Environmental Science and Pollution Research (2022) 29:59483–59501
https://doi.org/10.1007/s11356-022-20013-7

RESEARCH ARTICLE

The effect of renewable energy development, market regulation, and environmental innovation on CO2 emissions in BRICS countries

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Received: 2 December 2021 / Accepted: 28 March 2022 / Published online: 6 April 2022

Abstract
The relationship between energy, environment, and economic growth has been received a lot of attention recently among scientific studies, but environmental sustainability remains a global issue. Renewable energy development, green technological innovations, and regulatory policy mechanisms can all help to reduce greenhouse gas emissions and support environmental sustainability. The purpose of this study was to look at the influence of renewable energy development, market regulation, and environment-related innovation on CO_2 emissions in the BRICS countries from 1990 to 2020. For empirical analysis, it uses second-generation panel unit root test and updated linear and nonlinear cointegration techniques. To this end, this study employs symmetric and asymmetric approach to linear and nonlinear relationship among study variables. The findings indicate that there is long-run symmetric and asymmetric relationship between renewable energy development, market regulation, environment-related innovation, and CO_2 emissions. The market regulation plays significant mediating role in relation between renewable energy development, environment-related innovation, and CO_2 emissions. Our findings suggest that BRICS countries need to more focus on the environment-related innovation and renewable energy development. They should design market-based environmental regulation policies, emphasize on environmental taxes, expand renewable energy development, and environment-related innovations. Such strategies are key to limiting CO_2 emissions and gain environmental sustainable.

Keywords Renewable energy · Market regulation · Environment-related innovation · CO_2 emissions · BRICS

Abbreviations

RE	Renewable energy
TIN	Environment-related innovation
MR	Market-based environmental regulation
CE	Carbon emissions per capita
ECT	Error correction term

Introduction

The BRICS (Brazil, Russia, India, China, and South Africa) countries conquer 30% of the global land and 40% of the global population, and contribute more than 50% to the global GDP. These countries have different economic, political, and social characteristics with different population growths, energy consumption patterns and production, urban and infrastructure development, and industrial structure. Over the past decades, it is witnessed that rapid economic growth and economic prosperity of BRICS countries significantly influence the global environment (Pathak and Shah 2019).. The over-increased fossil fuel consumption and greenhouse gas emissions in BRICS countries enforced to switch from fossil fuel to renewable energy (RE) resources. The demand for RE resources (wind, solar, and hydropower) has also increased and grown rapidly in the BRICS countries. BRICS countries are rich and abundant in RE resources. For example, China's wind resources in Inner Mongolia are vast, and biomass energy is a major source of energy in rural areas (Meisen and Hawkins 2009).

Communicated by Roula Inglesi-Lotz

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India is a tropical country with average temperatures ranging from 25 to 27 °C. The country receives 5000 trillion kW equivalent in solar energy and climate is also ideal for solar energy development. Russia is the world's largest country in terms of land area. Mineral resources abound in the region, which exports and consumes a significant amount of fossil fuel each year. Russia is considering the third and largest producer and consumer of energy resources with 10% of world production and 5% energy consumption after the USA and China (Bächtold 2012). Brazil is the world's sixth-largest green energy stockholder (Pathak and Shah 2019). The country has abundant agricultural resources, mineral reserves, and clean energy hydroelectric resources. In 2014, RE accounted for 75% of total energy production in Brazil, with hydropower accounting for 90% of total electricity generation (Dudley 2018). The contribution of wind power remained relatively low. South Africa has smaller population and economy as compared to other BRICS countries. The country South Africa is ideal for solar energy resources and enriched with natural reserves such as coal, natural gas, and gold and diamond. UNEP reports claimed that the country will get 50% of its electricity from renewable energy resources by 2030 (Global 2017).

Over the last two decades, the nexus between energy, environment, and economic growth has been studied extensively among scientific studies and research scholars, but environmental sustainability and economic growth are remaining one of the biggest challenging issues to global community. Many countries adopt the new growth models and try to boost economic growth and foreign competitiveness by increasing industrial and manufacturing production. Studies indicate that the extensive use of fossil fuel energy resources for industrial and manufacturing production is the primary source of carbon emissions that cause global warming and climate change (Liu and Xiao 2018; Mi et al. 2018). There is wide consensus among scientific studies and research scholars that RE is a viable alternative to fossil fuel energy for achieving sustainable development goals (Dogan and Ozturk 2017; Shuai et al. 2017). Widespread use of RE resources is vital to achieving sustainable development goals and is considered secure, cost-effective, and environmentally sustainable options to underpin economic and social development (Breyer et al. 2020). Several studies and policy reports emphasized the role of RE resources, including solar energy, wind, tide, biofuel, hydroelectricity, and geothermal, in diversifying renewable energy supply as well as mitigating environmental and energy issues (Mert et al. 2019; REN21 2018; Zaidi et al. 2019). Jabeen et al. (2019) analyzed consumer intention to utilize renewable power generation technological access in remote areas, advantages, knowledge, and moral norms in prospects of Pakistan. The study found that relative advantage, environmental knowledge, perceived behavioral control, and subjective norms play positive role in adaptation of renewable energy process. RE resources are not only essential in limiting CO_2 emissions, but they are also crucial in contributing to the economy in a sustainable manner (Dong et al. 2018; Shahbaz et al. 2017). Thus, apart from the contribution of RE resources to reducing CO_2 emissions, it also positively contributes to the economy and promotes environmental quality (Breyer et al. 2020; Damette and Marques 2019; Moutinho et al. 2018). Therefore, promoting RE will help to boost economic development and improve environmental quality and energy efficiency (Dechezleprêtre and Sato 2017). Anser et al. (2021b) examined the relationship between renewable energy resources and clean economic growth among the Asian countries. The study found that the long-run association exists between variables. Hydropower, geothermal, wind, and solar energy have valuable positive impact on clean economic growth.

Thus, it is important to focus more attention at the national, regional, and global level on reducing the usage of traditional non-renewable energy and prioritize the adaptation of RE resources to achieve sustainable development goals. Many countries throughout the world are striving to convert their fossil fuel energy consumption to RE, and are enacting policies both individually and as part of a worldwide network to minimize CO_2 emissions. For instance, Peru has set a goal of generating 60% of its electricity from RE by 2024. Norway and Iceland are now generating 100% of their electricity from renewable sources. Germany and Sweden have also claimed that they would be carbon-free by 2050 (Al-Mahrouqi and Amin 2014; Dean et al. 2016). At the same time, the Organization of Economic Cooperation and Development (OECD), the International Energy Agency (IEA), the Center for Climate and Energy Solution (C2ES), and the International Renewable Energy Agency (IRENA) also play a significant role in designing market-based regulation policies for RE development. The United Nations General Assembly (UNGA) established the Sustainable Development Goals (SDGs) in 2015 which also provide a powerful basis for international collaboration to achieve a sustainable future for the world. The goals include three key objectives: ensuring sustainable, secure, and universal access to modern energy; significantly increasing the use of renewable energy; and doubling the global energy efficiency rate (Bank et al. 2017). Thus, preserving environmental protection has become one of the world's most challenging issues, requiring stricter environmental norms and regulations (Costa-Campi et al. 2017; Jardón et al. 2017; Sheffield and Landrigan 2011; Wolde-Rufael and Weldemeskel 2020).

A number of empirical studies have explored the causes of pollutant emissions and assessed the impact of RE development in reducing CO_2 emissions at regional and global levels by using a range of quantitative methods. For example, Gao et al. (2021) and Fatima et al. (2021) used panel space measurement and threshold estimation, multi-factor content analysis method, and partial least square-based structural equation modeling approach. They identified ten crucial factors that influence RE development. Among these, lack of governance, RE adaptation, energy policies, endowment resources, power production approaches, investment in renewable energy project, and their economic returns are the main factors that influence RE development. However, despite all these measures and policies, CO_2 emissions are growing and one of the major environmental problems. It is necessary to identify the main factors in reducing the pollution emissions and promoting RE development. Therefore, this study is designed to identify the factor and empirically investigate the impact of RE development, market regulations, and environment-related innovation on CO_2 emissions in BRICS countries over the period 1990–2020. There are two main factors that motivate to conduct current study: first, the BRIC countries comprised 40% of the total world population and are considered the fastest-growing countries in terms of population, economic growth, and development around the world (Chen and De Lombaerde 2014). Among these countries, India and China are considered the largest economies in population growth and leading suppliers of manufacturing goods and services. Brazil and Russian are considered the largest raw material suppliers in the world manufacturing market. Second, the BRICS countries' economic expansion is predominantly driven by high-energy-consuming industries such as building, mining, and manufacturing, resulting in increased CO_2 emissions (Cowan et al. 2014). Based on the above-mentioned factors, this study seeks to answer the following research questions: How does renewable energy development and environment-related innovation affect CO_2 emissions? Do market-based environmental regulation policies affect CO_2 emissions in BRICS countries?

This research makes a significant contribution to the growing literature on sustainable RE development in multifaceted ways; first, this study investigates the role of RE development in reducing CO_2 emissions. Second, to the best of our knowledge, none of the previous study checks the mediating role of market-based environmental regulation polices and environment-related innovation in relation to CO_2 emissions. We explore the mediating role of market-based environmental regulation polices and environment-related innovation in reducing CO_2 emissions. Third, this study used most recent developed panel asymmetric and symmetric method for the linear and non-liner cointegration among study variables. This can help to provide accurate and robustness insights into the policymaking process for mitigating pollutant emissions across the five BRICS countries.

Apart from the "1ntroduction" section, the current study is divided into fiver sections. In the "Review of literature" section, we look at relevant literature on renewable energy development, market regulation, and the role of environment-related technology innovation. The literature review is followed by the "Data and methodology" section, where we explain the source of data, description of variables, econometric model and method of analysis. The empirical findings and discussions are presented in the "4" section. The study's results are summarized in the "5" section, along with policy recommendations and limitation of study.

Review of literature

Both renewable and non-renewable energy resources play a vital role in economic development of modern economies. Proper functions of all economic activities, i.e., production, consumption, employment, education, and health care, all need energy. However, the non-renewable energy consumption has adversely impact on environmental suitability. Studies indicate that there is need to look for alternate energy resources (Anser et al. 2021b). Fatima et al. (2019) examined the long-term empirical association between RE generation, human capital, energy use, and economic performance in the case of Pakistan. The study found bilateral causal relation between the study variables such as energy use and economic performance, renewable energy and economic performance, and human capital.

Renewable energy development and CO_2 emissions

Developing renewable energy resources has become a critical component of combating global climate change, reducing greenhouse gas emissions, and preserving the environment. Several scientific studies investigate the impact of RE development on CO_2 emissions by using diverse econometric methods and different datasets. For example, Wang et al. (2018) explored the factors regulating renewable energy growth, energy security, and carbon emissions in China using the Divisia index approach. They used the Grey relational model to confirm the relation between renewable energy and its drivers. The findings suggest that energy security has a substantial influence on the development of renewable energy. They claimed that robust and sustained RE policies will enable China in attaining its long-term energy policy objectives.

Zeng et al. (2017) survey the historical renewable development in BRICS countries from 1992 to 2011. According to the study, China, India, and Brazil have a better track record and a greater number of achievements than Russia and South Africa. After decades of hard work, China has mastered a variety of innovative clean energy technologies, while installed capacity in India and Brazil is quickly rising. Russia and South Africa, on the other hand, are committed to growing their RE industries. The study brought attention to a few critical challenges in the development of renewable energy in the BRICS countries. The key challenges include a lack of finance, a lack of investment in small- and medium-sized enterprises, and inefficient government initiatives.

The recent studies highlight the factors that have influenced the production and usage of RE resources. For example, Wang et al. (2020) investigate the regional RE development across the 29 provinces in China. The study constructed a multidimensional measure of RE development in China from 2008 to 2014 using a dynamic principal component analysis tool. They developed a quantitative assessment system and implemented the multidimensional approach. They choose five-dimensional variables such as the economy, institutions, technical development potentials, energy security and environmental conservation, and the RE market. The empirical findings show that RE development varies greatly across China's regions. The more economically developed areas, such as Beijing, Shanghai, and Guangdong, have high rankings and consistent advantages in all dimensions. Renewable energy development is at its peak in Beijing and Shanghai while Guangdong, Zhejiang, Jiangsu, and Tianjin are at second place. At the same time, western provinces such as Ningxia, Qinghai, and Guizhou have the lowest RE development over the entire sample period. They came to the conclusion that China's institutional policies, as well as the position and economic foundations of the government, are more relevant and play a significant role in energy security, environmental protection, RE production, and CO_2 emission reduction. Shah et al. (2021) also emphasize that the track to achieve sustainable energy and SDGs-7 needs to build equitable, sustainable, and more resilient economic policies. The study argued that rising RE policy targets, having green technological innovations, initiating stringent regulation, and safeguarding renewable energy projects are the ways to sustainable environment.

Banday and Aneja (2020) examine the causal link between renewable and fossil fuel energy, economic development, and CO_2 emissions in BRICS countries over the 1990–2017. They used bootstrap Dumitrescu and Hurlin (2012) panel causality test for heterogeneity and dependency in cross-sectional units across the sample countries. The findings indicate that India, China, Brazil, and South Africa have unidirectional causality from GDP to CO_2 emissions, whereas Russia has no causality. In comparison, the causality from RE to GDP shows that GDP growth causes renewable energy in India, China, Brazil, and Russia and not causality for South Africa. This suggests that GDP growth is an important driving factor in both CO_2 emissions and RE. Theoretically, the results support the environmental Kuznets curve (EKC) hypothesis, which predicts an inverted *U*-shaped relationship between income and environmental indicators. Thus, in the long run, RE development is one of the most important solutions to an environmental problem. Li et al. (2021) explored the factors that contribute to the renewable electricity output in realizing carbon neutrality in China from 1989 to 2019. They found that trade and export diversification plays significant role in renewable electric output and carbon neutrality. In the long run, export diversification and renewable electricity output are predicted to decelerate CO_2, supporting carbon neutrality targets.

Khan et al. (2020) investigate the relationship between energy usage, economic development, and CO_2 emissions in Pakistan using annual time series data from 1965 to 2015. They used the autoregressive distributed lag model (ARDL), and the estimated results show that in the short and long run, energy use and economic growth increase CO_2 emissions. They claimed that RE resources would replace conventional energy sources, lowering CO_2 emissions and ensuring Pakistan's long-term economic development. Rehman et al. (2021a) studied the asymmetric relationship between CO2 emissions, trade, FDI, and RE in Pakistan. They employed the asymmetric ARDL approach to validate constructive and negative relationship between variables. The study findings revealed that the negative shocks to RE consumption increase the level of CO_2 emissions.

Balakrishnan et al. (2020) analyzed the RE installed capacity of developing countries emphasizing on China as a leader in RE development. They addressed the legislation and policies surrounding the use of RE. The study found that the most significant impediment to RE development in developing countries is the private sector's inability to invest due to the long time it takes for capital to return and the high cost. The study suggested that government plays a significant role in resolving this issue through the support and guaranteed purchase generated of electricity. Similarly, Ahmad et al. (2019) examine the interaction between FDI, renewable power generation, hydropower, non-hydropower generation, and CO_2 emissions in China. In order to achieve the short and long run, the study employed Bayer-Hanck cointegration test and ARDL model. To confirm the direction of casualty between variables, the study used Toda-Yamamoto and Granger causality tests. They found long-run cointegration among variables; the expansion of FDI and CO_2 emissions boosted renewable power, hydropower, and non-hydropower generation. Furthermore, causality test shows bidirectional causality between CO2 emissions, power, hydropower, and non-hydropower generation.

Saidi and Omri (2020) examined the short- and long-run impact of RE and nuclear energy consumption on CO_2 emissions in 15 OECD countries from 1990 to 2015. The study used a fully modified OLS (FMOLD) and vector error correction (VECM) approach. The overall panel estimation results show both renewable and nuclear energies reduce CO_2 emission. While in the case of a single country, FMOLS shows mixed results. CO_2 emissions increase in the Netherlands and South Korea with an investment in renewable and non-renewable energy sectors. In some countries like Canada, Japan, France, and Germany, investment in nuclear and renewable energy reduces CO_2 emissions. Moreover, the VECM method results show investment in both sectors can help reduce CO_2 emissions in the long run.

Elavarasan et al. (2020) reviewed the drivers and barriers of RE development in China, India, Iceland, Sweden, and the USA. This study provides a comprehensive evaluation framework based on the four major parameters: strength, weakness, opportunities, and threats for RE resources. The analysis has been found that well-structured policies and abundant resources can benefit the renewable energy sector. The major factors influencing the RE sectors are greater dependency on fossil fuel consumption and a multi-level government system that causes a delay in implementing policies. The other factors are lack of awareness within the country's people, absence of widespread installation of small-scale micro and Pico-hydropower, and lack of grid captivity and transmission lines.

Market-based environmental regulation and CO_2 emissions

Market-based environmental regulation refers to the environmental policies used by the state administrative department to control or regulate emissions using various market mechanisms, i.e., environmental taxes. The effect of regulation on the environment has been extensively researched in different aspects. The scientific studies identified variety of economic factors, including a rapid economic growth, low industrial structures, and backward pollution abatement environment-related technological innovations with environmental pollution that causes global warming and climate change (Zhu et al. 2014). The market-based environmental regulation tools such as environmental taxes are considering to be an effective way to alleviate carbon emissions and improving environmental quality (Guo and Yuan 2020). Market-based environmental regulation policies increase firms' cost burden, increase new constraints on firm performance, and make firms' production and sales more difficult. The firms increase their energy efficiency and utilize their resources efficiently. This can help to control carbon emissions and improve environmental quality. In the most recent study, Wang et al. (2021) also argued that government intervention and market-based environmental regulation are the main mechanism for protecting environmental quality and control CO_2 emissions in China.

In scientific research, several studies used different methods to measure market-based environmental; the recent measures are provided (Althammer and Hille 2016; Brunel and Levinson 2016; Ren et al. 2018). Althammer and Hille (2016) provide a sector-specific indicator of climate policy stringency on multiple levels. This method is used to determine sector-specific emissions in climate policy. The study used first time a shadow price approach to environmental policy stringency for the 28 OECD countries over the time period 1995–2009. Similarly, Brunel and Levinson (2016) evaluate the stringency of environmental regulation. They measure the environmental regulation into five broad categories and argued that each has a strength and weakness. Furthermore, Shan et al. (2021) argued that institutional quality and fiscal decentralization help to limiting CO_2 emissions and RE development. Improvement in country institutions and transferring of power from center to the local bodies bring more sustainable economic growth, resource utilization, and better efficiency, as a result allowing to achieve better outcomes. Based on the empirical results, the study emphasized that strengthening local institutions and further devaluation of power to local units, particularly focusing on environmental policy issues, achieve the United Nation Sustainable Development goals (SDGs).

Ren et al. (2018) examine the impact of three types of market-based environmental policies on eco-efficiency across the 30 provinces in Chinese. The first is command and control-based regulation, second, market-based regulation, and third is voluntary-based ER. They found mixed results across the provinces, with market-based and voluntary market-based environmental having a positive effect on eco-efficiency improvement in the eastern region, while command and control-based environmental regulation policies have no significant impact. In the central region, on the other hand, command and control, as well as market-based environmental regulation, will foster eco-efficiency more effectively than voluntary ER. Thus, this finding suggests that the effect of different types of market-based environmental regulation policies has different impacts on different regions.

Hille et al. (2020) measured market-based environmental regulation in two dimensions: regulation design and regulation strength. In the first dimension, the authors used renewable energy goals, R&D&D schemes, renewable energy quotas, energy output payment or feed-in-tariff, fiscal incentive, and a carbon trading scheme. In the second dimension, the length of regulation is measured by the policy period, such as the number of years a particular policy instrument. The findings revealed that policies that promote a broader range of market-based environmental regulation technologies result in further patenting of wind and solar power-related technologies. The environmental policy instruments including R&D and research programs, targets, and fiscal incentives have strong impact on reducing carbon emissions and help to improve renewable energy technologies. Ouyang et al. (2020) used generalized method of moment (GMM) estimation to investigate the factor behind CO_2 emission reduction in Chinese heavy industries. The findings show that industrial structure, fixed investment, and historical emissions are the primary drivers of increased sectoral emissions, while energy efficiency is a critical factor in CO_2 emission reduction. Furthermore, to assess the policy results, the study used a propensity score matching and difference in difference (PSM-DID) approach. They found that implementing an emission reduction strategy minimizes CO_2 emissions from heavy industries in China over the sample period.

Environmental innovation and CO_2 emissions

Theoretically and empirically, the contribution of technological progress to environmental quality, especially CO_2 emissions, is not clear. Endogenous economic growth theory explains that an increased R&D investment and technical capabilities can improve economic efficiency and energy resources (Aghion and Howitt 1992; Romer 1990). Many studies show that coordinating R&D spending and technical capabilities enhances environmental quality and lowers CO_2 emissions (Costantini et al. 2017; Suzuki 2015; Yang and Li 2017). Technical advancements bring innovative and more effective technological applications that can directly improve energy efficiency and reduce fossil fuel consumption. Furthermore, technological advancement helps to restructure the economy, which can help to shift the conventional factor-driven model to innovation-driven economic development (Sohag et al. 2015). Xin-gang et al. (2021) construct the system dynamic model to study R&D investment, photovoltaic power generation, and government incentive policies. The study found R&D investment and government incentive policies are favorable to technological innovation in photovoltaic power generation industry in China. The study emphasized that higher level of R&D investment can reduce the cost of production and promote the growth of photovoltaic power generation industry installed capacity. R&D and technological innovation can force to endogenous growth factors such as capital and labor and it has change the traditional output growth to technological innovation-driven factors. Thus, R&D investment and environment-related innovation-driven based economic models promote clean energy, ultimately reducing CO_2 emissions. However, several empirical studies test this argument and found evidence supporting environment-related innovations significantly reduce CO_2 emissions (Ahmed et al. 2016; Churchill et al. 2019). Similarly, Iqbal et al. (2021) investigate the role of export diversification and environmental innovation in achieving carbon neutrality targets for 37 OECD countries from 1970 to 2019. The study found that RE consumption and environment-related technological innovation assure environmental improvement, while export diversification hinders environmental improvement in the long run. The short-run results show causal linkages between export diversification and environment-related technological innovation to CO_2 emissions. Jabeen et al. (2021) investigate the critical factors affecting consumer intention to purchase renewable generation technologies (RGT) in rural and urban region of Punjab province of Pakistan. The critical factors include cost component of RGT, investment risk component, and green solution to power blackout. However, overall results are categorized into three major components, i.e., conditional components, inhibitory components, and neutrality components. They found that there is heterogeneous effect across the rural and urban region toward consumer intention to purchase RGT. The size of all components is relatively larger in urban than rural areas.

Some researchers, on the other hand, conclude that R&D spending and technological progress may have a negative impact on environmental quality due to the scale effect of large-scale development, trade openness, and economic growth. As technology advances, demand for energy rises, resulting in increased pollution (Cheng et al. 2019; Kivyiro and Arminen 2014). Accordingly, environment-related technologies can improve resource use efficiency, but their marginal role is diminishing, and a rapid increase in economic scale may still require more investment in natural resources. Cheng et al. (2019) investigate the impact of RE and innovation on CO_2 emissions for the OECD countries. The study found a positive and significant relationship between CO_2 emissions and overall technological progress, as well as a negative relationship between RE and CO_2 emissions.

Rehman et al. (2021b) investigate the nexus between information technology, FDI, trade, RE, and economic progress in Pakistan. The ARDL bound testing approach is used to check the dynamic short- and long-run results. The findings indicate that information technology, FDI, trade, and RE have positive effect GDP. Furthermore, Chen and Lee (2020) examined the impact of green technological innovation on CO_2 emissions. This study used a spatial panel data model to look at the problem from a global perspective and view the variability of technological progress across countries. In overall sample estimations, they found that technical progress has no major mitigating impact on CO_2 emissions. Sub-sample results show green technological progress can substantially reduce CO_2 emissions in high-income, high-technology, and high-CO_2 emission countries. Furthermore, the greater a country's degree of globalization, the more evident the impact of green technological progress on CO_2 emission reduction. Furthermore, Gao et al. (2021) depicted several economic, social, technological, human resource, and policy barriers to RE development in Pakistan. The economic barriers include unaware potentials of renewable energy, high economic cost of new projects, unavailability of government subsidies, and limited access to loans from banking sectors. Technical and policy barriers to RE development include confusing polices regarding the private investor participation, high priority to traditional source of energy, lack of structural regulation, unreliable local technology, limited production and facilities, and relying on foreign technologies.

Anser et al. (2021a) analyzed the dynamic relationship between technological factors and CO_2 emission in 26 European countries from 2000 to 2017. They found that there is monotonic relationship between agriculture technology and CO_2 emissions over the sample period, while in contrast, there exists *U*-shaped relationship between different quantiles. The results further show negative relationship between high-technology exports and CO_2 emissions. This implies that high-technology exports contribute positively to environmental performance across the sample countries, while R&D expenditures have negative relationship with CO_2 emissions. The study concluded that green technological innovation is imperative for sustainable production, consumption, environmental protection, and regulation that shaped international polices toward the sustainable environment.

To sum up, several studies used different datasets and diverse econometric methods over different periods in different regions and countries. All existing research on the effect of environment-related technological innovation, market regulation reforms, and RE on CO_2 emissions is controversial and provides mixed outcomes. Studies indicate that developing countries' renewable energy development and environment-related technological progress are insufficient to reduce CO_2 emissions. In contrast, in some developed countries, there is a strong impact on reducing CO_2 emissions. At the same time, the empirical studies on emerging and developing countries are limited. The BRICS countries in particular have received little attention. Thus, to fill this gap and provide good supplementary to existing literature, this paper investigates the effects of RE development, market policy reforms, and environment-related technology on CO_2 emissions in BRICS countries for the period 1990–2020.

Data and methodology Our sample consists of five BRICS countries, namely Brazil, Russia, India, China, and South Africa, over 1990–2020. The selection of time period is based on the data availability. The data has been obtained from the World Bank Development Indicators (World Bank, 2019) and Organization of Economic Cooperation and Development (OECD) Environmental Database (OECD, 2019). Our main study variables include the following:

Explained variable CO_2 emissions (CE) per capita is used as core explanatory variable of our study that represents a per-unit of CO_2 emissions from primary energy combustion, such as crude oil, natural gas, coal, and other fuels, divided by the total population.

Core explanatory variables Our core explanatory variables include RE development, which is proxy by the contribution of renewables to total primary energy supply. The data on this variable has been taken from the OECD energy database. The second core explanatory variable of our study is market regulation, representing the measure of environmental regulation policies that the state administrative department uses to manage or limit pollution through different market mechanisms tools. To consider data quality and availability, we use environmentally related taxes to GDP as a proxy indicator for the market-based environmental regulation tool. The third core explanatory variable is environment-related innovation (TIN). The most recent research literature selects environment-related innovation from the OECD input and output indicators. The input indicator of technological innovation mainly includes the investment in R&D sector and government expenditures on environment-related technologies. The output indicators of environment-related innovation mainly includes the patent applications, number of patent grants, and technological market value (Wang et al. 2012; Wurlod and Noailly 2018). So, this study used the output indicator of technological innovation, which represents the development of environment-related technologies. TIN represents creative activities; specifically, it depicts the patents which belong to environment-related technological domains, including environmental management, climate change mitigation technologies, and water resource management (Wang et al. 2012).

Control variables GDP per capita (GDP), trade openness (TR), and foreign direct investment (FDI) are used as control variables. GDP per capita measures a country's economic wealth of population. GDP per capita income is also implying the economic growth of the nation. Moreover, economic growth is widely recognized as one of the chief drivers of CO_2 emission (Ren et al. 2019; Zhou et al. 2018). The current study used GDP per capita income expressed at the constant 2010 USD PPP prices. Trade openness (TR) measures the sum of exports and imports of goods and services. TR reveals the role of international trade in a nation's CO_2 emissions (Hu et al. 2018; Piaggio et al. 2017). The data on TR (sum of exports and imports of goods and services % of GDP) has been collected from the World Bank Indicators. Foreign direct investment (FDI) is another control variable of this study that measures the inward investment volume provided by non-residents of the country. FDI influence country CO_2 emissions; according to the pollution haven hypothesis, developed countries tend to transfer energy and pollution-intensive industries to developing countries with a weaker environmental regulation to save production cost. The developing countries welcome any kind of investment from other countries which may cause serious pollution. On the other hand, according to the halo effect hypothesis, FDI may help to reduce CO_2 emissions (Sarkodie and Strezov 2019; Zhu et al. 2016). FDI from developed countries bring advanced environment-related technologies to developing countries and cause lowering the environmental pollution.

Table 1 Descriptive statistics and sources

Variables	Description	Units	Source
CO_2 emissions (CE)	CO_2 emissions per capita	Tones, millions	OECD
Renewable energy development (RED)	The contribution of renewable energy to total energy supply (excluding solid biofuels)	Percentage of total energy supply	OECD
Environment-related innovation (TIN)	Development of environment-related technologies	Percentage of all technologies	OECD
Market regulation (MR)	Environmentally related taxes	Percentage of GDP	OECD
GDP per capita (GDPP)	Real GDP per capita	US dollar, 2015	WDI
Trade openness (TR)	sum of exports and imports of goods and services	Percentage of GDP	WDI
Foreign direct investment (FDI)	Foreign direct investment, net inflows	Percentage of GDP	WDI

Fig. 1 Theoretical framework

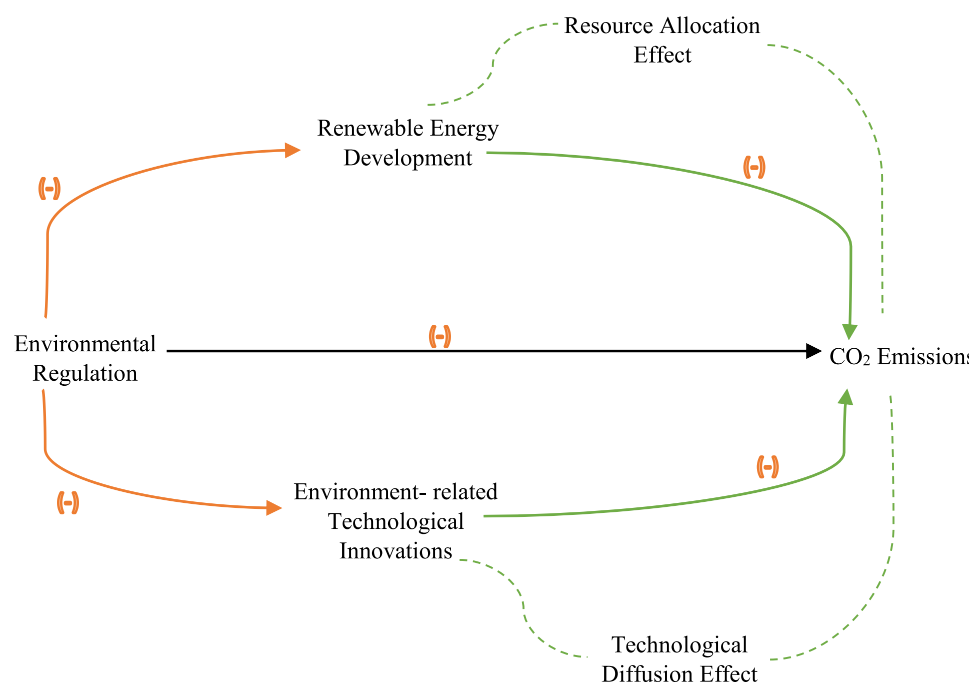

Table 1 shows the data source, definition, and measurement of variables used in the analysis.

Theoretical framework and model construction

Theoretically, the relationship between renewable energy development, environment-related innovation, and CO_2 emissions gains an importance in the field of ecological economics, innovation and development, environment, and sustainability. The CO_2 emission relation is linked with various factors like country level of income, RE consumption, economic growth, fossil fuel energy consumption, regulation policies, and financial development. Several factors provide different pathways either negative or positive to CO_2 emissions. Moreover, the theoretical linkages between CO_2 emissions, RE, environment-related innovation, and market regulation are straightforward. The more utilization of renewable energy resources lowers the demand for fossil fuel energy and CO_2 emissions (Doğan et al. 2021; Dogan and Seker 2016).

On the other hand, the market-based environmental regulation policies significantly promote environment-related innovations and reduce pollution in the process of industrial transformation. The environmental regulation policies force to improve energy efficiency and reduce undesired output such as CO_2 emissions (Du et al. 2021). Similarly, environment-related technologies promote the green innovations and production and, as a result, improve the industrial ecological chain (Yang et al. 2020). They study used two-step econometric model and nonlinear mediating effect model. Based on this study, we construct the theoretical model as shown in Fig. 1.

This study investigates the impact of renewable energy development, market regulation, and environment-related innovation on CO_2 emissions over the period 1990 to 2020 in a panel of 5 BRICS countries. First, the following benchmark model is set to test the relationship among variables.

$$CE_{it} = \beta_o + \beta_1 RED_{it} + \beta_2 TIN_{it} + \beta_3 MR_{it} + \Sigma\beta_4 X_{it} + \mu_i + \omega_t + \varepsilon_{it} \quad (1)$$

where i and t denote country and year respectively. CE_{it} denotes the dependent variable CO2 emissions per capita, RED_{it} is renewable energy development, TIN_{it} is environment-related innovation, and MR_{it} is market regulation. X_{it} represents the set of control variables such as GDP per capita (GDPP), trade openness (TR), and foreign direct investment, net inflows (FDI). μ_i represents unobserved country individual effects, ω_t is time effects, and ε_{it} is random error term.

The existing literature (Yang et al. 2020) shows that market regulation policies directly and indirectly affect the carbon emissions, environment-related innovations, and renewable energy development. In this regard, we check the role of market-based environmental policies; the interaction terms $MR_{it} \times RED_{it}$ and $MR_{it} \times TIN_{it}$ are added in model (1), respectively.

$$\begin{aligned} CE_{it} = \beta_o + \beta_1 RED_{it} + \beta_2 TIN_{it} + \beta_3 MR_{it} + \beta_4 \\ (MR_{it} \times RED_{it}) + \beta_5 (MR_{it} \times TIN_{it}) \\ + \Sigma\beta_6 X_{it} + \mu_i + \omega_t + \varepsilon_{it} \end{aligned} \quad (2)$$

Finally, in order to explore the linear and nonlinear relationship, the panel nonlinear autoregressive distributed lag model (NARDL) is employed to estimate symmetric and asymmetric relationship among study variables. This methodology has several advantages over the traditional approaches. First, this approach can be used for both order of integration, whether repressors are purely I (1) or I (0) or mutually integrated order of integration (Pesaran and Shin 1996; Pesaran et al. 2001). Second, this approach makes estimation possible even though variables are found to be endogenous (Pesaran and Shin 1996; Pesaran et al. 2001). Third, the ARDL approach provides both short- and long-run effects of independent variables on dependent variable simultaneously. Because of these advantages, we estimate the following nonlinear models.

$$\begin{aligned} CE_{it} = \beta_o + \beta_1 RED^+_{it} + \beta_2 RED^-_{it} + \beta_3 TIN^+_{it} \\ + \beta_4 TIN^-_{it} + \beta_5 MR^+_{it} + \beta_6 MR^-_{it} + \beta_7 MR \times RED^+_{it} \\ + \beta_8 MR \times RED^-_{it} + \beta_9 MR \times TIN^+_{it} + \beta_{10} MR \times TIN^-_{it} \\ + \Sigma\beta_{11} X_{it} + \mu_i + \omega_t + \varepsilon_{it} \end{aligned} \quad (3)$$

Equation (3) shows the nonlinear asymmetric relationship, response of positive and negative changes in renewable energy development (RED_{it}), environment-related innovation (TIN_{it}), market regulation (MR_{it}), and their interaction terms to carbon emissions (CE_{it}), respectively, while Eqs. (1) and (2) assumed the linear relationship among the variables Eqs. (4-13).

$$RED^+_{it} = \sum_{i=1}^{t} \Delta RED^+_i = \sum_{i=1}^{t} \max(\Delta RED_i, 0) \quad (4)$$

$$RED^-_{it} = \sum_{i=1}^{t} \Delta RED^-_i = \sum_{i=1}^{t} \min(\Delta RED_i, 0) \quad (5)$$

$$TIN^+_{it} = \sum_{i=1}^{t} \Delta TIN^+_i = \sum_{i=1}^{t} \max(\Delta TIN_i, 0) \quad (6)$$

$$TIN^-_{it} = \sum_{i=1}^{t} \Delta TIN^-_i = \sum_{i=1}^{t} \min(\Delta TIN_i, 0) \quad (7)$$

$$MR^+_{it} = \sum_{i=1}^{t} \Delta MR^+_i = \sum_{i=1}^{t} \max(\Delta MR_i, 0) \quad (8)$$

$$MR^-_{it} = \sum_{i=1}^{t} \Delta MR^-_i = \sum_{i=1}^{t} \min(\Delta MR_i, 0) \quad (9)$$

$$MR \times RED^+_{it} = \sum_{i=1}^{t} \Delta MR \times RED^+_i = \sum_{i=1}^{t} \max(\Delta MR \times RED_i, 0) \quad (10)$$

$$MR \times RED^-_{it} = \sum_{i=1}^{t} \Delta MR \times RED^-_i = \sum_{i=1}^{t} \min(\Delta MR \times RED_i, 0) \quad (11)$$

$$MR \times TIN^+_{it} = \sum_{i=1}^{t} \Delta MR \times TIN^+_i = \sum_{i=1}^{t} \max(\Delta MR \times TIN_i, 0) \quad (12)$$

$$MR \times TIN^-_{it} = \sum_{i=1}^{t} \Delta MR \times TIN^-_i = \sum_{i=1}^{t} \min(\Delta MR \times TIN_i, 0) \quad (13)$$

Data analysis methods

This study used standard econometric methodology; our analysis starts with the testing cross-sectional dependency, panel unit root test, cointegration, and linear and nonlinear ARDL, respectively.

Cross-sectional dependency

The first step toward the empirical analysis is to test the existence of cross-sectional dependency (CD) across the countries. To examine the cross-sectional dependency, this study conducts parametric test suggested by Pesaran (2004). The test has better power properties and can be used with both balance and unbalance panels. The test has also good properties for both small cross-section and time series dimensions (Pesaran 2004). The CD test is robust to parameter heterogeneity and structural breaks, and does not require a priori specification. The test is applicable for a wide range of panel data models. The null hypothesis of test is no cross-sectional dependence; $H_0 : Cov(\varepsilon_{it}, \varepsilon_{jt}) = 0$ for all t, and $i \neq j$ is tested against alternative hypothesis of $H_1 : Cov(\varepsilon_{it}, \varepsilon_{jt}) \neq 0$ for at least one pair of $i \neq j$. Pesaran (2004) developed CD test statistics as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i-1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \tag{14}$$

where $\hat{\rho}_{ij}$ is the estimates of pairwise correlation of residuals from the OLS estimates of Eq. (1) for each i.

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t=1}^{T} \hat{\varepsilon}_{it}\hat{\varepsilon}_{jt}}{\left(\sum_{t=1}^{T} \hat{\varepsilon}_{it}^2\right)^{1/2}\left(\sum_{t=1}^{T} \hat{\varepsilon}_{jt}^2\right)^{1/2}} \tag{15}$$

where $\hat{\varepsilon}_{it}$ is the OLS estimates of ε_{it} in Eq. (1). The results of CD test are reported in Table 3.

Panel unit root test

In the panel data framework, two generations of test are used. In the first generation, panel unit root test assumes that the cross sections are cross-sectional independent, while the second-generation unit root test relaxes the assumption of cross-sectional independent and it allows the cross-sectional dependency among the cross-sectional units. This study used the second-generation panel unit root test, namely, Maddala and Wu (1999) test (WU) and Pesaran (2007) panel unit (CIPS) test, in determining the degree of integration of each variable. The advantage of these tests is that it allows for the cross-sectional dependency. The test statistics developed by Pesaran (2007) can be written as follows.

$$CIPS(N,T) = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T) \tag{16}$$

Linear and nonlinear panel cointegration tests

After determining the order of integration, the next step will be to look into the possibility of a long-term relationship between variables. To test the presence of long-run relationship among variables, this study used both linear and nonlinear panel cointegration tests. In the first step, we apply Westerlund (2007) panel cointegration test. The test allows cross-sectional dependency. Westerlund (2007) test includes four statistics, two for mean group statistics and two for the panel statistics. The null hypothesis of test statics is no cointegration, while alternative hypothesis is at least one individual unit of panel is cointegrated. The test statistics is written as follows.

$$G_t = N^{-1} \sum_{i-1}^{N} \frac{\psi}{Se(\psi)} \tag{17}$$

$$G_a = N^{-1} \sum_{i-1}^{N} \frac{T\psi}{\psi(1)} \tag{18}$$

$$P_T = \frac{\psi}{Se(\psi)} \tag{19}$$

$$P_a = T\psi \tag{20}$$

where G_t and G_a represent the mean group statistics, while P_T and P_a represent panel statistics.

In the second step, we conduct the nonlinear panel cointegration test proposed by Hatemi-J (2020). This test detects the eventual hidden cointegration relationship between positive and negative components of variables. This study follows the method of Altıntaş and Kassouri (2020); we consider multi-version of cointegration analysis by allowing the control variables. It is assuming that control variables enter symmetrically in the cointegration relations. Consider the following potential cointegration model.

$$y_{it}^{+} = \gamma_i^{+} + \varphi_i^{+} Z_{it}^{+} + X_{it} + \eta_i^{+} \tag{21}$$

$$y_{it}^{-} = \gamma_i^{-} + \varphi_i^{-} Z_{it}^{-} + X_{it} + \eta_i^{-} \tag{22}$$

where y_{it}^{+} and y_{it}^{-} denote the positive and negative partial cumulative of carbon emissions, respectively. Z_{it}^{+} and Z_{it}^{-} represent positive and negative partial integers of our core explanatory variables, respectively. X_{it} are control variables of our study. We test the hypothesis; $\left[y_{it}^{+};Z_{it}^{+}\right]$ are cointegrated in the panel if η_i^{+} is stationary, $\left[y_{it}^{-};Z_{it}^{-}\right]$ are cointegrated in the panel if η_i^{-} is stationary, $\left[y_{it}^{+};Z_{it}^{-}\right]$ are cointegrated in the panel if η_i^{+} is stationary, and $\left[y_{it}^{-};Z_{it}^{+}\right]$ are cointegrated in the panel if η_i^{-} is stationary. The cross-sectional Dickey-Fuller (CDF) test is used for testing the cointegration relations.

Table 2 Descriptive statistics and sources

Variables	Mean	Std. Dev	Min	Max
CO_2 emissions (CE)	6.902	1.095	5.217	9.219
Renewable energy development (RED)	5.062	6.517	0.014	22.745
Environment-related innovation (TIN)	2.102	0.364	1.163	2.76
Market regulation (MR)	1.268	0.583	0.169	2.756
GDP per capita (GDPP)	9.045	0.766	7.25	10.164
Trade openness (TR)	3.653	0.408	2.719	4.706
Foreign direct investment (FDI)	2.032	1.496	−0.066	6.187

Linear and nonlinear ARDL

In the panel data framework, mean group (MG) and pooled mean group (PMG) model was developed by Pesaran and Smith (1995) and Pesaran et al. (1999) to estimate the linear and nonlinear relationship among the variables. In this study, we follow the method of Pesaran et al. (1999) and developed the following linear dynamic heterogeneous panel ARDL model.

$$\begin{aligned}\Delta CE_{it} &= \zeta_{i1} CE_{it-1} + \psi_{i2} RED_{it-1} + \psi_{i3} TIN_{it-1} \\ &+ \psi_{i4} MR_{it-1} + \psi_{i5}(MR \times RED)_{it-1} + \psi_{i6}(MR \times TIN)_{it-1} \\ &+ \psi_{i7} X_{it-1} + \sum_{j=1}^{m} \beta_{1ij} \Delta CE_{it-j} + \sum_{j=0}^{m} (\beta_{2ij} \Delta RED_{it-j} \\ &+ \beta_{3ij} \Delta TIN_{it-j} + \beta_{4ij} \Delta MR_{it-j} + \beta_{5ij} \Delta MR \times RED_{it-j} \\ &+ \beta_{6ij} \Delta MR \times TIN_{it-j} + \beta_{7ij} \Delta X_{it-j}) + \mu_i + \omega_t + \varepsilon_{it}\end{aligned} \tag{23}$$

where ψ_i and β_{ij} denote the long-run and short-run coefficients. m represents the optimal lag length and Δ is the first difference. μ_i and ω_t show the group-specific effect and time effect. Equation (25) contains two parts; the first part of the equation represents long-run relationship among the variables and second part represents error correction dynamics. The long-run coefficients are computed as $-\frac{\psi_{ij}}{\zeta_{i1}}$. The error correction mechanism is . This represents the speed of adjustment term. The linear type of error correction model can be written as follows.

$$\begin{aligned}v_{it-1} &= \alpha_{1i} - \psi_i(CE_{it-1} + RED_{it-1} \\ &+ TIN_{it-1} + MR_{it-1} + MR \times RED_{it-1} \\ &+ MR \times TIN_{it-1} + Control_{it-1})\end{aligned}$$

$$\begin{aligned}\Delta CE_{it} &= \Gamma_1 v_{it-1} + \sum_{j=1}^{m} \beta_{1ij} \Delta CE_{it-j} + \sum_{j=1}^{m} \beta_{2ij} X_{it-1} + \sum_{j=0}^{m} \\ &(\beta_{2ij} \Delta RED_{it-j} + \beta_{3ij} \Delta TIN_{it-j} + \beta_{4ij} \Delta MR_{it-j} + \beta_{5ij} \Delta MR \times RED_{it-j} + \beta_{6ij} \Delta MR \times TIN_{it-j} + \beta_{7ij} \Delta X_{it-j}) \\ &+ \mu_i + \omega_t + \varepsilon_{it}\end{aligned} \tag{24}$$

Under the nonlinear scenario of the panel ARDL, known as asymmetric ARDL, one assumed positive and negative shocks in the regression mode. We implement the Pesaran and Smith (1995) method and consider the following asymmetric version of equation.

$$\begin{aligned}\Delta CE_{it} &= \omega_{ij1} CE_{it-1} + \psi_{ij2} RED^+_{it-1} + \psi_{ij3} RED^-_{it-1} \\ &+ \psi_{ij4} TIN^+_{it-1} + \psi_{ij5} TIN^-_{it-1} + \psi_{ij6} MR^+_{it-1} \\ &+ \psi_{ij7} MR^-_{it-1} + \psi_{ij8} MR \times RED^+_{it-1} + \psi_{ij9} MR \times RED^-_{it-1} \\ &+ \psi_{ij10} MR \times TIN^+_{it-1} + \psi_{ij11} MR \times TIN^-_{it-1} \\ &+ \pi_{ij12} X_{it-j} + \sum_{j=1}^{m} \pi_{1ij} \Delta CE_{it-j} + \sum_{j=0}^{m} (\varphi_{2ij} \Delta RED^+_{it-j} \\ &+ \varphi_{ij3} \Delta RED^-_{it-j} + \varphi_{ij4} \Delta TIN^+_{it-j} + \varphi_{ij5} \Delta TIN^-_{it-j} \\ &+ \varphi_{ij6} \Delta MR^+_{it-j} + \varphi_{ij7} \Delta MR^-_{it-j} + \varphi_{ij8} \Delta MR \times RED^+_{it-j} \\ &+ \varphi_{ij9} \Delta MR \times RED^-_{it-j} + \varphi_{ij10} \Delta MR \times TIN^+_{it-j} \\ &+ \varphi_{ij11} \Delta MR \times TIN^-_{it-j} + \varphi_{ij12} \Delta X_{it-j}) + \mu_i + \omega_t + \varepsilon_{it}\end{aligned} \tag{25}$$

Equation (27) shows the asymmetric relationship among variables of study in the short and long run. The long-run coefficients are computed as $-\frac{\psi_{ijs}{}^+}{\omega_{ij1}}$ and $-\frac{\psi_{ijs}{}^-}{\omega_{ij1}}$. The nonlinear version of error correction model can be further simplified as follows.

$$\begin{aligned}\Delta CE_{it} &= \Gamma_2 v_{it-1} + \omega_{ij2} X_{it-j} + \sum_{j=1}^{m} \pi_{1ij} \Delta CE_{it-j} + \sum_{j=0}^{m} \\ &(\varphi_{2ij} \Delta RED^+_{it-j} + \varphi_{ij3} \Delta RED^-_{it-j} + \varphi_{ij4} \Delta TIN^+_{it-j} + \varphi_{ij5} \Delta TIN^-_{it-j} \\ &+ \varphi_{ij6} \Delta MR^+_{it-j} + \varphi_{ij7} \Delta MR^-_{it-j} + \varphi_{ij8} \Delta MR \times RED^+_{it-j} \\ &+ \varphi_{ij9} \Delta MR \times RED^-_{it-j} + \varphi_{ij10} \Delta MR \times TIN^+_{it-j} + \varphi_{ij11} \Delta MR \times TIN^-_{it-j} + \varphi_{ij12} \Delta X_{it-j}) \\ &+ \mu_i + \omega_t + \varepsilon_{it}\end{aligned} \tag{26}$$

where v_{it-1} represents the asymmetric error term, capture the long-run equilibrium in equation. Γ_2 represents the speed of adjustment toward the long-run equilibrium after a shock.

Empirical results

Table 2 reports the descriptive statistics of dataset including mean, standard deviation, and minimum and maximum values of CO_2 emissions (CE), renewable energy development (RED), environment-related innovation (TIN), market regulation (MR), GDP per capita (GDPP), trade openness (TR), and foreign direct investment (FDI) over the sample period 1990–2020.

Table 3 Pairwise correlation matrix

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Carbon emission (CE)	1.000						
(2) Renewable energy development (RED)	-0.379*	1.000					
(3) Environment-related innovation (TIN)	-0.032	-0.059	1.000				
(4) Market regulation (MR)	-0.166*	-0.537*	0.323*	1.000			
(5) GDP per capita (GDPP)	-0.132	0.273*	0.246*	0.358*	1.000		
(6) Trade openness (TR)	0.346*	-0.640*	0.280*	0.604*	0.316*	1.000	
(7) Foreign direct investment (FDI)	0.258*	0.252*	0.050	-0.345*	0.025	0.041	1.000

***, **, and * denote statistical significant at 1%, 5%, and 10 %, respectively

Table 4 Cross-sectional dependency (CD) test

Variables	Breusch-Pagan LM	Pesaran scaled LM	Bias-corrected scaled LM	Pesaran CD
Carbon emission (CE)	189.662***	39.056***	38.972***	7.492***
Renewable energy development (RED)	117.772***	22.981***	22.897***	8.338***
Environment-related innovation (TIN)	15.988***	0.221	0.138	2.371***
Market regulation (MR)	49.739***	7.768***	7.685***	2.193***
GDP per capita (GDPP)	257.209***	54.159***	54.076***	16.002***
Trade openness (TR)	106.180***	20.388***	20.305***	8.005***
Foreign direct investment (FDI)	43.666***	6.410***	6.327***	3.881***

*** denotes the rejection of null hypothesis of cross-sectional independency.

The correlation between variables is reported in Table 3. The first column shows the correlation between carbon emissions (CE) and other variables of study. The results revealed negative and significant correlation ($r = -0.379$*) between CE and renewable energy development (RED). Environment-related innovation (TIN) is also negatively related with CE but it is statistically insignificant ($r = -0.032$). Market-based environmental regulation (MR) is negative and statistically significant with CE ($r = -0.166$*). This implies that imposition of taxes on production activities decreases the carbon emissions. Trade openness (TR) and foreign direct investment (FDI) are statistically significant and positively correlated with CE. This indicates that inflow of foreign direct investment and sum of exports and imports increase the carbon emissions.

Cross-sectional dependency and panel unit root test results

We begin formal analysis by testing the cross-sectional dependency. In doing this, we apply Breusch-Pagan LM, Pesaran scaled LM, bias-corrected scaled LM, and Pesaran CD test as shown in Table 4. The findings show the strength and cross-sectional dependency among the sample countries. The null hypothesis of no cross-sectional dependency presented by the test statistics is rejected at a high statistical significance level for all variables. As a result, we adopt the alternative hypothesis of panel country cross-sectional dependency.

Table 5 reports the second-generation panel unit root test. We check the stochastic properties of panel data. We used Maddala and Wu (1999) test and Pesaran (2007) panel unit root test and allow the cross-sectional dependency among the panel countries. The tests are done for both constant and constant and trend. It is clear that both test statistics do not reject the null hypothesis of unit root with constant and constant and trend at level for all variables as shown in Table 5. Results indicate that the variables under study are integrated of order I (1).

Linear and nonlinear panel cointegration test results

After testing the stationarity of data, the next step is to check the cointegration among the study variables. We used Westerlund (2007) test for linear cointegration and Hatemi-J (2020) test for asymmetric relationship among the ascending and descending component of study variables as shown in Table 6. The overall findings suggest that CE, RED, MR, and TIN are all linked through symmetric and asymmetric cointegrating vectors. This supports the presence of long-run symmetric and asymmetric stable relationships among the variables over the sample period 1990–2020.

Table 5 Panel unit root test results

Variables	Lags	Maddala and Wu		Pesaran CIPS	
		Constant	Constant and trend	Constant	Constant and trend
CE	0	15.557	3.006	– 1.060	2.020
	1	20.510***	11.240	– 2.426***	0.490
	2	16.004	12.824	– 3.459***	– 1.037
	3	13.927	17.357*	– 4.495***	– 2.545***
RED	0	10.913	5.777	2.087	2.458
	1	15.558	9.237	1.108	1.726
	2	14.997	11.363	1.670	2.740
	3	14.885	17.362**	0.986	1.692
TIN	0	20.521***	14.267	– 2.565***	– 3.827***
	1	16.834***	10.786	– 1.463***	– 2.857***
	2	7.441	2.280	0.723	– 0.283
	3	6.359	2.621	1.440	1.344
MR	0	9.532	4.867	1.138	1.028
	1	13.790	6.030	0.744	0.874
	2	20.104***	9.710	0.189	0.028
	3	12.498	5.840	– 0.051	– 0.356
GDPP	0	11.140	12.488	– 1.138	1.562
	1	6.457	10.307	– 4.314***	– 3.610***
	2	4.789	5.121	– 2.639***	– 4.610***
	3	6.035	4.467	– 1.116	– 2.721***
TR	0	30.211***	1.125***	– 2.323***	– 1.334*
	1	41.837***	8.152***	– 3.543***	– 3.426***
	2	10.835	4.527	– 1.681***	– 1.963***
	3	9.783	9.043	– 1.763***	– 3.552***
FDI	0	29.445***	6.234***	– 1.810***	– 1.766***
	1	21.493***	7.870***	– 1.221	– 1.965***
	2	17.327**	7.166***	– 1.132	– 2.411***
	3	12.890	8.099	1.503	0.541

*, **, and *** denote the rejection of null hypothesis of no unit root at 1%, 5%, and 10%, respectively. Lag length selected based on the Akaike information criteria (AIC).

Table 6 Linear and nonlinear cointegration test results

	Linear cointegration test		Nonlinear cointegration test		
	Stat	*p* value	H_0: I(1) vs H_1: I(0)	Stat	*p* value
G_t	– 1.766	0.926	$[y_{it}^{+};Z_{it}^{+}]$	– 4.676	0.000[a]
G_a	– 5.519[c]	0.067	$[y_{it}^{+};Z_{it}^{-}]$	– 2.826	0.010[c]
P_T	– 4.621[b]	0.023	$[y_{it}^{-};Z_{it}^{-}]$	– 3.397	0.000[a]
P_a	– 6.891[a]	0.000	$[y_{it}^{-};Z_{it}^{+}]$	– 4.434	0.000[a]

Note: [a, b, c] denotes statistical significant at 1%, 5%, and 10%, respectively. We set the maximum lags/led length 1 by including constant and trend. The lags are selected based on the AIC.

Linear and nonlinear ARDL results

We estimated the short- and long-run symmetric and asymmetric relationships using the mean group and pooled mean group estimation methods after determining the presence of symmetric and asymmetric cointegration relationships between research variables as shown in Tables 7 and 8.

Panel A of Table 7 shows long-run results which indicates that RED has significant negative impact on CE. This implies that in 1% increase in renewable energy, CO_2 emissions will decrease by – 0.3%. The coefficient of TIN has also significant negative impact with CE; this implies that more efficient and environment-related technology helps to reduce CO_2 emissions. In 1% increase in environment-related innovation, CO_2 emission will decrease by – 0.31 to – 0.83% respectively. This indicates that environment-related technologies are the key to improve environmental quality and energy efficiency. These findings are consistent with the previous study (Chen and Lee 2020). Meanwhile, environmental regulation has direct and indirect significant negative impact on CE. In 1% increase taxes

Table 7 Linear ARDL results

Variables	Mean group estimates			Pooled mean group estimates		
	Coefficients	Standard err	Prob	Coefficients	Standard err	Prob
Panel A: Long-run estimates						
RED	−0.398	0.201	(0.001)*	−0.312	0.026	(0.008)***
TIN	−0.832	0.386	(0.000)***	−0.314	0.118	(0.006)***
MR	−0.914	0.288	(0.007)**	−0.226	0.041	(0.001)***
MR_RED	−1.287	0.102	(0.000)***	−1.032	0.019	(0.010)***
MR_TIN	−1.441	0.287	(0.000)***	−1.123	0.017	(0.000)***
GDPP	0.203	0.101	(0.009)***	0.116	0.012	(0.007)***
TR	1.890	0.206	(0.000)***	0.002	0.013	(0.881)
FDI	0.034	0.053	(0.520)	0.012	0.012	(0.853)
Panel B: Short-run estimates						
ΔRED	−0.856	0.454	(0.005)*	−0.629	0.336	(0.065)**
ΔTIN	0.145	0.122	(0.713)	−0.381	0.083	(0.001)***
ΔMR	−0.545	0.206	(0.035)**	−0.726	0.288	(0.003)***
ΔMR_RED	−1.404	0.984	(0.154)	−1.292	0.167	(0.010)***
ΔMR_TIN	−1.086	1.101	(0.393)	−1.274	0.064	(0.000)***
ΔGDPP	0.700	0.255	(0.006)***	0.448	0.075	(0.000)***
ΔTR	0.095	0.047	(0.009)***	0.079	0.019	(0.000)***
ΔFDI	−0.004	0.006	(0.540)	−0.175	0.012	(0.000)***
ECT	−0.956	0.454	(0.005)*	−0.996	0.050	(0.000)***
Panel C: Diagnostic statistics						
Hausman test		2.94 (0.417)				

***, **, and * denote statistical significant at 1%, 5%, and 10 %, respectively

related to environmental pollution, the CO_2 emissions decreased by – 0.22 to – 0.91%, respectively. This shows that the government policies regarding the limiting of environmental pollution, i.e., market-based regulation, support to the environmental performance and enforced to control emission pollution in study sample countries. The market-based regulation also plays significant mediating role between TIN and CE and RED and CE. The findings support that the environmental regulation is more conducive to environmental quality, promoting green technological innovations and renewable energy consumption. Our findings are more consistent with the previous studies (Hao et al. 2018; Hille and Lambernd 2020; ling Guo et al. 2017). The GDP per capita income and FDI are insignificant while trade openness has positive significant impact on CE. This indicates that in 1% increase in trade openness, CE are increased by 1.89%.

Panel B of Table 7 shows short-run relationship between variables. The short-run results are different from long run. In the short-run RED, GDP per capita income and TR have significant impact on CE. The symmetric error correction (ECT) term is negative and significant, indicating the symmetric cointegration relationship. This supports earlier studies and suggests that there is convergence of system toward the equilibrium in the long run after the any shock. Finally, panel C shows diagnostic test to select the most appropriate method of estimations. We employ the Hausman test to select the more appropriate estimator. According to the Hausman test, pooled mean group model (PMG) is more appropriate than the mean group estimate (MG).

Table 8 shows the nonlinear/asymmetric ARDL results. We observed that positive and negative shocks to RED, TIN, MR, and their interaction terms MR_RED and MR_TIN have no uniform impact on the CE over the sample period. The positive shocks to any variable have negative impact on CE, while negative shocks to our core explanatory variable has positive impact. Panel A of Table 8 shows positive shocks to RED influence CE negatively, while negative shocks to RED influence CE positively. The findings suggest that any positive shocks to renewable energy development negatively affect the CE and vice versa. Similarly, positive shocks to MR decrease the CE while negative shocks to MR increase CE. This implies that market regulation policies are more friendly, protecting the natural environment and limiting carbon emissions. However, the difference between long-run and short-run estimates is that long-run coefficients are quite high as compared to short-run coefficients. This indicates that the renewable energy development,

Table 8 Nonlinear ARDL results

Variables	Mean group estimates			Pooled mean group estimates		
	Coefficients	Standard err	Prob	Coefficients	Standard err	Prob
Panel A: Long-run estimates						
RED^{+}	−1.176	0.531	(0.027)**	−1.347	0.102	(0.000)***
RED^{-}	0.293	0.132	(0.026)**	0.241	0.173	(0.168)
TIN^{+}	0.004	0.093	(0.963)	−0.150	0.040	(0.000)***
TIN^{-}	0.041	0.155	(0.793)	0.172	0.034	(0.000)***
MR^{+}	−1.670	0.936	(0.074)*	−0.958	0.223	(0.000)***
MR^{-}	0.650	0.389	(0.095)*	0.053	0.251	(0.834)
MR_RED^{+}	−0.628	0.240	(0.009)***	−0.221	0.056	(0.000)***
MR_RED^{-}	0.154	0.079	(0.050)**	0.187	0.070	(0.010)**
MR_TIN^{+}	0.099	0.155	(0.522)	−0.209	0.041	(0.000)***
MR_TIN^{-}	0.134	0.221	(0.546)	0.135	0.038	(0.001)***
GDPP	0.431	0.327	(0.187)	0.076	0.053	(0.161)
TR	0.038	0.037	(0.304)	0.227	0.039	(0.000)***
FDI	−0.003	0.008	(0.734)	0.004	0.004	(0.358)
Panel B: Short-run estimates						
ΔRED^{+}	0.900	2.014	(0.655)	0.063	0.642	(0.922)
ΔRED^{-}	1.256	0.471	(0.008)***	0.813	0.375	(0.034)**
ΔTIN^{+}	0.078	0.162	(0.629)	0.082	0.102	(0.424)
ΔTIN^{-}	−0.153	0.141	(0.279)	−0.022	0.088	(0.802)
ΔMR^{+}	−0.882	0.955	(0.356)	−1.534	0.835	(0.071)*
ΔMR^{-}	−1.200	0.780	(0.124)	−1.161	0.800	(0.152)
ΔMR_RED^{+}	−0.343	0.212	(0.106)**	0.350	0.295	(0.239)
ΔMR_RED^{-}	0.386	0.219	(0.078)**	0.221	0.272	(0.420)
ΔMR_TIN^{+}	0.005	0.166	(0.977)	0.067	0.076	(0.384)
ΔMR_TIN^{-}	0.121	0.141	(0.392)	0.055	0.065	(0.396)
ΔGDPP	0.338	0.270	(0.211)	−0.072	0.147	(0.628)
ΔTR	0.023	0.025	(0.371)	0.054	0.021	(0.015)***
ΔFDI	−0.004	0.005	(0.498)	0.001	0.005	(0.763)
ECT	−0.843	0.057	(0.005)***	−0.251	0.151	(0.100)*
Panel C: Diagnostic statistics						
Wald LR		5.963[a] (0.003)***		9.326[a] (0.000) ***		
Wald SR		7.180[b] (0.007)**		11.029[a] (0.000) ***		

environment-related innovation, and market-based environmental regulation have more significant impact in long run as compared to short run.

Our results provide empirical evidence that renewable energy development, environment-related innovation, and market-based regulation policies are the main mechanism to control and limit the carbon emission in a sample of BRICS countries in the long run. Our findings are more consistent with the previous studies (Chen and Lee 2020; Hille and Lambernd 2020).

Conclusion

The rising fossil fuel energy demand has had environmental consequences. There is need for protect the natural environment and limit the carbon emissions for the sustainable environmental development. The aim of the current work was to investigate the effect of renewable energy development, market-based environmental regulation, and environment-related innovation on CO_2 emissions in BRICS countries from 1990 to 2020. Additionally, we check the mediating role of market-based environmental regulation and environment-related innovation. The key outcomes are as follows: first, renewable energy development, environment-related innovation, and market-based environmental regulation policies play significant positive role in reducing CO_2 emissions in BRICS countries. Second, market-based environmental regulation plays significant positive mediating role in relation between renewable energy development, environment-related innovation, and CO_2 emissions. Third, GDP per capita income and trade openness positively contribute to CO_2 emissions. Fourth, inflow of foreign direct investment has significant negative impact on CO_2 emission in the short run, while it has insignificant impact in the long run. Fifth, positive shocks and negative shocks to renewable energy development, environment-related innovation, and market-based regulation have no uniform influence on CO_2 emissions. Meanwhile, the magnitudes of coefficients are high in the long run while small in the short run.

In order to overcome the environmental pressure and gain environmental sustainability, the current study provides some valuable policy implications. Our initial results reveal that renewable energy development plays significant positive role in reducing CO2 emissions. Consistent with these outcomes, the BRICS countries need to focus on the development of renewable energy sector. The government should encourage both private and public sectors to invest more in renewable energy projects and subsidize them to enhance share of renewable energy production. Environment-related technological innovations and market-based environmental regulation policies play positive role in limiting CO_2 emissions. The government should implement strict market-based environmental tax policy. In this regard, more polluted industries will intimidate for producing CO_2 emissions. This can help to get positive economic gain as well as reduce CO_2 emissions. With regard to the environment-related technological innovation, the BRICS countries should build a collective platform and collaboration to reinforce, and exchange the country-level environment-related technological innovations.

In the view of data availability and variables with time dimension, the current study has some limitations which can be consider future research direction. This study has not included sociopolitical and cultural factors. Using environmental Kuznets curve hypothesis, the future research could be looked at the role of culture, social structure, and political institutions which have diverse properties in every country and influence CO_2 emissions. This can make more contribution to the literature.

Author contribution The idea of the original draft belongs to Shah Abbas. He designed the overall experiment and methodology and collects data with the help of Peng Gui and Chen Ai. The Introduction and Literature review sections are written by Najabat Ali. Shah Abbas analyzed the data and interpret the empirical outcomes. All the authors read and approved the final manuscript.

Data availability The dataset used during the current study is available from the corresponding author on reasonable request.

Declarations

Ethics approval This study follows all ethical practices during writing. We confirmed that this manuscript has not been published elsewhere and is not under consideration in any journal. Ethical approval and consent do not apply for this study.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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