 and φ_2 are also expected to be positive. The basic model has only produced long-run results. To acquire the short-run estimates as well, so we have decided to apply the panel nonlinear ARDL model. An econometric approach that yields both short-run and long-run coefficients estimates in one step are called error-correction as shown below:

$$\Delta CO_{2,it} = \omega_0 + \sum_{k=1}^{n} \beta_{1k} \Delta CO_{2,i,t-k} + \sum_{k=0}^{n} \beta_{2k} \Delta Patent_{i,t-k} + \sum_{k=0}^{n} \beta_{3k} \Delta Trademark_{i,t-k}$$
$$+ \sum_{k=0}^{n} \beta_{4k} \Delta GDP_{i,t-k} + \sum_{k=0}^{n} \beta_{5k} \Delta FDI_{i,t-k} + \omega_1 CO_{2,i,t-1} + \omega_2 Patent_{i,t-1}$$
$$+ \omega_3 Trademark_{i,t-1} + \omega_4 GDP_{i,t-1} + \omega_5 FDI_{i,t-1} + \varepsilon_t \qquad (2)$$

The specification (2) is normally called panel nonlinear ARDL (Pesaran et al. 2001). This method has some benefits as compared to other time series methods. ARDL gives us short and long-run coefficient estimates simultaneously. In specification (2) the estimates of the coefficients attached to the first difference "Δ" indicators provide the short-run outcomes, and the long-run estimates are reflected from λ2 to λ4. For the soundness of estimates, Pesaran et al. (2001) mentioned two cointegration tests, such as F-test and ECM or t-test. The F-test is tabulate new critical values for integrating properties of indicators. Indeed, under this approach, variables could be a blend of I(1) and I(0). This approach offers different estimates at different lags order in analysis for better results. Specifications (1) assume that the response of the CO2 emissions to changes in technological shocks is symmetric. However, Ullah et al. (2021) argued that since technological shocks could be different from positive versus negative shocks, technological innovation changes could have asymmetric effects on the environment. Thus, we will spilt main variable i.e. patent and trademark into four components viz. the positive shocks in patent and trademark and negative shock in patent and trademark by applying the partial sum technique of Shin et al. (2014) and introduce new time-series as follows:

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

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

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

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

Where $Patent^{+}{}_{it}$ and $Trademark^{+}{}_{it}$ represents the rising trend or positive shocks and $Patent^{-}{}_{it}$ and $Trademark^{-}{}_{it}$ represents the decreasing trend or negative shock in the above equations (3a-3d). Next, these positive and negative time series should be replaced in the original model and the new augmented model will look like as follows:

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

Specification (4) has been taken the form of non-linear panel ARDL and the procedure of estimating this equation is more similar to the linear panel ARDL. Also, this is an extension of the linear model, hence, it is subject to the same diagnostic tests and a similar method of estimation. Additionally, in an augmented model, we can test short and long-run asymmetry assumptions via the Wald test.

Study Data

The current study is to examine the impact of technological shocks on CO2 emissions over a data period from 1991 to 2019 for BRICS-Brazil, Russia, India, China, and South Africa-economies. Patent and trademark are used as a proxy to measure the technology innovation, following the work of Ahmad et al. (2019). The dataset of carbon dioxide emissions (CO2), patent applicants (patent), trademark applications (trademark), GDP per capita (GDP), and foreign direct investment (FDI) variables are taken from the world development indicators (WDI) complied by World Bank. The GDP and FDI are used as control variables to deal with the problem of omitted variables in the study. We converted CO2, patent, trademark, GDP, and FDI variables into the natural logarithm. The data definitions and descriptive statistics are shown in Table 1.

Table 1: Descriptive statistics of data

Variables	**Symbol**	**Definitions**	**Mean**	**Std. Dev.**	**Min**	**Max**
Carbon dioxide emissions	CO2	Carbon dioxide emissions (Kilotons)	13.94	1.067	12.29	16.27
Patent applications	Patent	Patent applications, total (residents and nonresidents)	10.14	1.360	8.052	14.24

Trademark applications	Trademark	Trademark applications, total (direct residents and direct nonresidents)	11.39	1.224	9.269	14.56
Foreign direct investment	FDI	Foreign direct investment, net inflows (BoP, current US$)	23.17	1.992	15.02	26.39
GDP per capita	GDP	GDP per capita (constant 2010 US$)	8.390	0.925	6.355	9.390

Results and discussion

Before executing regression analysis, there is a need to test the stationarity properties of data. As we are dealing with panel data, and the relevant tests for gauging stationary properties of data are LLC test, IPS test, and ADF test. We also tested cross sectional dependence in Table 2 and infer that cross-sectional dependence exists among the group. the According to the findings of these three tests shown in Table 2, we conclude that there is a mixture of level stationary and first difference stationary variables, however, none of the variables holds the stationarity property of second difference. On the basis of the results of unit root testing, we are assured to adopt panel ARDL and panel nonlinear ARDL (NARDL) estimation techniques for empirical analysis. Table 3 demonstrates the outcomes of short-run and long-run relationships among variables in panel ARDL and panel NARDL framework. The study used two proxies to measure technological innovations namely Patent and Trademark. However, GDP and FDI are treated as control variables.

Table 2: Cross sectional dependence test

	CO2	Patent	Trademark	GDP	FDI
Pesaran's test	0.429	3.094***	2.602***	0.091	3.433***
Prob.	0.667	0.002	0.009	0.927	0.000
Off-diagonal elements	0.447	0.313	0.236	0.189	0.323

Table 2: Unit root testing

	LLC			**IPS**			**ADF**		
	I(0)	I(1)	Decision	I(0)	I(1)	Decision	I(0)	I(1)	Decision
CO2	-0.652	-1.95**	I(1)	-0.341	-6.343***	I(1)	-1.915**		I(0)
Patent	-1.912**		I(0)	-0.711	-6.426***	I(1)	-0.656	-9.934***	I(1)
Trademark	-2.247**		I(0)	-0.1351	-5.824***	I(1)	-0.196	-8.977***	I(1)
GDP	-0.531	-2.32**	I(1)	-0.611	-3.856***	I(1)	-0.786	-4.984***	I(1)
FDI	-2.98***		I(0)	-3.03***		I(0)	-3.75***		I(0)

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

The long-run findings of the panel ARDL model show that Patent has a positive and significant impact on carbon emissions in BRICS countries. In a more precise manner, the findings demonstrate that a 1 unit increase in Patent results in increasing carbon emission by 0.381 percent. Trademark, GDP, and FDI have no significant impact on pollution emissions in BRICS countries in the long-run. The short-run findings of PARDL model reveal that Patent impact on pollution emissions is significant and negative, which states that a 1 percent increase in innovation activity leads to 0.059 percent reduction in pollution emissions. On the other hand, Trademark impact on pollution emissions is statistically insignificant. Both control variables, GDP and FDI, exert a significant positive impact on pollution emissions in the short-run. It shows that due to 1 percent increase in GDP and FDI, 0.580 percent and 0.017 percent increase occurs in pollution emissions. To confirm the stability of the findings of PARDL model, the study performed few diagnostic tests. The F-statistics value is statistically significant which confirms the existence of long-run cointegration among variables. Statistically significant coefficient estimate of log-likelihood confirms the goodness of fit of the model. The coefficient estimate of ECT is negative and significant as required for convergence towards stability. The coefficient value of ECT is -0.199, which states that the speed of convergence towards achieving stability is almost 20 percent in one year.

The long-run findings of PNARDL demonstrate that positive and negative shocks in PATENT have a negative and significant impact on carbon emissions in BRICS countries. The findings suggest that in response of 1 percent increase in positive components of Patent 0.418 percent decrease occurs in pollution emissions and in response of 1 percent increase in negative components of Patent 0.854 percent reduction occurs in carbon emissions in the long-run. In contrast, any negative and positive shock in trademark exerts a significant positive impact on carbon emissions. The findings elaborate that a 1 percent increase in positive components of trademarks leads to 0.416 percent upsurge in carbon emissions and a 1 percent increase in negative components of trademark tends to 1.352 percent rise in carbon emissions in BRICS countries.

The upsurge in technological innovation results in reducing carbon emissions it suggests that any positive change in technological innovation encourages investors to invest more in activities related to innovations that ultimately enhance the usage of economic friendly technologies in the process of production. Likewise, firms enrich in awareness, skills, and knowledge are more likely to develop and search those technologies that result in reducing carbon emissions. As innovation and clean technologies need skills and determined participation in research and development to attain economic-friendly products and processes. Similarly, various BRICS countries offered incentives to firms through numerous policy measures to invest in economic friendly and green innovative technologies that positively cause overall environmental quality. Furthermore, the focus on transforming the existing training system and developing the new one, education and research centers in BRICS countries has contributed greatly at a higher rate of return from investing in technological innovation. The effectiveness of technological innovations generates from the policy initiatives familiarized by the BRICS economies including the efforts to remove and reduce the hurdles faced by innovations and entrepreneurship like pro-innovation regulations of administration and growth-oriented tax reforms. Demand-oriented innovation policies result in significantly increasing economic growth along with enhancing the efficiencies of the energy sector in OECD countries. Effective macroeconomic policies contributed significantly to managing market demand and supply structure. Furthermore, the need for innovation emerged due to relaxation in entry barriers for entrepreneurs and firms that allowed them to fulfill the suppressed demands through advanced and improved products and goods. More recently, the emerging countries' economies are focusing on demand-oriented innovation policies related to standards, consumer policies, public procurement, regulation, reforms related to lead markets to address the issues of market failure and social needs. The positive shocks in technological innovations in the form of clean technologies and improved efficiency of energy result in the successful integration of green technologies in the production process in industries. These environmental policies significantly facilitated the research, development, consumption, and exploration of sources of renewable energy. The above-mentioned connection between technological innovations shocks (e.g., Patent and Trademark) and pollution emissions supports previous studies conducted for developing economies (Fernandez et al., 2018), China (Zhuang et al. 2021; Li, Wang, and Che, 2021; Shen et al. 2020; Khan et al. 2019; Jin et al. 2017), USA (Dinda 2018), Malaysia (Ali et al. 2016), G7 economies (Churchill et al. 2019), OECD countries (Mensah et al. 2018 and Ahmad et al. 2019), Japan (Lee and Min 2015), France (Shahbaz et al. 2018), and Korea (Long et al. 2017). However, the findings of our study contradict the findings of studies done for the panel of Russia, Germany, US, and UK (Shaari et al. 2016) and a sample of 13 advanced countries (Garrone and Grilli 2010).

Regarding control variables, GDP and FDI have a significant positive impact on carbon emissions revealing that a 1 percent increase in GDP and FDI increases carbon emissions by 0.919 percent and 0.232 percent, respectively. The short-run findings of PNARDL reveal that positive shock in Patent has a significant positive impact on carbon emissions and Trademark has a significant negative impact on carbon emissions in BRICS countries. However, the negative shocks in Patent and Trademark have a statistically insignificant impact on pollution emissions in the short run. GDP impact on pollution emissions is significant and negative in the short run, however, FDI has no impact on pollution emissions due to a statistically insignificant coefficient. Similar to PARDL, diagnostic tests are performed to confirm the stability of the results of PNARDL model. ECT holds a statistically significant coefficient value -0.259, which states that almost 26 percent stability will be achieved in a period of one year. The findings of F-statistics confirm the long-run cointegration among the variables. The goodness of fit of the model is confirmed from the statistically significant coefficient value of the Log-likelihood ratio.

Table 3: ARDL and NARDL Estimates

PARDL					PNARDL				
Variable	**Coefficient**	**Std. Error**	**t-Stat**	**Prob.***	**Variable**	**Coefficient**	**Std. Error**	**t-Stat**	**Prob.***
Long run					**Long-run**				
PATENT	0.381***	0.050	7.608	0.000	PATENT_POS	-0.418***	0.066	-6.296	0.000
TRADEMARK	0.008	0.067	0.120	0.904	PATENT_NEG	-0.854***	0.189	-4.532	0.000
GDP	-0.041	0.121	-0.338	0.736	TRADEMARK_POS	0.416***	0.045	9.171	0.000
FDI	-0.008	0.014	-0.595	0.553	TRADEMARK_NEG	1.352***	0.088	15.35	0.000
Short run					GDP	0.919***	0.069	13.31	0.000
D(PATENT)	-0.059*	0.035	-1.690	0.094	FDI	0.232***	0.031	7.547	0.000
D(TRADEMARK)	0.026	0.023	1.104	0.272	**Short-run**				
D(GDP)	0.580**	0.244	2.378	0.019	D(PATENT_POS)	0.484**	0.236	2.050	0.048
D(FDI)	0.017***	0.005	3.788	0.000	D(PATENT_POS(-1))	0.080	0.116	0.697	0.491
C	2.165	1.340	1.616	0.109	D(PATENT_POS(-2))	-0.037	0.097	-0.376	0.709
Diagnostic					D(PATENT_NEG)	-0.200	0.453	-0.441	0.662
F-test	1.798				D(PATENT_NEG(-1))	-0.244	0.295	-0.825	0.415
Log likelihood	267.3				D(PATENT_NEG(-2))	0.285	0.297	0.962	0.343
ECM(-1)	-0.199*	0.115	-1.730	0.098	D(TRADEMARK_POS)	-0.183*	0.106	-1.726	0.092
					D(TRADEMARK_POS(-1))	-0.301	0.214	-1.405	0.169
					D(TRADEMARK_POS(-2))	-0.049	0.152	-0.320	0.751
					D(TRADEMARK_NEG)	-0.034	0.312	-0.110	0.913
					D(TRADEMARK_NEG(-1))	0.527	0.365	1.445	0.158
					D(TRADEMARK_NEG(-2))	0.060	0.292	0.205	0.839
					D(GDP)	-0.436*	0.249	-1.751	0.098
					D(GDP(-1))	0.800	0.853	0.938	0.355
					D(GDP(-2))	0.275	0.400	0.687	0.497

D(FDI)	-0.008	0.041	-0.195	0.846
D(FDI (-1))	-0.039	0.029	-1.351	0.186
D(FDI (-2))	-0.060	0.022	-2.654	0.012
C	-0.095	0.242	-0.390	0.699
Diagnostic				
F-test	3.897**			
Log-likelihood	390.2***			
ECM(-1)	-0.259*	0.137	-1.890	0.090

Finally, we have reported the estimates of the causal analysis in table 4. From the results of symmetric causality, we confer that two-way causality runs from Patent →CO_2 and Trademark→CO_2. However, in the case of asymmetric causality, we confer that Patent_POS, Trademark_POS, Trademark_NEG granger cause CO_2, whereas, CO_2 is granger causing Patent_NEG and Trademark_POS. Hence, from these findings, we deduce that there is uni-lateral causality running from one variable to another but we find evidence of bi-directional causality between Trademark_POS and CO_2.

Table 4: Non-asymmetric and asymmetric causality

Null Hypothesis:	**W-Stat.**	**Zbar-Stat.**	**Prob.**	**Null Hypothesis:**	**W-Stat.**	**Zbar-Stat.**	**Prob.**
PATENT →CO2	5.958	3.455	0.001	PATENT_POS → CO2	9.226	6.385	0.000
CO2 →PATENT	7.783	5.133	0.000	CO2 → PATENT_POS	1.840	-0.337	0.736
TRADEMARK →CO2	5.645	3.167	0.002	PATENT_NEG →CO2	3.846	1.489	0.137
CO2 →TRADEMARK	4.346	1.973	0.049	CO2 →PATENT_NEG	4.225	1.833	0.067
GDP →CO2	11.14	8.225	0.000	TRADEMARK_POS →CO2	7.655	4.955	0.000
CO2 →GDP	4.411	2.033	0.042	CO2 → TRADEMARK_POS	4.424	2.014	0.044
FDI →CO2	3.572	1.262	0.207	TRADEMARK_NEG →CO2	7.357	4.684	0.000
CO2 →FDI	4.292	1.923	0.054	CO2 → TRADEMARK_NEG	3.327	1.016	0.309
TRADEMARK →PATENT	8.001	5.334	0.000	GDP → CO2	11.14	8.225	0.000
PATENT →TRADEMARK	5.113	2.678	0.007	CO2 →GDP	4.411	2.033	0.042
GDP →PATENT	10.29	7.443	0.000	FDI → CO2	3.572	1.262	0.207
PATENT →GDP	2.266	0.061	0.952	CO2 →FDI	4.292	1.923	0.054
FDI →PATENT	10.86	7.930	0.000	PATENT_NEG →PATENT_POS	32.50	27.57	0.000
PATENT → FDI	2.364	0.151	0.880	PATENT_POS →PATENT_NEG	2.745	0.486	0.627
GDP →TRADEMARK	4.241	1.876	0.061	TRADEMARK_POS →PATENT_POS	3.445	1.123	0.261
TRADEMARK →GDP	2.493	0.269	0.788	PATENT_POS	5.197	2.718	0.007

				→TRADEMARK_POS			
FDI →TRADEMARK	2.833	0.582	0.561	TRADEMARK_NEG →PATENT_POS	3.571	1.238	0.216
TRADEMARK → FDI	4.720	2.317	0.021	PATENT_POS →TRADEMARK_NEG	6.437	3.847	0.000
FDI →GDP	1.207	0.913	0.361	GDP → PATENT_POS	4.669	2.237	0.025
GDP →FDI	7.530	4.900	0.000	PATENT_POS →GDP	3.851	1.493	0.136
				FDI → PATENT_POS	4.854	2.406	0.016
				PATENT_POS → FDI	3.934	1.569	0.117
				TRADEMARK_POS →PATENT_NEG	2.600	0.355	0.723
				PATENT_NEG →TRADEMARK_POS	3.336	1.024	0.306
				TRADEMARK_NEG →PATENT_NEG	2.322	0.102	0.919
				PATENT_NEG →TRADEMARK_NEG	3.056	0.769	0.442
				GDP →PATENT_NEG	3.801	1.448	0.148
				PATENT_NEG →GDP	3.502	1.176	0.240
				FDI →PATENT_NEG	3.636	1.297	0.195
				PATENT_NEG →FDI	2.776	0.514	0.607
				TRADEMARK_NEG	2.684	0.431	0.666

→TRADEMARK_POS			
TRADEMARK_POS →TRADEMARK_NEG	13.33	10.11	0.000
GDP →TRADEMARK_POS	4.601	2.175	0.030
TRADEMARK_POS →GDP	4.545	2.125	0.034
FDI →TRADEMARK_POS	2.480	0.245	0.807
TRADEMARK_POS →FDI	3.728	1.381	0.167
GDP →TRADEMARK_NEG	9.375	6.521	0.000
TRADEMARK_NEG →GDP	4.201	1.812	0.070
FDI →TRADEMARK_NEG	2.793	0.530	0.596
TRADEMARK_NEG →FDI	5.386	2.890	0.004
FDI →GDP	1.207	-0.913	0.361
GDP →FDI	7.530	4.900	0.000

Conclusion and Implications

Energy consumption is the biggest source of carbon emissions in the world and the story of BRICS economies is not different. BRICS countries are collectively consuming one-third of the total world's energy consumption, hence, their share in the world's carbon emissions has reached 41%. This has raised the eyebrows of environmentalists not only from the BRICS countries but from all around the globe. Among other ways, technology innovation is one of the best options for reducing carbon emissions produced through energy consumption. Hence, in this study, our main focus is to see the asymmetric impact of technology shocks on the CO2 emissions in BRICS economies. To that end, we have picked two different proxies of technology i.e. Patent and Trademark, and applied linear and non-linear panel ARDL-PMG. Asymmetry assumption is more reliable because in the real-world variables do behave in an asymmetric manner i.e. positive and negative technology stocks could have a different impact on the CO2 emissions not only in signs but magnitudes as well.

The findings of the linear model confirm that, in the short run, estimates of all the variables are significant except the variable of Trademark. Similarly, the short-run asymmetric estimates are significant for three variables i.e., Patent, Trademark, and GDP. In the long run, the estimate attached to the Patent is significant and positive in the linear model and the estimates attached to all other variables are insignificant. However, the asymmetric estimates, in the long run, are significant for all the variables. By comparing the findings of linear and non-linear models we can confirm that the non-linear model produced more significant results. Nonetheless, if we closely look at the estimates attached to Patent_POS (Trademark_POS) and Patent_NEG(Trademark_NEG) both have the same sign implying that positive shock reduces(increases) the carbon emissions and negative shock increases (decreases) the carbon emissions. Due to the difference in the magnitude of these effects and more significant results produced by the asymmetric model we can say that this model performs better than the linear model. Moreover, the causality results from both the methods, linear and non-linear, only provide evidence of a one-way causal relationship between different variables.

On the basis of these findings, the study put forward some important policy implications. It is suggested that environmentalists and policymakers should formulate their policies by considering the effects of both negative and positive shocks. Furthermore, it is suggested that the BRICS countries should stimulate the patent and trademark policies for those innovations and products that are eco-friendly and conserve more energy. In this regard, governments should impose a carbon tax on such technologies that are involved in the deterioration of environmental quality. Governments should also increase the registration fee of these technologies in order to increase the overall welfare of society and the environment. The study also suggests that the BRICS economies should reinforce international exchanges and corporations and stimulate the spread of green eco-friendly technologies. Governments of BRICS economies need to stimulate adjustment of energy structure and promote low carbon-based technologies. BRICS economies should develop eco-friendly frameworks and policies to promote the automobiles and vehicles manufacturing sector that can be made possible by attracting foreign investment and green technologies.

The research could be extended to the country-specific and regional for future research. Future empirical research can consider the role of environmental technology in influencing environmental quality.

Compliance with ethical standards

Ethical approval : Not applicable

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

Consent to publish : Not applicable

Authors' Contributions: The idea was given by Xiaoqiang Ma and Nafeesa Mughal. Xiaoqiang Ma, Asma Arif, Prabjot Kaur, Vipin Jain, Laila Rafanina, and Nafeesa Mughal have done the data acquisitions, analysis and written the whole draft. Nafeesa Mughal and Xiaoqiang Ma read and approved the final version.

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Research Article

Revealing the effectiveness of technological innovation shocks on CO_2 emissions in BRICS: emerging challenges and implications

Xiaoqiang Ma Affiliationids : Aff1

Asma Arif Affiliationids : Aff2

Prabjot Kaur Affiliationids : Aff3

Vipin Jain Affiliationids : Aff4

Laila ~~Rafaina~~REFIANA SAID Affiliationids : Aff5

Nafessa Mughal

Email : nafeesamughal@stu.xjtu.edu.cn

Affiliationids : Aff6, Correspondingaffiliationid : Aff6

Aff1 School of Economics and Management, Northwest University, Xi'an, China

Aff2 Department of Economics, University of Wah, Wah Cantt, 47040, Pakistan

Aff3 Department of Mathematics, Birla Institute of Technology Mesra, Ranchi Jharkhand, India

Aff4 College of Management, ~~Teerthanker Mahaveer University Moradabad~~Teerthanker Mahaveer University, Moradabad, Uttar Pradesh, India

Aff5 Universitas Lambung Mangkurat, Banjarmasin, Indonesia

Aff6 School of Economics, Xi'an Jiaotong University, Xi'an, Shaanxi, China

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Abstract

The debate on technological innovation shocks and its effect AQ1 on the environment are of great interest to academicians and impact on CO_2 emissions for BRICS economies. The linear and non-linear panel ARDL models are applied to compute both short-run and long-run dynamics of technology shocks and CO_2 emissions. Asymmetric estimates confer that a positive shock in patents reduces the CO_2 emissions by 0.418%, whereas negative shock increases the CO_2 emissions by 0.854%. Contrariwise, the trademark positive shock increases the carbon emissions by 0.416% and vice versa. The non-linear analysis provides an opportunity to measure the direction and magnitude 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 positive and negative shocks.

Keywords

Technology shocks
CO_2 emissions
Energy consumption
Sustainability
BRICS

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Introduction

The last few decades have experienced unusual fluctuations in global temperature due to increased economic growth worldwide. Policymakers and empirics widely recognize that anthropogenic emissions of greenhouse gases are primarily responsible for rising global temperature, damaging human health, and the ecological setup of nature(Chen and Lee 2020). The share of CO_2 emissions is the largest among all GHGs emissions, and its ratio has been augmented many times since the 1960s (Bhattacharya et al. 2016). Since then, CO_2 emissions have become an essential factor in representing environmental quality. Empirical evidence largely supports this notion that economic activities damage environmental quality in different countries (Wang and Zhang 2020). Two agreements, the Kyoto protocol, and the latest Parsi Agreement have been signed considering the importance of preserving the environment for this and upcoming generations. The main crux of both agreements is to protect the environment without compromising on environmental quality (Rehman et al. 2020).

In the year 2015, the Paris agreement was signed by international leaders from 195 member states during the 21st Conference of Parties (COP) in Paris (Rehman et al. 2021). The Paris agreement demanded the member states make united efforts in combating the menace of climate (Nathaniel et al. 2021). Further, the document of the Paris agreement also provides a future course of action to protect the environment worldwide (UNFCCC 2015). Another binding condition for all the member states is to “hold warming well below 2 °C in global mean temperature (GMT), relative to pre-industrial levels, and to pursue efforts to limit warming to 1.5 °C”. Consistent with this view, the United Nations Development Program proposed a complete and comprehensive charter for attaining the sustainable development of the world known as sustainable development goals (SDGs). Goal 13 of the SGDs stresses upon the world to swiftly respond to climate change and its related effects. However, the world is not responding to the call of the UNDP and Paris Agreement, and in 2020 the world’s average temperature is 1.2 °C higher than the pre-industrial baseline (Murshed et al. 2020; Li et al. 2021a, b).

Despite the growing universal concerns on the depletion of the environment, due to the rise in economic activities, emerging economies are still preferring economic interests over environmental (Murshed et al. 2021). However, following the footprints of advanced economies, the policymakers in emerging economies are now stressing the need for technological innovations to conserve energy, curb CO_2 emissions, and attain long-term economic growth (Balsalobre-Lorente et al. 2021; Ullah et al. 2021). It is widely recognized that energy contributes to the rising energy demand that causes environmental degradation by emanating CO_2 emissions. But the conservation of energy through innovation can help the market improve its efficiency and remove an imperfection in the supply chains. For example, advancements in the technological process to build and create environmentally-friendly products cycles and units, deployment of end-to-end pipe technology, creation of technology, and fluctuations in fuel mix have been the driving factors behind rising global market efficiency (Murshed et al. 2020; Wang et al. 2020; Usman et al. 2021).

In this regard, many studies are available that confirm that technological innovations and rising expenditures on research and development expenditures (R&D) are vital in the fight against CO_2 emissions (Ullah et al. 2021). Adoption of technology uplift the economy as result CO_2 emissions enrichment (Wu et al. 2022; Wang et al. 2021; Su et al. 2021; Pattnayak et al. 2019; Biswas et al. 2021). Conversely, few studies have highlighted the cyclical nature of technological innovations irrespective of whether the cyclical nature is pro or counter. Barlevy (2004) demonstrated that firms and businesses participate in R&D activities to attain short-term benefits. The firms’ effort to achieve short-term profits gives rise to R&D activities in a boom period and a decline in recessions or depressions. Comin and Gertler (2006) observed that there occurs a strong cointegration amid embodied and disembodied innovations and total productivity. The outcome of the analysis posits that factor productivity behaves in a procyclical manner but only for medium-term. Conversely, the R&D activities are procyclical, whereas the relative price of capital (a representative of embodied innovations) movement is countercyclical. It highlighted that a shock in the capital stock forecast unrests in R&D investments (An et al. 2019; Artuç and Pourpourides 2012; Srinivas and Sundarapandian 2019). They further argued that a rise in capital investments causes the innovations to rise during the boom and vice versa during recessions. According to Francois and Lloyd-Ellis (2009) if the innovation activities are procyclical then a positive shock in technological change spur the R&D investments. However, investing in R&D is a long-term activity, and the stock of new knowledge experience a diminishing rate of return. Once again, Wälde and Woitek (2004) argued that innovation activities flourished during the depression. Though the previous studies have primarily focused on the innovation actitivites in relation to their procyclical nature; however, very little evidence is available that deals with counter cyclical nature of the innovations. Considering the positive and negative shocks in technological innovations may have long-lasting implications for innovations and the whole economy, particularly the environment.

Therefore, this study is an effort to explain the relationship between positive and negative shocks in technological innovation and CO_2

because BRICS economies are among the largest contributors to global CO_2 emissions. Further, these economies are the fastest-growing economies and the largest consumers of energy sources. Therefore, these economies provide an ideal case to test this relationship. To the best of our knowledge, this is the first-ever study in the context of BRICS economies that have analyzed the asymmetric linkage between CO_2 emissions and technological innovations. Asymmetry assumption gives us an opportunity to measure the impact of positive and negative shocks on the CO_2 emissions separately. For empirical analysis, we have relied on the Panel NARDL, which provides short- and long-run results simultaneously. Most of the previous studies only focus on the long-run results.

Material and methods

Following the literature and very closely Ullah et al. (2021), we assume that the main determinant of the CO_2 emissions is technological innovation shocks. Therefore, we begin with the following long-run models:

$$C0_{2,it} = \varphi_0 + \varphi_1 Patent_{it} + \varphi_2 Trademark_{it} + \varphi_3 GDP_{it} + \varphi_4 FDI_{it} + \varepsilon_{it} \quad (1)$$

where the carbon emission (CO_2) is a function of technological shocks that are assessed through patent and trademark, GDP per capita (GDP), foreign direct investment (FDI), and random-error term (ε_{it}). Many researchers consider that technological innovation is helpful to reducing CO_2 emissions and improving environmental quality (Chen and Lee 2020; Ullah et al. 2021), thus estimates of φ_1 and φ_2 are also expected to be positive. The basic model has only produced long-run results. To acquire the short-run estimates as well, so we have decided to apply the panel nonlinear ARDL model. An econometric approach that yields both short-run and long-run coefficients estimates in one step are called error-correction as shown below:

$$\Delta CO_{2,it} = \omega_0 + \sum\nolimits_{k=1}^{n} \beta_{1k} \Delta CO_{2,i,t-k} + \sum\nolimits_{k=0}^{n} \beta_{2k} \Delta Patent_{i,t-k} + \sum\nolimits_{k=0}^{n} \beta_{3k} \Delta Trademark_{i,t-k} + \sum\nolimits_{k=0}^{n} \beta_{4k} \Delta GDP_{i,t-k} + \sum\nolimits_{k=0}^{n} \beta_{5k} \Delta FDI_{i,t-k} + \omega_1 CO_{2,i,t-1} + \omega_2 Patent_{i,t-1} + \omega_3 Trademark_{i,t-1} + \omega_4 GDP_{i,t-1} + \omega_5 FDI_{i,t-1} + \varepsilon_t \quad (2)$$

The specification (2) is normally called panel nonlinear ARDL (Pesaran et al. 2001). This method has some benefits as compared to other time series methods. ARDL gives us short and long-run coefficient estimates simultaneously. In specification (2) the estimates of the coefficients attached to the first difference "Δ" indicators provide the short-run outcomes, and the long-run estimates are reflected from λ2 to λ4. For the soundness of estimates, Pesaran et al. (2001) mentioned two cointegration tests, such as F-test and ECM or t-test. The F-test is tabulate new critical values for integrating properties of indicators. Indeed, under this approach, variables could be a blend of I(1) and I(0). This approach offers different estimates at different lags order in analysis for better results. Specifications (1) assume that the response of the CO_2 emissions to changes in technological shocks is symmetric. However, Ullah et al. (2021) argued that since technological shocks could be different from positive versus negative shocks, technological innovation changes could have asymmetric effects on the environment. Thus, we will spilt main variable i.e. patent and trademark into four components viz. the positive shocks in patent and trademark and negative shock in patent and trademark by applying the partial sum technique of Shin et al. (2014) and introduce new time-series as follows:

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

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

$$Trademark^{+}{}_{it} = \sum_{n=1}^{t} \Delta Trademark^{+}{}_{it} = \sum_{n=1}^{t} max(\Delta Trademark^{+}{}_{it}, 0) \quad (3c)$$

$$Trademark^{-}{}_{it} = \sum_{n=1}^{t} \Delta Trademark^{-}{}_{it} = \sum_{n=1}^{t} min(\Delta Trademark^{-}{}_{it}, 0) \quad (3d)$$

where $Patent^{+}{}_{it}$ and $Trademark^{+}{}_{it}$ represents the rising trend or positive shocks and $Patent^{-}{}_{it}$ and $Trademark^{-}{}_{it}$ represents the decreasing trend or negative shock in the above Eqs. (3a-3d). Next, these positive and negative time series should be replaced in the original model and the new augmented model will look like as follows:

$$\Delta CO_{2,it} = \alpha_0 + \sum_{k=1}^{n} \beta_{1k} \Delta CO_{2,it-k} + \sum_{k=0}^{n} \beta_{2k} \Delta Patent^{+}{}_{it-k} + \sum_{k=0}^{n} \delta_{3k} \Delta Patent^{-}{}_{it-k} \sum_{k=0}^{n} \beta_{4k} \Delta Trademark^{+}{}_{it-k} + \sum_{k=0}^{n} \delta_{5k} \Delta Trademark^{-}{}_{it-k} + \sum_{k=0}^{n} \beta_{6k} GDP_{it-k} + \sum_{k=0}^{n} \beta_{7k} FDI_{it-k} + \omega_1 CO_{2,it-1} + \omega_2 Patent^{+}{}_{it-1} + \omega_3 Patent^{-}{}_{it-1} + \omega_4 Trademark^{+}{}_{it-1} + \omega_5 Trademark^{-}{}_{it-1} + \omega_6 GDP_{it-1} + \omega_7 FDI_{it-1} + \varepsilon_{it} \quad (4)$$

Specification (4) has been taken the form of non-linear panel ARDL and the procedure of estimating this equation is more similar to the linear panel ARDL. Also, this is an extension of the linear model, hence, it is subject to the same diagnostic tests and a similar method of estimation. Additionally, in an augmented model, we can test short and long-run asymmetry assumptions via the Wald test.

The current study is to examine the impact of technological shocks on CO_2 emissions over a data period from 1991 to 2019 for BRICS-Brazil, Russia, India, China, and South Africa-economies. Patent and trademark are used as a proxy to measure the technology innovation, following the work of Ahmad et al. (2021). Th **AQ2** e dataset of carbon dioxide emissions (CO_2), patent applicants (patent), trademark applications (trademark), GDP per capita (GDP), and foreign direct investment (FDI) variables are taken from the world development indicators (WDI) complied by World Bank. The GDP and FDI are used as control variables to deal with the problem of omitted variables in the study. We converted CO_2, patent, trademark, GDP, and FDI variables into the natural logarithm. The data definitions and descriptive statistics are shown in Table 1.

Table 1

Descriptive **AQ3** statistics of data

Variables	Symbol	Definitions	Mean	Std. Dev	Min	Max
Carbon dioxide emissions	CO_2	Carbon dioxide emissions (Kilotons)	13.94	1.067	12.29	16.27
Patent applications	Patent	Patent applications, total (residents and nonresidents)	10.14	1.360	8.052	14.24
Trademark applications	Trademark	Trademark applications, total (direct residents and direct nonresidents)	11.39	1.224	9.269	14.56
Foreign direct investment	FDI	Foreign direct investment, net inflows (BoP, current US$)	23.17	1.992	15.02	26.39
GDP per capita	GDP	GDP per capita (constant 2010 US$)	8.390	0.925	6.355	9.390

Results and discussion

Before executing regression analysis, there is a need to test the stationarity properties of data. As we are dealing with panel data, and the relevant tests for gauging stationary properties of data are LLC test, IPS test, and ADF test. We also tested cross-sectional dependence in Tables 2 and 3 and infer that cross-sectional dependence exists among the group. According to the findings of these three tests shown in Tables 2 and 3, we conclude that there is a mixture of level stationary and first difference stationary variables; however, none of the variables holds the stationarity property of second difference. On the basis of the results of unit root testing, we are assured to adopt panel ARDL and panel nonlinear ARDL (NARDL) estimation techniques for empirical analysis. Table 4 demonstrates the outcomes of short-run and long-run relationships among variables in panel ARDL and panel NARDL framework. The study used two proxies to measure technological innovations namely Patent and Trademark. However, GDP and FDI are treated as control variables.

Table 2

Cross-sectional dependence test

	CO_2	Patent	Trademark	GDP	FDI
Pesaran’s test	0.429	3.094***	2.602***	0.091	3.433***
Prob	0.667	0.002	0.009	0.927	0.000
Off-diagonal elements	0.447	0.313	0.236	0.189	0.323

Table 3

Unit root testing

	LLC			IPS			ADF		
	I(0)	I(1)	Decision	I(0)	I(1)	Decision	I(0)	I(1)	Decision
CO_2	− 0.652	− 1.95**	I(1)	− 0.341	− 6.343***	I(1)	− 1.915**		I(0)
Patent	− 1.912**		I(0)	− 0.711	− 6.426***	I(1)	− 0.656	− 9.934***	I(1)
Trademark	− 2.247**		I(0)	− 0.1351	− 5.824***	I(1)	− 0.196	− 8.977***	I(1)
GDP	− 0.531	− 2.32**	I(1)	− 0.611	− 3.856***	I(1)	− 0.786	− 4.984***	I(1)
FDI	− 2.98***		I(0)	− 3.03***		I(0)	− 3.75***		I(0)
* p value < 0.10 ** p value < 0.05 *** p value < 0.01									

Table 4

ARDL and NARDL estimates

	PARDL					PNARDL			
Variable	Coefficient	Std. Error	t-Stat	Prob.*	Variable	Coefficient	Std. Error	t-Stat	Prob.*
Long run					**Long-run**				
PATENT	0.381***	0.050	7.608	0.000	PATENT_POS	− 0.418***	0.066	− 6.296	0.000
TRADEMARK	0.008	0.067	0.120	0.904	PATENT_NEG	− 0.854***	0.189	− 4.532	0.000

Variable	Coefficient	Std. Error	t-Stat	Prob.*	Variable	Coefficient	Std. Error	t-Stat	Prob.*
FDI	− 0.008	0.014	− 0.595	0.553	TRADEMARK_NEG	1.352***	0.088	15.35	0.000
Short run					GDP	0.919***	0.069	13.31	0.000
D(PATENT)	− 0.059*	0.035	− 1.690	0.094	FDI	0.232***	0.031	7.547	0.000
D(TRADEMARK)	0.026	0.023	1.104	0.272	**Short-run**				
D(GDP)	0.580**	0.244	2.378	0.019	D(PATENT_POS)	0.484**	0.236	2.050	0.048
D(FDI)	0.017***	0.005	3.788	0.000	D(PATENT_POS(-1))	0.080	0.116	0.697	0.491
C	2.165	1.340	1.616	0.109	D(PATENT_POS(-2))	− 0.037	0.097	− 0.376	0.709
Diagnostic					D(PATENT_NEG)	− 0.200	0.453	− 0.441	0.662
F-test	1.798				D(PATENT_NEG(-1))	− 0.244	0.295	− 0.825	0.415
Log likelihood	267.3				D(PATENT_NEG(-2))	0.285	0.297	0.962	0.343
ECM(-1)	− 0.199*	0.115	− 1.730	0.098	D(TRADEMARK_POS)	− 0.183*	0.106	− 1.726	0.092
					D(TRADEMARK_POS(-1))	− 0.301	0.214	− 1.405	0.169
					D(TRADEMARK_POS(-2))	− 0.049	0.152	− 0.320	0.751
					D(TRADEMARK_NEG)	− 0.034	0.312	− 0.110	0.913
					D(TRADEMARK_NEG(-1))	0.527	0.365	1.445	0.158
					D(TRADEMARK_NEG(-2))	0.060	0.292	0.205	0.839
					D(GDP)	− 0.436*	0.249	− 1.751	0.098
					D(GDP(-1))	0.800	0.853	0.938	0.355
					D(GDP(-2))	0.275	0.400	0.687	0.497
					D(FDI)	− 0.008	0.041	− 0.195	0.846
					D(FDI (-1))	− 0.039	0.029	− 1.351	0.186
					D(FDI (-2))	− 0.060	0.022	− 2.654	0.012
					C	− 0.095	0.242	− 0.390	0.699
					Diagnostic				
					F-test	3.897**			
					Log-likelihood	390.2***			
					ECM(-1)	− 0.259*	0.137	− 1.890	0.090

The long-run findings of the panel ARDL model show that Patent has a positive and significant impact on carbon emissions in BRICS countries. In a more precise manner, the findings demonstrate that a 1 unit increase in Patent results in increasing carbon emission by 0.381%. Trademark, GDP, and FDI have no significant impact on pollution emissions in BRICS countries in the long-run. The short-run findings of PARDL model reveal that Patent impact on pollution emissions is significant and negative, which states that a 1% increase in innovation activity leads to 0.059% reduction in pollution emissions. On the other hand, Trademark impact on pollution emissions is statistically insignificant. Both control variables, GDP and FDI, exert a significant positive impact on pollution emissions in the short-run. It shows that due to 1 percent increase in GDP and FDI, 0.580% and 0.017% increase occurs in pollution emissions. To confirm the stability of the findings of PARDL model, the study performed few diagnostic tests. The F-statistics value is statistically significant which confirms the existence of long-run cointegration among variables. Statistically significant coefficient estimate of log-likelihood confirms the goodness of fit of the model. The coefficient estimate of ECT is negative and significant as required for convergence toward stability. The coefficient value of ECT is − 0.199, which states that the speed of convergence toward achieving stability is almost 20% in 1 year.

The long-run findings of PNARDL demonstrate that positive and negative shocks in PATENT have a negative and significant impact on carbon emissions in BRICS countries. The findings suggest that in response of 1% increase in positive components of Patent 0.418 percent decrease occurs in pollution emissions and in response of 1% increase in negative components of Patent 0.854% reduction occurs in carbon emissions in the long-run. In contrast, any negative and positive shock in trademark exerts a significant positive impact on carbon emissions. The findings elaborate that a 1% increase in positive components of trademarks leads to 0.416% upsurge in carbon emissions and a 1% increase in negative components of trademark tends to 1.352% rise in carbon emissions in BRICS countries.

The upsurge in technological innovation results in reducing carbon emissions it suggests that any positive change in technological innovation encourages investors to invest more in activities related to innovations that ultimately enhance the usage of economic friendly technologies in the process of production. Likewise, firms enrich in awareness, skills, and knowledge are more likely to develop and search those technologies that result in reducing carbon emissions. As innovation and clean technologies need skills and determined participation in research and development to attain economic-friendly products and processes. Similarly, various BRICS countries offered incentives to firms through numerous policy measures to invest in economic friendly and green innovative technologies that positively cause overall environmental quality. Furthermore, the focus on transforming the existing training system and developing the new one, education and research centers in BRICS countries has contributed greatly at a higher rate of return from investing in technological innovation. The effectiveness of technological innovations generates from the policy initiatives familiarized by the BRICS economies including the efforts to remove and reduce the hurdles faced by innovations and entrepreneurship like pro-innovation regulations of administration and growth-oriented tax reforms. Demand-oriented innovation policies result in significantly increasing economic growth along with enhancing the efficiencies of the energy sector in OECD countries. Effective macroeconomic policies contributed significantly to managing market demand and supply structure. Furthermore, the need for innovation emerged due to relaxation in entry barriers for entrepreneurs and firms that allowed them to fulfill the suppressed demands through advanced and improved products and goods. More recently, the emerging countries' economies are focusing on demand-oriented innovation policies related to standards, consumer policies, public procurement, innovations in the form of clean technologies and improved efficiency of energy result in the successful integration of green technologies in the production process in industries. These environmental policies significantly facilitated the research, development, consumption, and exploration of sources of renewable energy. The above-mentioned connection between technological innovations shocks (e.g., Patent and Trademark) and pollution emissions supports previous studies conducted for developing economies (Fernandez et al. 2018), China (Zhuang et al. 2021; Li et al., 2021a, b; Shen et al. 2020; Khan et al. 2019; Jin et al. 2017), USA (Dinda 2018), Malaysia (Ali et al. 2016), G7 economies (Churchill et al. 2019), OECD countries (Mensah et al. 2018 and Ahmad et al. 2021~~2019~~), Japan (Lee and Min 2015), France (Shahbaz et al. 2018), and Korea (Long et al. 2017). However, the findings of our study contradict the findings of studies done for the panel of Russia, Germany, USA, and UK (Shaari et al. 2016) and a sample of 13 advanced countries (Garrone and Grilli 2010).

Regarding control variables, GDP and FDI have a significant positive impact on carbon emissions revealing that a 1% increase in GDP and FDI increases carbon emissions by 0.919% and 0.232%, respectively. The short-run findings of PNARDL reveal that positive shock in Patent has a significant positive impact on carbon emissions and Trademark has a significant negative impact on carbon emissions in BRICS countries. However, the negative shocks in Patent and Trademark have a statistically insignificant impact on pollution emissions in the short run. GDP impact on pollution emissions is significant and negative in the short run, however, FDI has no impact on pollution emissions due to a statistically insignificant coefficient. Similar to PARDL, diagnostic tests are performed to confirm the stability of the results of PNARDL model. ECT holds a statistically significant coefficient value -0.259, which states that almost 26% stability will be achieved in a period of 1 year. The findings of F-statistics confirm the long-run cointegration among the variables. The goodness of fit of the model is confirmed from the statistically significant coefficient value of the Log-likelihood ratio.

Finally, we have reported the estimates of the causal analysis in Table 5. From the results of symmetric causality, we confer that two-way causality runs from Patent → CO2 and Trademark → CO2. However, in the case of asymmetric causality, we confer that Patent_POS, Trademark_POS, Trademark_NEG granger cause CO_2, whereas, CO_2 is granger causing Patent_NEG and Trademark_POS. Hence, from these findings, we deduce that there is uni-lateral causality running from one variable to another but we find evidence of bi-directional causality between Trademark_POS and CO_2.

Table 5

Non-asymmetric and asymmetric causality

Null hypothesis:	W-Stat	Zbar-Stat	Prob	Null hypothesis:	W-Stat	Zbar-Stat	Prob
PATENT → CO2	5.958	3.455	0.001	PATENT_POS → CO2	9.226	6.385	0.000
CO2 → PATENT	7.783	5.133	0.000	CO2 → PATENT_POS	1.840	-0.337	0.736
TRADEMARK → CO2	5.645	3.167	0.002	PATENT_NEG → CO2	3.846	1.489	0.137
CO2 → TRADEMARK	4.346	1.973	0.049	CO2 → PATENT_NEG	4.225	1.833	0.067
GDP → CO2	11.14	8.225	0.000	TRADEMARK_POS → CO2	7.655	4.955	0.000
CO2 → GDP	4.411	2.033	0.042	CO2 → TRADEMARK_POS	4.424	2.014	0.044
FDI → CO2	3.572	1.262	0.207	TRADEMARK_NEG → CO2	7.357	4.684	0.000
CO2 → FDI	4.292	1.923	0.054	CO2 → TRADEMARK_NEG	3.327	1.016	0.309
TRADEMARK → PATENT	8.001	5.334	0.000	GDP → CO2	11.14	8.225	0.000
PATENT → TRADEMARK	5.113	2.678	0.007	CO2 → GDP	4.411	2.033	0.042
GDP → PATENT	10.29	7.443	0.000	FDI → CO2	3.572	1.262	0.207
PATENT → GDP	2.266	0.061	0.952	CO2 → FDI	4.292	1.923	0.054
FDI → PATENT	10.86	7.930	0.000	PATENT_NEG → PATENT_POS	32.50	27.57	0.000
PATENT → FDI	2.364	0.151	0.880	PATENT_POS → PATENT_NEG	2.745	0.486	0.627
GDP → TRADEMARK	4.241	1.876	0.061	TRADEMARK_POS → PATENT_POS	3.445	1.123	0.261
TRADEMARK → GDP	2.493	0.269	0.788	PATENT_POS → TRADEMARK_POS	5.197	2.718	0.007
FDI → TRADEMARK	2.833	0.582	0.561	TRADEMARK_NEG → PATENT_POS	3.571	1.238	0.216
TRADEMARK → FDI	4.720	2.317	0.021	PATENT_POS → TRADEMARK_NEG	6.437	3.847	0.000
FDI → GDP	1.207	0.913	0.361	GDP → PATENT_POS	4.669	2.237	0.025
GDP → FDI	7.530	4.900	0.000	PATENT_POS → GDP	3.851	1.493	0.136
				FDI → PATENT_POS	4.854	2.406	0.016
				PATENT_POS → FDI	3.934	1.569	0.117
				TRADEMARK_POS → PATENT_NEG	2.600	0.355	0.723
				PATENT_NEG → TRADEMARK_POS	3.336	1.024	0.306
				TRADEMARK_NEG → PATENT_NEG	2.322	0.102	0.919
				PATENT_NEG → TRADEMARK_NEG	3.056	0.769	0.442
				GDP → PATENT_NEG	3.801	1.448	0.148
				PATENT_NEG → GDP	3.502	1.176	0.240
				FDI → PATENT_NEG	3.636	1.297	0.195
				PATENT_NEG → FDI	2.776	0.514	0.607
				TRADEMARK_NEG → TRADEMARK_POS	2.684	0.431	0.666

Null hypothesis:	W-Stat	Zbar-Stat	Prob	Null hypothesis:	W-Stat	Zbar-Stat	Prob
				GDP → TRADEMARK_POS	4.601	2.175	0.030
				TRADEMARK_POS → GDP	4.545	2.125	0.034
				FDI → TRADEMARK_POS	2.480	0.245	0.807
				TRADEMARK_POS → FDI	3.728	1.381	0.167
				GDP → TRADEMARK_NEG	9.375	6.521	0.000
				TRADEMARK_NEG → GDP	4.201	1.812	0.070
				FDI → TRADEMARK_NEG	2.793	0.530	0.596
				TRADEMARK_NEG → FDI	5.386	2.890	0.004
				FDI → GDP	1.207	-0.913	0.361
				GDP → FDI	7.530	4.900	0.000

Conclusion and implications

Energy consumption is the biggest source of carbon emissions in the world and the story of BRICS economies is not different. BRICS countries are collectively consuming one-third of the total world's energy consumption, hence, their share in the world's carbon emissions has reached 41%. This has raised the eyebrows of environmentalists not only from the BRICS countries but from all around the globe. Among other ways, technology innovation is one of the best options for reducing carbon emissions produced through energy consumption. Hence, in this study, our main focus is to see the asymmetric impact of technology shocks on the CO_2 emissions in BRICS economies. To that end, we have picked two different proxies of technology i.e. Patent and Trademark, and applied linear and non-linear panel ARDL-PMG. Asymmetry assumption is more reliable because in the real-world variables do behave in an asymmetric manner i.e. positive and negative technology stocks could have a different impact on the CO_2 emissions not only in signs but magnitudes as well.

The findings of the linear model confirm that, in the short run, estimates of all the variables are significant except the variable of Trademark. Similarly, the short-run asymmetric estimates are significant for three variables i.e., Patent, Trademark, and GDP. In the long run, the estimate attached to the Patent is significant and positive in the linear model and the estimates attached to all other variables are insignificant. However, the asymmetric estimates, in the long run, are significant for all the variables. By comparing the findings of linear and non-linear models, we can confirm that the non-linear model produced more significant results. Nonetheless, if we closely look at the estimates attached to Patent_POS (Trademark_POS) and Patent_NEG(Trademark_NEG) both have the same sign implying that positive shock reduces(increases) the carbon emissions and negative shock increases (decreases) the carbon emissions. Due to the difference in the magnitude of these effects and more significant results produced by the asymmetric model we can say that this model performs better than the linear model. Moreover, the causality results from both the methods, linear and non-linear, only provide evidence of a one-way causal relationship between different variables.

On the basis of these findings, the study puts forward some important policy implications. It is suggested that environmentalists and policymakers should formulate their policies by considering the effects of both negative and positive shocks. Furthermore, it is suggested that the BRICS countries should stimulate the patent and trademark policies for those innovations and products that are eco-friendly and conserve more energy. In this regard, governments should impose a carbon tax on such technologies that are involved in the deterioration of environmental quality. Governments should also increase the registration fee of these technologies in order to increase the overall welfare of society and the environment. The study also suggests that the BRICS economies should reinforce international exchanges and corporations and stimulate the spread of green eco-friendly technologies. Governments of BRICS economies need to stimulate adjustment of energy structure and promote low carbon-based technologies. BRICS economies should develop eco-friendly frameworks and policies to promote the automobiles and vehicles manufacturing sector that can be made possible by attracting foreign investment and green technologies.

The research could be extended to the country-specific and regional for future research. Future empirical research can consider the role of environmental technology in influencing environmental quality.

Publisher's note

Author contribution

The idea was given by Xiaoqiang Ma and Nafeesa Mughal. Xiaoqiang Ma, Asma Arif, Prabjot Kaur, Vipin Jain, Laila Rafanina, and Nafeesa Mughal have done the data acquisitions, analysis and written the whole draft. Nafeesa Mughal and Xiaoqiang Ma read and approved the final version.

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Data availability

The datasets/materials used and/or analyzed for present manuscript, are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate I am free to contract any of the people involved in the research to seek further clarification and information.

Conflict of interest The authors declare no competing interests.

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