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RESEARCH ARTICLE

Realizing the Sustainable Development Goals through technological innovation: juxtaposing the economic and environmental effects of financial development and energy use

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Abstract

The BRICS comprise of group of emerging market economies which are committed to achieving the Sustainable Development Goals agenda of the United Nations by the end of the year 2030. In this regard, it is critically important for these nations to sustain their annual rise in their economic growth rates while simultaneously declining the rate of discharge of carbon dioxide emissions. Against this backdrop, this study aims to investigate how financial development, greater primary energy consumption, and technological innovation affect the prospects of the BRICS nations in achieving economic and environmental sustainability. Considering the period from 1990 to 2020 and utilizing methods that are robust to working with cross-sectionally dependent, heterogeneous, and endogenous panel data, the key analytical findings derived in this study reveal that higher levels of financial development, primary energy consumption, and technological innovation boost the per capita economic growth rates of the BRICS nations. Besides, technological innovation also moderates the financial development–economic growth and the primary energy consumption–economic growth nexuses by jointly boosting economic growth rates with these two macroeconomic variables. On the other hand, financial development and higher primary energy consumption are seen to boost the annual per capita carbon dioxide emission growth in these emerging nations, while technological innovation is observed to do the opposite. Furthermore, technological innovation is witnessed to moderate the nexus between energy use and economic growth to further reduce the emission growth rate in the BRICS nations. Accordingly, a set of policies are recommended to the concerned governments in order to enable the BRICS nations to attain the Sustainable Development Goals agenda.

Keywords Sustainable Development Goals · Sustainable economic growth · Sustainable environmental quality · CO_2 emissions · Technological innovation · Financial development

Introduction

Sustainable development, despite having multifarious dimensions, can be summarized as the sort of development that can help to realize the present needs without jeopardizing the prospects of meeting the future needs. Consequently, in 2015, the United Nations came up with the Sustainable Development Goals (SDG) declaration, putting forward 17 comprehensive global goals that are envisioned to leave no one behind in sustainably attaining economic, social, and environmental well-being (Ahmed and Ozturk 2018; Xue et al. 2021; Abbasi et al. 2022). Notably, the SDG declarations collectively strive for uplifting the quality of life, particularly by promoting the growth of the world economies without causing harm to the global environment

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(Bandyopadhyay and Rej 2021; Khan et al. 2022a). The ratification of the SDG agreement has therefore motivated the signatories to form nationally determined, as well as regionally cooperative, action plans that can enable them to achieve the underlying targets concerning the SDG by the end of 2030. Under such circumstances, development planners worldwide are now highly interested in ascertaining the channels/mechanisms through which higher economic growth and lower environmental pollution can be simultaneously established across the globe (Kartal et al. 2022a; Alam 2022; Depren et al. 2022).

Although, the neoclassical theories of growth postulate that a particular nation's economic growth is conditional on its stocks of labor and capital, this view has been challenged by highlighting the importances of other key macroeconomic for stimulating sustainable economic growth. Among these major growth enablers, the role of the financial sector in promoting economic progress cannot be doubted. For instance, since the financial sector injects funds into the private sector, in particular, the development of this sector is expected to scale up private credit supplies which, in turn, can be assumed to boost economic growth through capital accumulation-led industrialization (Sobiech 2019). Besides, financial inclusion is also assumed to help resolve budget constraints to stimulate higher levels of private consumption so that inclusive economic growth can be established; thus, an inclusive financial sector can go hand in glove with inclusive growth achievements (Siddik and Kabiraj 2020). On the other hand, the crucial role of energy resources in respect of stimulating higher economic growth cannot be overlooked either. Energy supply is recognized as the most important economic input, whereby its employment within different economic sectors contributes to the production of greater national output (Stern 2019; Alkhateeb and Mahmood 2019). Accordingly, unreliable supply of energy, especially electricity, is often responsible for underpinning industrialization whereby the rate of economic growth attainment can be assumed to slow down (Nepal and Paija 2019; Ateba et al. 2019).

Similarly, financial development and energy use are also asserted to influence the environmental conditions, both favorably and adversely (Kartal 2022; Ali et al. 2022; Kartal et al. 2022b). Firstly, concerning the financial sector's environmental impacts, investment of private sector funds in dirty industries is likely to inflict environmental welfare-inhibiting impacts (Khan et al. 2022b). Conversely, the role of the financial sector in respect of green climate financing for controlling environmental pollution has been widely acknowledged within the finance-environment narrative (Lee and Lee 2022; Zhang 2022). Besides, several recently published studies have highlighted the relevance of developing the financial sector digitally in order to reduce its carbon footprint (Cao et al. 2021). On the other hand, emphasizing the nexus between energy use and environmental quality, ambiguous environmental impacts are believed to accompany greater production and consumption of energy resources. For example, the use of hydrocarbon-based fossil fuels is often held responsible for profusely releasing greenhouse gases into the atmosphere; consequently, climate change adversities can be triggered (Rehman et al. 2021; Ramzan et al. 2022). Contrarily, the employment of hydrocarbon-free renewable energy resources is assumed to inhibit the deterioration of the global climate (Majeed et al. 2022; Shahbaz et al. 2021; Sheraz et al. 2022). Accordingly, often we hear that switching from non-renewable to renewable energy could resolve environmental hardships (Murshed 2020; Koondhar et al. 2021; Zhao et al. 2022). However, this conjecture has also been criticized in few studies that have concluded that such clean energy transitions actually deteriorate the environment further by concurrently boosting the demand for environmentally unfriendly minerals (Islam et al. 2022a, b).

Apart from financial development and energy use, technology is regarded as another key influencer of both economic growth and environmental quality (Mahmood 2020). Firstly, regarding economic growth, both endogenous and exogenous theories of growth have highlighted the respective importance of research and development-driven and globalization-led technological progress for catalyzing economic growth rates (Jones 2019; Hassan et al. 2019; Ahmed et al. 2021). Besides, in the era of the Fourth Industrial Revolution, the role of technological innovation-driven automation in boosting output production (synonymous with a potential surge in economic growth rate) has duly been mentioned in the literature (Prettner 2019). Conversely, refuting the idea of technology-led economic growth, several studies have also portrayed the dark side of technology by linking technological innovation with poor labor productivity and lower rate of economic growth (Wellisz 2016).

Furthermore, exploring the dynamic relationships between technological change and environmental quality, equivocal environmental impacts of technology have been documented in the literature. Assuming that a particular economy is its juvenile phase of development, its stock of technology is justifiably expected to be low. Under such circumstances, this nation may not be efficient in using its underdeveloped technologies for controlling the rate of greenhouse gas emissions. However, considering the theoretical underpinnings of the environmental Kuznets curve (EKC) hypothesis of Grossman and Krueger (1995), if this economy grows to reach a substantial level, it can be assumed to significantly improve its technological stock; consequently, it can reinstate the environmental welfare that was lost during the early phases of growth. Thus, several studies modeling the EKC hypothesis have controlled for the environmental impacts associated with technological innovation (Sinha et al. 2020; Ullah et al. 2021). Besides, technological innovation can also indirectly impact the environment through the channel of energy use. It has been argued that technological advancement-led improvement in the rate of energy productivity is ideal for limiting energy-related greenhouse gas emissions (Murshed et al. 2022; Zhang et al. 2018). Nevertheless, the rebound effect challenges this favorable environmental effect of technological innovation by postulating that energy productivity gains can induce an income effect to boost energy use and trigger higher emissions of greenhouse gases (Wang et al. 2019).

Hence, taking into account these ambiguous impacts on economic growth and environmental quality, this study considers data from the BRICS countries (comprising Brazil, Russia, India, China, and South Africa) for juxtaposing the long-run effects of financial development, energy consumption, and technological innovation on annual per capita real gross domestic product (GDP) and carbon dioxide (CO_2) emission rates in these emerging countries. The BRICS nations have come of age, especially with the broad-basing of their industrial expansions, in spurring rapid economic growth and are therefore these nations have evolved to be major contributors to the global economy as a whole (Anser et al. 2021; Jiang et al. 2022a). Concurrently, these nations have also emerged as leading emitters of CO_2 and other greenhouse gases. In 2020, China accounted for almost one-third of the total volume of CO_2 emitted worldwide, while the BRICS nations collectively were responsible for contributing to around half of the global volumes of CO_2 emissions (British Petroleum 2022). Therefore, controlling the rate of discharge of greenhouse gases into the atmosphere is not only important for the BRICS nations but also important for the well-being of the global environment. Besides, the BRICS nations have also signed the SDG agreement which obliges them to strategize action plans for achieving achieving sustainable economic and environmental performances.

This study makes some interesting contributions to the associated literature. First, almost all of the preceding studies on the BRICS nations have measured economic growth and environmental degradation in terms of the rise in the absolute per capita levels of GDP and CO_2 emissions, respectively. However, keeping the sustainability issue into cognizance, simply boosting the per capita national income and emission figures do not guarantee whether these performances would sustain or not in the future. Hence, to address this gap in the literature, in this study we consider the annual per capita real GDP and CO_2 emission growth rates as indicators of economic and environmental sustainability, respectively. Second, this study is one of the few that assesses both the direct and indirect consequences of technological development on economic growth and environmental quality in the context of the BRICS nations. In particular, it is pertinent to explore these indirect channels because the effects of technological innovation on the economy and the environment can be assumed to pass through the channels of financial development and energy use. As a result, the potential moderating/mediating roles of technological innovation are examined in this study for recommending holistic economic and environmental development-related policies. Lastly, the existing literature documents a wide range of panel data studies that have taken the issues of cross-sectional dependency and slope heterogeneity into consideration but have largely overlooked the endogeneity concerns. However, endogeneity is a serious problem in panel data modeling since it leads to the prediction of biased and inconsistent regression outcomes (Dong et al. 2022; Ben Lahouel et al. 2022). More importantly, the overarching relationships between the macroeconomic variables considered in this study can be expected to inflict endogeneity concerns. Hence, the issue of endogeneity has been duly addressed while designing the estimation strategy.

In the next section, some information regarding the economic, financial, and energy sectors of the BRICS nations are provided. Then, the subsequent sections chronologically present the literature review, methodology, findings and discussion, and concluding remarks and policy suggestions.

Literature review

The literature on economic effects of financial development and energy use

Theoretically, the financial sector is considered one of the major engines of economic growth through the channel of financial development-capital formation. For instance, for the national output level to increase, the role of finance cannot be questioned. Thus, the role of the financial sector in providing the funds for investment, especially within private industries, cannot be denied. Under such assumptions, several researchers have empirically examined the effects of financial development on economic growth. Among these prior studies, mostly the development of the financial sector within an economy was captured in terms of the proportion of the GDP that comprises private sector credit (Sepehrdoust and Ghorbanseresht 2019). In a study on selected Sub-Saharan African nations, Abeka et al. (2021) concluded that developing the financial system for the private sector, especially in respect of enhancing loan availability, is important for harnessing the economic growth agendas in these countries. Besides, the authors added that digitalization within the financial sector is more effective in promoting growth. Similarly, Ustarz and Fanta (2021) explored the impacts of financial development on sector-based economic growth in Sub-Saharan African countries. The results showed that although financial development facilitates growth in the agriculture and services sectors, it promotes industrial growth only after a substantial level of development in the financial sectors of these countries is achieved.

Using data from the BRICS, Raghutla and Chittedi (2021) also found evidence of the positive impacts of financial development on economic growth. Contrarily, evidence regarding the growth-inhibiting effects of financial development has also been highlighted in the literature. Siddikee and Rahman (2021), in the context of Bangladesh, found that financial development despite positively affecting economic growth in the short-run, albeit the impact is small, it dampens economic growth in the long run. In another study on 62 middle- and high-income countries, Osei and Kim (2020) quoted that financial development indirectly influences growth by moderating the impact of foreign direct investments on the growth of the economy. The authors claimed that initially although financial development helps the foreign direct investments in promoting economic growth, once the share of private credit in the GDP goes beyond 95.6%, it can no longer foster the positive relationship between foreign direct investments and economic growth. Thus, the authors concluded that too much domestic finance (indicating financial development) is not conducive to stimulating higher economic growth. Likewise, in a study using data from 29 Sub-Saharan African nations, Ibrahim and Alagidede (2018) remarked that financial development can be detrimental to economic growth if it enhances finance for risky projects. Furthermore, Shahbaz et al. (2022) recently concluded that the effect of financial development on economic growth in the top financially developed world economies can both be positive and negative; moreover, the authors added that these effects can be expected to change along with regime shifts concerning changes in the level of financial efficiency.

On the other hand, much like the financial sector, the paramount importance of the energy sector in respect of influencing the economic growth indicators cannot be doubted. However, similar to the ambiguous nexuses between financial development and economic growth, the existing findings portray both positive and negative effects of energy use on economic growth. Among the empirical studies concentrating on the energy use-economic growth relationship, Shahbaz et al. (2016) opined that for the economies of the BRICS nations to grow, it is essential for these nations to boost biomass energy consumption. In another study featuring 45 emerging market and developing nations, including the BRICS, Le and Sarkodie (2020) reported that energy consumption, irrespective of its type, positively contributes to economic growth in the long run. Likewise, in the context of selected South Asian nations, Rahman and Velayutham (2020) asserted that both renewable and non-renewable energy consumption are key determinants of greater economic growth. Additionally, using data from the BRICS nations and Turkey, Yıldırım et al. (2019) also documented statistical evidence regarding higher energy use being translated into greater economic growth.

In the case of China, Ouyang and Li (2018) found evidence that as the aggregate level of energy consumed in China goes up, the size of the Chinese economy tends to grow as well; thus, the energy sector can be regarded as a major influencer of the economic well-being in China.

Balsalobre-Lorente and Leitão (2020) reported evidence concerning higher renewable energy consumption accounting for higher economic growth in 28 members of the European Union. Contrarily, specifically for the BRICS nations, Akram et al. (2021) reported that renewable energy consumption dampens economic growth, especially in the relatively more-polluted BRICS nations. In another study on top 38 renewable energy-consuming nations, Shahbaz et al. (2020a) concluded that renewable energy use does not guarantee higher growth of economic output since the results suggested that only in 22 of the selected countries renewable energy consumption positively stimulates economic growth. On the other hand, linking non-renewable energy use with economic growth, Awodumi and Adewuyi (2020) found that higher consumption of natural gas and petroleum promotes economic growth in Angola and Gabon but retards growth in Nigeria. Besides, juxtaposing the effects of non-renewable energy consumption on economic growth across separate samples of developed and developing countries, Polat (2021) asserted that although higher non-renewable energy consumption is linked with higher growth in developing economies, it cannot influence the economic growth performances of developed nations.

The literature on environmental effects of financial development and energy use

Empirical studies showcasing the impacts of the financial sector on the environment have documented mixed findings. Focusing on selected developing nations, Khan and Ozturk (2021) concluded that the development of the financial sector is a pre-requisite for addressing environmental concerns since financial development was found to independently reduce CO_2 emissions and also indirectly contribute to CO_2 emission reduction by lessening the adverse environmental concerns associated with economic growth, international trade, and foreign direct investment inflows. Especially in the context of developed nations, Habiba and Xinbang (2022) stated that financial development curbs CO_2 emissions. Likewise, in the context of Australia, Rahman and Alam (2022) reported evidence that financial development helps in abating the CO_2 emission figures.

Conversely, Ibrahim et al. (2022) recently concluded that financial development in the BRICS countries amplifies their per capita CO_2 emission levels in the long run. Similarly, Abbasi et al. (2022) said that the financial sector of Pakistan is responsible for environmental hardships experienced by the nation since the results confirmed that financial development triggers higher emissions of both consumption and territory-based CO_2 emissions. On the other hand, using data from countries under China's one belt and road initiative, Weili et al. (2022) also found evidence of financial development leading to a rise in the per capita CO_2 emission levels in these countries. The environmental adversities accompanying financial development were also reported by Habiba and Xinbang (2022) as the findings in that study showed that although financial development is effective in mitigating CO_2 emission levels in developed countries, it triggers higher CO_2 emissions in emerging nations. Also, using data from 57 Belt and Road initiative nations, the negative environmental effects of financial development were verified by Jiang et al. (2022b). Meanwhile, in another relevant study on selected Latin American nations, Adebayo et al. (2021) opined that the financial sector's development has limited power in influencing environmental indicators.

Furthermore, the findings presented in the existing studies on the effects of energy use on CO_2 emissions are also mixed. In the context of the BRICS countries, Zhu et al. (2018) opined that higher energy consumption degrades the environment through the stimulation of higher emissions of CO_2. Besides, this finding was evidenced to be homogeneous for all quantiles of per capita CO_2 emissions. In contrast, Aziz et al. (2020) and Dingru et al. (2021) also used data from the BRICS nations and found evidence that as more renewable energy is consumed the CO_2 emission levels tend to decline. Also, this finding was found to hold for both the less- and highly-polluted BRICS nations. Identical conclusions were drawn in the study on BRICS nations by Adebayo et al. (2022). Furthermore, linking natural gas and renewable energy consumption with environmental quality in the BRICS nations, Dong et al. (2017) said these emerging nations can mitigate CO_2 emission levels by scaling up their natural gas and renewable energy consumption figures. Bhat (2018) showed that non-renewable energy use in the BRICS nations is responsible for higher CO_2 emissions in the long run only, while higher use of renewable energy is efficient in reducing CO_2 emissions both in the short- and long-run.

In existing studies that featured non-BRICS nations as well, Zhu et al. (2016) considered data from five Southeast Asian nations and found evidence that although higher energy consumption results in higher per capita CO_2 emissions, this impact is conditional on the level of pollution in those countries. Using data from a large sample of 170 countries, Wang et al. (2019) claimed that irrespective of the level of economic growth, higher energy use is associated with higher emissions of CO_2. Similarly, for a case study on 35 global economies, Zaman et al. (2016) also concluded that energy consumption imposes environmental adversities by amplifying the per capita CO_2 emission figures of the selected countries. In another country-specific study on Pakistan, Danish et al. (2017) asserted that renewable energy use improves the environment by reducing CO_2 emission levels, while non-renewable energy use degrades it by boosting the emission levels. Moreover, in the context of the Next Eleven nations, Paramati et al. (2017) remarked that boosting renewable energy consumption can be an effective means of curbing the CO_2 emission levels in these energy nations.

The literature on the economic and environmental effects of technological innovation

The Fourth Industrial Revolution has bolstered the importance of technological innovation in catalyzing economic activities under the assumption that improved technology can help to enhance factor productivity to stimulate higher growth. Empirical studies, in this regard, have mostly found technological progress to positively influence economic growth. Accordingly, using data on several indicators of technological innovation, Anakpo and Oyenubi (2022) recently found statistical evidence of positive impacts of these technological innovation-related indicators on per capita economic figures of selected Southern African nations. In another study on Singapore, Meirun et al. (2021) concluded that the greening of technologies can enhance the nation's economic growth level, both in the short- and long-run. For the cases of the Next Eleven nations, the positive effects of technological innovation, measured in terms of a rise in the number of patents applied, on economic growth were also reported in the study conducted by Rahim et al. (2021). Besides, using a higher mobile phone penetration rate as an indicator of greater application of advanced information and communications technology, Haftu (2019) asserted that technology innovation is likely to boost economic growth in Sub-Saharan African nations. Meanwhile, for China, Zhou et al. (2021) concluded that the effect of technological innovation on economic growth can be illustrated as an inverted U-shaped graph; thus, the results implied that as more advanced technologies are utilized, the Chinese economy initially grows up to a threshold point beyond which further innovation dampens economic growth in China. Similarly, Kahouli (2018) employed data from selected Mediterranean countries and reported that research and development-led technological innovation retards economic growth levels in the long run.

On the other hand, regarding the environmental effects accompanying technological innovation, existing studies have highlighted that technologies progress inflicts ambiguous impacts on the level of CO_2 emissions. In general, these studies have argued that while non-green technologies promote higher emissions of CO_2, green technologies can neutralize these negative environmental effects. Accordingly, Chen and Lee (2020) questioned whether or not technological innovation homogeneously contributes to reduce emission across the globe. Based on their findings, the authors concluded that technological innovation has a minimal CO_2 emission-inhibiting effect on a global scale. However, the impacts are heterogeneous when smaller samples of countries are considered as case studies. Precisely, the authors identified that in countries with high levels of national income, technological endowment, and CO_2 emissions, an improvement in the level of technological innovation is effective in curbing CO_2 emissions. However, in countries that do not have these characteristics, technological innovation imposes CO_2 emission-boosting effects. In another study on China, Shahbaz et al. (2020b) asserted that the environmental impacts of technological innovation are intertemporal since the findings indicated that technological innovation in the short run boosts CO_2 emissions while it reduces emissions in the long run.

It is also evident from the technology-CO_2 emission-based literature that most studies have used a single indicator to proxy environmental innovation. However, the study by Zafar et al. (2021) explored the effects of technological innovation on CO_2 emissions, in selected countries that are members of the Asia Pacific Economic Cooperation (APEC), by estimating a technological innovation index using data concerning different technological innovation indicators (including patent and trademark applications and technical cooperation grants data). The results showed that technological innovation is a key driver of higher CO_2 emissions in these countries. Likewise, Sinha et al. (2020) also utilized a technological innovation index and concluded that technological progress is associated with emission reduction in less-polluted Next Eleven nations; contrarily, an opposite impact was evidenced for the highly polluted Next Eleven nations. Furthermore, although most of the related studies available in the literature focus on the direct impacts of technological innovation on CO_2 emissions, only a few have emphasized the indirect channels through which technology can enforce environmental consequences. Among these, Cheng et al. (2021) claimed that technological innovation in the members nations of the Organization for Economic Cooperation and Development indirectly mitigates their CO_2 emission levels by jointly reducing emissions with higher renewable energy consumption. Similarly, Zhao et al. (2021) concluded that technological innovation indirectly inhibits CO_2 emissions by mediating the relationship between financial risk and CO_2 emissions.

The review of the aforementioned literature identifies certain gaps that motivate this study. It is apparent that the existing studies featuring the BRICS nations did not emphasize the need for increasing and reducing the rate of economic growth and CO_2 emissions, respectively, and have rather focused on increasing and decreasing their respective levels. However, from the perspective of sustainable development, it is imperative to sustain the increments in economic growth rate while persistently declining CO_2 emission growth rates as well. Besides, limited information (none in the context of BRICS) is documented regarding the indirect impacts of technological innovation on economic growth and CO_2 emission rates. Another additional research gap that can be found from the related literature review is that the majority of the studies have not considered the issue of endogeneity when modeling the determinants of sustainable economic and environmental development. However, since the possible reverse causalities between the study variables (i.e., between the dependent and the independent variables) can give rise to endogeneity concerns, it is critically important to strategize the estimation plan by including methods that are robust in handling models containing endogenous covariates. Therefore, taking into account these literature gaps, this study attempts to bridge them in the context of the BRICS countries.

Research methodology

Empirical modeling and data attributes

Since the objective of this study is to identify how financial development, energy consumption, and technological innovation affect the annual rates of changes in economic growth and CO_2 emissions in the context of the BRICS countries, the following model is considered:

$$\begin{aligned}\textbf{Model } 1: YPC\_GR_{it}|CO2PC\_GR_{it} &= \partial_0 + \partial_1 YPC\_GR_{t-1,it}|\partial_1 CO2PC\_GR_{t-1,it} \\ &+ \partial_2 FIN\_DEV_{it} + \partial_3 LnENERGY_{it} \\ &+ \partial_4 TECH\_INNOV_{it} + \varepsilon_{1t}\end{aligned} \tag{1}$$

In Eq. 1, the dependent variables YPC_GR and CO_2PC_GR are respectively representing the annual rates of changes in per capita real GDP (a proxy for economic growth rate) and CO_2 emissions (a proxy for environmental pollution rate). Besides, the independent variables YPC_GR_{t-1} and $CO2\_GR_{t-1}$ represent the one-period lagged levels of the dependent variables. These variables are included in the model because it has been mentioned in the literature that controlling for lagged levels of the dependent variable within the model can address endogeneity concerns (Chudik and Pesaran 2015; Churchill et al. 2021). The variable *FIN_DEV* represents the financial development level which is proxied by the percentage share of private sector credit in the GDP of the respective BRICS nations. A rise in the percentage share indicates the development of the financial sector and vice-versa (Sepehrdoust and Ghorbanseresht 2019).

The other independent variable *LnENERGY* represents the per capita primary energy consumption levels of the BRICS countries (measured in exajoules). This variable is naturally log-transformed to make sure that the elasticity of rates of economic growth and CO_2 emissions with respect to financial development can be easily predicted. Lastly, the variable *TECH_INNOV* represents the technological innovation index (a proxy for the level of technological progress) which is predicted using the principal component analysis technique and utilizing three technological innovation-related indicators: (i) patent and trademark applications by residents, (ii) patent and trademark applications by non-residents, and (iii) technical cooperation grants receipts. Higher values of the technological innovation index can be interpreted as an improvement in the level of technology and vice-versa (Sinha et al. 2020; Zafar et al. 2021). The values and signs of parameters $\partial_1, \partial_2, \partial_3$, and$\partial_4$ indicate the marginal impacts of a rise in the levels of the independent variables on the dependent variable. Furthermore, to check whether technological innovation indirectly affects rates of economic growth and CO_2 emissions, we modify our baseline models (shown in Eq. 1) as follows:

$$\begin{aligned}\textbf{Model } 2: YPC\_GR_{it}\left|CO2PC\_GR_{it} = \partial_5 + \partial_6 YPC\_GR_{t-1,it}\right|\partial_6 CO2PC_{GR\,t-1,it}\\ + \partial_7 FIN\_DEV_{it} + \partial_8 LnENERGY_{it} + \partial_9 TECH\_INNOV_{it}\\ + \partial_{10}\left(TECH\_INNOV_{it} * FIN\_DEV_{it}\right) + \varepsilon_{2t}\end{aligned} \tag{2}$$

$$\begin{aligned}\textbf{Model } 3: YPC\_GR_{it}\left|CO2PC\_GR_{it} = \partial_{11} + \partial_{12} YPC\_GR_{t-1,it}\right|\partial_{12} CO2PC_{GR\,t-1,it}\\ + \partial_{13} FIN\_DEV_{it} + \partial_{14} LnENERGY_{it} + \partial_{15} TECH\_INNOV_{it}\\ + \partial_{16}\left(TECH\_INNOV_{it} * LnENERGY_{it}\right) + \varepsilon_{3t}\end{aligned} \tag{3}$$

In Eqs. 2 and 3, the variables TECH_INNOV*FIN_DEV and TECH_INNOV*LnENERGY represent the interaction terms between technological innovation and financial development and between technological innovation and energy consumption, respectively. Hence, the values and signs of parameters ∂_{10} and ∂_{16} would indicate whether technological innovation indirectly, with financial development and energy consumption, influences the rates of economic growth and CO_2 emissions in the BRICS nations. For the purpose of conducting the empirical analysis, the study period considered extends from 1990 to 2020. Although ideally a longer data period would have been more appropriate, we have to curtail the duration of the study period since relevant data before and beyond the chosen period is not available. Regarding data sources, the World Bank's World Development Indicators database provides data from the variables *YPC_GR* and *FINDEV* and the three indicators of *TECH_INNOV* (patent and trademark applications by residents and non-residents and technical cooperation grant receipts). The data of the variable *LnENERGY* is provided by the British Petroleum's Statistical Review of World Energy database. Lastly, the Global Carbon Atlas database provides the data of the variable CO_2PC_GR.

Table 1 presents the descriptive statistics of the key variables for the respective BRICS nations. It can be seen that during the study period, Russia, on average, recorded the lowest rate of annual per capita economic growth, while China accounted for the highest annual per capita economic growth rate. Besides, in terms of growth volatility, Russia recorded the most-volatile economic growth performances. On the other hand, the average annual rate of growth in per capita CO_2 emissions was highest for Russia and lowest for India. Although China is the most-polluted global economy, its large population size could be the reason why the nation does not top the list of the BRICS nations in terms of the average rate of growth in the annual per capita CO_2 emission levels. Besides, China is seen to have the most-developed financial system, while the financial system of Russia is the least-developed nation among the BRICS countries. In terms of energy consumption, it is of no surprise that the two most-populated BRICS countries China and India have the highest annual primary energy consumption levels, while South Africa has the lowest level of annual energy consumption. Lastly, China is seen to be the most technologically innovative BRICS nation. The variance inflation factor (VIF) outcomes, for the panel of the BRICS nations, are shown in Table 2. It is clear from the outcomes that there are no multicollinearity issues in the models considered in this study since the VIF scores are below 5 and the mean VIF score is below 10.

Estimation strategy

Our estimation strategy involves six steps. In the first step, this study conducts the panel data analysis of cross-sectional dependence. The presence of cross-sectional dependence is a serious concern since it lessens the possibility of predicting consistent and unbiased analytical outcomes (Koseoglu et al. 2022). Besides, Hamid et al. (2022) argued that due to strong globalization ties among the BRICS nations, the presence of cross-sectional dependence in panel data sets concerning the BRICS nations can be anticipated. In the second step, this study performs the analysis of heterogeneous slope coefficients, considering the macroeconomic differentials among the BRICS nations. For instance, the BRICS countries differ in terms of per capita national income level (World Bank 2022); thus, it can be assumed that these countries, despite commonly being emerging markets, are somewhat at different phases of development. Under such circumstances, the predicted slope coefficients can vary for the individual BRICS nations whereby the issue of slope heterogeneity cannot be overlooked.

Table 1 Descriptive statistics

Country	Statistics	Min	Max	Mean	St. Dev	Skewness	Kurtosis
Brazil	**YPC_GR**	−6.067	6.524	0.780	2.969	−0.430	2.805
	CO$_2$PC_GR	1.328	2.523	1.852	0.329	0.155	2.285
	FIN_DEV	27.686	133.076	51.208	21.667	1.737	1.569
	LnENERGY	1.879	2.519	2.188	0.267	−0.301	1.898
	TECH_INNOV	−0.288	−0.078	−0.231	0.061	0.634	2.539
Russia	**YPC_GR**	−14.614	10.464	0.771	6.384	−0.631	2.698
	CO$_2$PC_GR	10.070	14.621	11.485	1.071	1.604	5.359
	FIN_DEV	16.838	59.772	33.400	14.878	0.364	1.477
	LnENERGY	3.222	3.587	3.347	0.092	1.135	2.056
	TECH_INNOV	−0.278	−0.135	−0.216	0.078	0.663	2.546
India	**YPC_GR**	−7.516	7.082	4.192	2.938	−2.198	1.342
	CO$_2$PC_GR	0.645	1.812	1.146	0.395	0.419	1.658
	FIN_DEV	22.511	54.652	38.295	12.273	−0.081	1.242
	LnENERGY	2.109	3.523	2.837	0.450	0.023	1.682
	TECH_INNOV	−2.885	−0.192	−0.204	0.095	0.711	2.308
China	**YPC_GR**	1.997	13.636	8.296	2.697	−0.126	3.187
	CO$_2$PC_GR	1.915	7.606	4.638	2.157	0.132	1.317
	FIN_DEV	83.097	182.868	118.577	26.758	0.572	2.552
	LnENERGY	3.357	4.980	4.224	0.564	−0.093	1.403
	TECH_INNOV	−0.268	7.045	0.929	1.999	1.899	5.449
South Africa	**YPC_GR**	−7.616	4.278	0.326	2.612	−0.976	1.228
	CO$_2$PC_GR	6.175	8.573	7.321	0.747	−0.220	1.655
	FIN_DEV	46.570	70.382	58.790	6.330	−0.230	2.272
	LnENERGY	1.303	1.673	1.522	0.129	−0.415	1.707
	TECH_INNOV	−0.295	−0.169	−0.279	0.008	−0.097	1.121
BRICS	**YPC_GR**	−14.614	13.636	2.873	4.481	−0.565	1.882
	CO$_2$PC_GR	0.645	14.621	5.289	3.971	0.483	1.879
	FIN_DEV	16.823	182.868	60.054	35.426	1.279	3.178
	LnENERGY	1.303	4.980	2.824	0.996	0.312	2.275
	TECH_INNOV	−0.268	7.045	−0.000	1.001	5.243	1.590

Table 2 The outcomes from variance inflation factor (VIF) analysis

Variable	VIF	1/VIF	Mean VIF
FIN_DEV	1.91	0.553	1.75
LnENERGY	1.85	0.542	
TECH_INNOV	1.50	0.668	

In the context of this study, the number of cross-sections (N) is small, while the time dimension (*T*) is fairly large. Consequently, for assessing cross-sectional dependency, the Pesaran (2021) and Breusch and Pagan (1979) techniques are applied. While the Pesaran (2021) technique is more suited to panel data sets with a large time dimension, the

Table 3 The cross-sectional dependency test outcomes

Variable	Pesaran (2021)	Breusch and Pagan (1979)	Decision
YPC_GR	6.569***	61.022***	Cross-sectional dependency exists
CO$_2$PC_GR	−0.047	359.198***	Cross-sectional dependency exists
FIN_DEV	2.206**	18.954**	Cross-sectional dependency exists
LnENERGY	0.528	158.227***	Cross-sectional dependency exists
TECH_INNOV	1.549*	83.600***	Cross-sectional dependency exists

***Significance at 1%; **significance at 5%; *significance at 1%

Table 4 The Pesaran and Yamagata (2008) slope heterogeneity test outcomes

Model	Dep. Var	Delta statistic	Adj. Delta statistic	Decision
1	YPC_GR	2.593***	2.831***	Slope heterogeneity exists
1	CO_2_GR	18.271***	19.951***	Slope heterogeneity exists

***Significance at 1%

Breusch and Pagan (1979) technique favors data sets with small cross-sectional dimensions (Dong et al. 2018). The statistical significance of the test statistics predicted using these techniques rejects the null hypothesis of independent cross-sectional units. Accordingly, the issue of cross-sectional dependence in our data set is confirmed by the outcomes reported in Table 3. On the other hand, we use the Pesaran and Yamagata (2008) technique for assessing slope heterogeneity. This method predicts test statistics that, if found to be statistically significant, reject the null hypothesis of homogeneous slope coefficients. Hence, the corresponding outcomes reported in Table 4 confirm slope heterogeneity issues in our data set.

In the third step, we perform the panel unit root analysis. According to Jahanger et al. (2022), to account for cross-sectional dependence in the data, the Pesaran (2007) technique should be applied. In this panel data unit root estimation approach, two tests are conducted: cross-sectional adjusted augmented Dickey-Fuller (CADF) and cross-sectional adjusted Im-Pesaran-Shin (CIPS). Both these tests predict statistics, considering and not considering trends, to examine the null hypothesis that there is a unit root in the series of concerns. The presence of unit root implies that the series does not revert to its mean value whereby regression analysis comprising variables with unit root concerns leads to the estimation of spurious effect of the independent variable on the dependent variable (Li et al. 2022). In the second step, we perform the panel cointegration analysis keeping the cross-sectional dependence issue into consideration. In this study, we choose the Westerlund (2007) approach for cointegration estimation to check whether there are long-run associations between the independent and dependent variables in the corresponding model. The test statistics predicted under Westerlund (2007)'s method consider the null hypothesis that there are no cointegrating/long-run relationships among the variables (Usman et al. 2022) and are predicted by controlling for cross-sectional dependency using a bootstrapped replication approach (Huang et al. 2022).

In the fifth step, the penultimate one before conducting the regression analysis, we perform the panel causality analysis to identify the pairwise direction of causation among the study variables. This is particularly important for checking whether the model suffers from endogeneity problems arising from reverse causal associations among the response (dependent) and the explanatory (independent) variables (Sadiq et al. 2022). Nevertheless, the majority of the empirical studies documented in the literature do not emphasize the analysis of causality before designing the regression technique; however, without knowing whether endogeneity exists in the model/s, it is not possible to select the appropriate regression estimator. Moreover, to control for the issues of dependent cross-sectional units and heterogeneous slope coefficients in our data, we employ the causality test proposed by Dumitrescu and Hurlin (2012). In this test, the statistical significance of the test statistics rejects the null hypothesis of the independent variable not causally influencing the dependent variable (Ahmad et al. 2021; Ehigiamusoe et al. 2022). Lastly, in the sixth step, we conduct the panel regression analysis using Ditzen's (2021) instrumental variable (IV) version of the dynamic common correlated effects (DCCE) panel regression technique of Chudik and Pesaran (2015). While the conventional DCCE technique addresses the issue of endogeneity by including the lagged level of the dependent variable as a covariate, the DCCE-IV approach goes one step further in accounting for endogeneity concerns by treating the endogenous covariate with the lagged levels of the other explanatory variables (the lagged variables are considered as instruments). Besides, the DCCE-IV method is also suitable for handling cross-sectionally dependent heterogeneous panel data sets (Ditzen 2021).

Empirical results and discussion

At first, we interpret the panel unit root results that are reported in Table 5. The predicted test statistics from both the CADF and CIPS tests, calculated both considering and not considering a trend, are statistically significant only at the first difference for all variables. Therefore, we can claim that the variables considered in this study have identical integration order, precisely at I(1).

Regarding the findings from the Westerlund (2007) analysis, as shown in Table 6, it is evident that in the context of the BRICS nations, the annual rates of changes in economic growth and CO_2 emissions have long-run relationships with the levels of financial development, energy consumption, and technological innovation.

Table 7 reports the findings from the Dumitrescu and Hurlin (2012) causality analysis. Firstly, the results identify a bidirectional causal association (reverse causality) between economic growth and financial development in the case of the BRICS nations. This finding can be explained by the

Table 5 The Pesaran (2007) panel unit root test outcomes

Variable	CADF test		Decision	CIPS test		Decision
Trend assumption	No trend	Trend	Stationary	No trend	Trend	Stationary
YPC_GR	−1.670	−2.690	Non-stationary	−2.186	−2.556	Non-stationary
ΔYPC_GR	−3.272***	−3.244***	Stationary	−5.410***	−5.557***	Stationary
CO$_2$PC_GR	−2.120	−2.241	Non-stationary	−2.046	−1.289	Non-stationary
ΔCO$_2$PC_GR	−1.706	−2.328*	Stationary	−2.428**	−3.359***	Stationary
FIN_DEV	−1.214	−2.406	Non-stationary	−0.697	−2.002	Non-stationary
ΔFIN_DEV	−2.997***	−3.037**	Stationary	−4.101***	−4.144***	Stationary
LnENERGY	−2.211	−2.135	Non-stationary	−2.095	−1.702	Non-stationary
ΔLnENERGY	−1.958	−3.012**	Stationary	−3.040**	−3.387***	Stationary
TECH_INNOV	−1.129	−1.352	Non-stationary	−0.919	−2.140	Non-stationary
ΔTECH_INNOV	−3.114*	−3.396**	Stationary	−4.353***	−4.386***	Stationary

The *t*-statistics are reported; Δ = first difference operator; Lag optimality = Schwarz Info. Cri.; ***significance at 1%; **significance at 5%; *significance at 10%

Table 6 The Westerlund (2007) panel cointegration test outcomes

Model	Dep. Var	Gt statistic	Ga statistic	Pt statistic	Pa statistic	Decision
1	**YPC_GR**	−4.216***	−8.867	−10.558***	−11.659*	Cointegrated
1	**CO$_2$PC_GR**	−4.406***	−8.081	−10.583***	−11.340	Cointegrated

Lag optimality = Schwarz Info. Cri.; bootstrapped reps. = 2000; ***significance at 1%; *significance at 10%

Table 7 The Dumitrescu and Hurlin (2012) panel causality test outcomes

Dep. Var	Indep. Var	Z-bar sat	Z-bar tilde stat	Decision
YPC_GR	**FIN_DEV**	1.576**	1.263	Bidirectional
FIN_DEV	**YPC_GR**	4.242**	3.584**	YPC_GR ↔ FIN_DEV
YPC_GR	**LnENERGY**	6.897***	5.896***	Unidirectional
LnENERGY	**YPC_GR**	0.600	0.381	YPC_GR ← LnENERGY
YPC_GR	**TECH_INNOV**	4.158*	3.509*	Unidirectional
TECH_INNOV	**YPC_GR**	−0.994	−0.973	YPC_GR ← TECH_INNOV
CO$_2$PC_GR	**FIN_DEV**	4.075***	3.438***	Unidirectional
FIN_DEV	**CO$_2$PC_GR**	−0.478	−0.529	CO$_2$PC_GR ← FIN_DEV
CO$_2$PC_GR	**LnENERGY**	6.777***	5.790***	Bidirectional
LnENERGY	**CO$_2$PC_GR**	5.761***	4.907***	CO$_2$PC_GR ↔ LnENERGY
CO$_2$PC_GR	**TECH_INNOV**	2.287***	1.883	Unidirectional
TECH_INNOV	**CO$_2$PC_GR**	2.083	1.579	CO$_2$PC_GR ← TECH_INNOV

Null Hypo: independent variable does not Granger cause dependent variable; Lag optimality = Bayesian info. Cri.; bootstrapped reps. = 5000; ***significance at 1%; **significance at 5%; *significance at 10%

assumption that as the financial sector gets more developed, the level of private investments can go up which, in turn, can be expected to expedite economic growth rates in the BRICS nations. On the other hand, as economic growth rates go up, there could be more demand for modern financial services; thus, it can lead to further development of the financial system. Under such a circumstance, the interdependency (reverse causality) between economic growth rate and financial development can be anticipated. Besides, the results also affirm that there is unidirectional causality stemming from primary energy consumption to economic growth rate. This finding is in line with the growth hypothesis which postulates that energy use is a central facilitator of greater economic affluence (Apergis and Tang 2013; Aslan et al. 2022; Dogan et al. 2020). Moreover, unidirectional causality from technological innovation to economic growth rate is also confirmed by the causality findings. This is an expected finding since technological progress is often hypothesized to positively influence the economic growth rate by enhancing the total factor productivity level (Surya et al. 2021).

On the other hand, the causality results also verify unidirectional causality running from financial development to the rate of change in annual CO_2 emission levels in the BRICS nations. This finding can be explained by the understanding that financial development can influence the CO_2 emission figures of these nations particularly through the channel of energy consumption. Besides, bidirectional causality (reverse causation) between primary energy consumption and annual CO_2 emission rate is also confirmed by the results. Based on the underlying preconceived notions, this two-way causal relationship can be explained from the point of view that as the level of energy consumption within an economy goes up, it can trigger a positive change in the level of energy-use-related emissions of CO_2, as well (Bouyghrissi et al. 2022). At the same time, a growth in the rate of annual CO_2 emissions can induce a reduction in the volume of energy use (i.e., energy conservation) which, in turn, can once again contribute to the inhibition of the future CO_2 levels. Accordingly, it can be said that energy consumption and the CO_2 emissions-triggered environmental pollution are interdependent. Lastly, the causality outcomes point out a unidirectional causality running from technological innovation to the annual rate of change in CO_2 emissions in the BRICS countries. This is also a likely outcome because both clean and unclean technologies are often claimed to impose ambiguous (both desirable and undesirable) environmental consequences (Shahbaz et al. 2020b).

Table 8 The DCCE-IV panel regression outcomes for economic growth rate model

Dep. var.: YPC_GR			
Regressors	Model 1	Model 2	Model 3
YPC_GR(-1)	1.029***	1.208***	1.295***
	(0.126)	(0.234)	(0.244)
FIN_DEV	0.487**	0.425***	0.551***
	(0.094)	(0.085)	(0.100)
LnENERGY	7.285***	9.112***	9.298***
	(3.130)	(3.750)	(2.930)
TEC_INNOV	15.716***	16.212***	16.750***
	(2.103)	(3.500)	(2.650)
TECH_INNOV*FIN_DEV		8.342***	
		(1.239)	
TECH_INNOV*LnENERGY			11.250***
			(3.893)
Constant	14.865	15.222	15.650
	(59.555)	(61.230)	(53.122)
Adj. R2	0.548	0.585	0.611
Observations	135	135	135

YPC_GR(− 1) = lagged level of the dependent variable YPC_GR; endogenous variable = FIN_DEV; standard errors are in parentheses; ***significance at 1%; **significance at 5%

Considering the fact that the causality test led to the discovery that economic growth rate and financial development and CO_2 emissions growth rate and primary energy use are bidirectionally associated, it can be assumed that the financial development and primary energy consumption indicating variables (i.e., *FINDEV* and *LnENERGY*) are endogenous when economic growth rate and CO_2 emission growth rate are respectively used as dependent variables in our models. Hence, under the *DCCE_IV* regression approach, the endogenous variables, in the respective model, are treated with the lagged levels of the other explanatory variables (considering the lagged variables as instrumental variables for treating the endogenous variables). The regression outcomes are presented in Tables 8 and 9. Firstly, we interpret the findings from the economic growth rate model as presented in Table 8. It is evident that the current annual economic growth rate of the BRICS nations is conditional on the previous year's economic growth rate. Since the corresponding estimated elasticity parameters (in all three models) concerning the one-period lagged level of per capita economic growth rate (i.e., *YPC_GR*(− 1)) are negative and statistically significant, it can be said that the previous period's economic achievements are likely to be sustained in the current period.

Besides, it is also evident from the results that the development of the financial sector is one of the important drivers of a higher economic growth rate in the BRICS nations. Precisely, a 1% rise in the share of private sector credit in the GDP (which indicates the development of the financial sector) is likely to amplify the annual rate of growth in the per capita real GDP level by 0.487–0.551%. This finding verifies the notion that if greater credit accessibility is ensured, it is likely that the private investors in the BRICS nations would be availing the loans that are on offer and invest them; consequently, private investment-led industrialization, in particular, can be anticipated to boost the economic growth rates of the BRICS nations. Likewise, Abeka et al. (2021) also remarked that financial development drives higher economic growth levels in Sub-Saharan African nations which are mostly developing countries. In contrast, our finding contradicts the long-run finding of financial development dampening Bangladesh's economic growth level that was reported in the study conducted by Siddikee and Rahman (2021). Among the other key results found in this current study, it is evident that energy consumption induces economic growth rate-boosting effects within the economies of the BRICS nations. Notably, if the level of primary energy consumption goes up by 1%, it is likely to enhance the annual per capita real GDP growth rate by 7.285–9.298%. This finding implies that economic growth in the context of the BRICS nations is highly elastic to changes in their respective primary energy consumption levels. To explain this finding, it can be said that since energy is consumed

Table 9 The DCCE-IV panel regression outcomes for CO_2 emissions growth rate model

Dep. var.: CO_2PC_GR

Regressors	Model 1	Model 2	Model 3
CO_2PC_GR(-1)	– 1.714	– 1.950	– 2.003
	(1.332)	(1.443)	(1.732)
FIN_DEV	0.454***	0.575***	0.590***
	(0.085)	(0.121)	(0.112)
LnENERGY	42.965***	46.213***	47.324***
	(8.825)	(11.560)	(12.040)
TEC_INNOV	– 131.840***	– 155.350***	– 158.230***
	(33.150)	(42.533)	(36.363)
TECH_INNOV*FIN_DEV		– 15.450	
		(13.243)	
TECH_INNOV*LnENERGY			– 4.250**
			(2.112)
Constant	– 35.215	– 41.221	– 45.221
	(82.333)	(86.333)	(90.550)
Adj. R^2	0.670	0.668	0.741
Observations	135	135	135

CO_2PC_GR(– 1) = lagged level of the dependent variable CO_2PC_GR; endogenous variable = LnENERGY; standard errors are in parentheses; ***significance at 1%; **significance at 5%

for consumption and production purposes, an economic growth rate-boosting impact associated with energy use is justified. Besides, this finding corroborates the energy-led growth hypothesis for the BRICS nations which was also verified in the earlier study by Apergis and Tang (2013).

Moreover, in respect of economic growth rate being impacted by technological innovation, especially for the BRICS nations to sustain their economic performances, it is critically important invest in projects that are closely linked with the development of their existing technological stocks. This statement is backed up by the finding that that a 1% rise in the value of the technological innovation index is likely to boost the annual per capita real GDP growth rate by 15.716–16.750%. This finding adheres to the understanding that technological innovation makes factors more productive whereby the national output production rates can be assumed to increase; consequently, technological innovation can also be justifiably anticipated to surge the rates of growth of the BRICS economies. Similar to our finding, Anakpo and Oyenubi (2022) and Meirun et al. (2021) also opined that technological innovation guarantees higher economic growth levels in Southern African nations and Singapore, respectively. Furthermore, regarding the indirect economic growth impacts of technological innovation, the results from this study indicate that technological innovation, jointly with financial development and energy use, contributes to a higher economic growth rate in the BRICS countries by moderating the financial development-economic growth rate and energy use-economic growth rate nexuses. In explanation, it can be said that improved technology within the financial system can be assumed to upscale private sector investments to promote further growth of the BRICS economies. Simultaneously, the utilization of improved technology can be expected to enhance the rate of energy use efficiency to amplify the economic growth rates further.

Secondly, we interpret the findings from the CO_2 emissions growth rate model which are presented in Table 9. Unlike the earlier finding of the previous year's economic growth rate influencing the current year's economic growth rate, it can be seen that the rate of change in per capita CO_2 emissions at present is not conditional on the last year's rate of change in per capita CO_2 emissions. This is understood from the statistical insignificance of the elasticity parameter (in all three models) attached to the one-period lagged level of per capita CO_2 emissions growth rate variable (i.e., $CO_2PC\_GR(-1)$). On the other hand, the development of the financial sector is found to trigger negative environmental outcomes in the BRICS nations. Notably, a 1% increment in the percentage share of private sector credit in the GDP is associated with a rise in the growth rate of the annual per capita CO_2 emission levels by 0.454–0.590%. This finding largely signals that the financial services provided by the financial institutions operating in the BRICS nations are unclean. For instance, the financial sectors in these emerging countries could be financing investments in pollution-prone industries whereby further development of the financial sectors can be accompanied by greater incidences of environmental pollution. In agreement with our finding, Ibrahim et al. (2022) also found evidence that developing the financial sector leads to higher emissions of CO_2 in the BRICS countries. Besides, Weili et al. (2022) also reported similar findings in the context of selected belt and road initiative countries. However, in the case of developed economies, Habiba and Xinbang (2022) asserted that financial development abates CO_2 emission to improve environmental quality. Therefore, upon comparing our results with those reported by Habiba and Xinbang (2022) it is reveal that financial development is likely to improve environmental quality in high-income countries.

Among the other important findings from this current study, we find that energy consumption also dampens environmental quality in the BRICS nations. This is because the corresponding elasticity estimates show that if the annual primary energy consumption level increases by 1%, it is likely to surge the annual rate of change in per capita CO_2 emissions by 42.965–47.324%. This is a predictable finding since the energy systems of the BRICS nations heavily rely on unclean energy resources; consequently, combusting unclean energy can be presumed to stimulate an upsurge in the discharge rate of CO_2 into the atmosphere. Notably, in 2019, the renewable energy shares in the primary energy consumption figures were merely 3.22% for Russia, 10.5% for South Africa, 14.45% for China, 32.93% for India, and 47.57% for Brazil (World Bank 2022). Therefore, the finding of greater energy use stimulating higher CO_2 emissions growth rates in the BRICS countries do not come as a surprise. This finding partially corroborates the results documented by Zhu et al. (2018) and Bhat (2018) for the BRICS nations. In contrast, Dong et al. (2017) opined that merging nations can curb CO_2 emissions by scaling up the use of relatively cleaner energy resources.

Lastly, in respect of environmental effects related to technological innovation, the results show that improvement in the level of technology in the BRICS nations is likely to deteriorate their environmental quality. A rise in the value of the technological innovation index by 1% is predicted to be accompanying a decline in the annual per capita CO_2 emission growth rates by 131.840–158.230%. Besides, technological innovation is also evidenced to indirectly reduce CO_2 emission rates jointly with primary energy consumption by moderating the relationship between energy use and CO_2 emissions growth rate. However, a similar moderating effect of technological innovation on the financial development-CO_2 emission growth rate could not be established. Hence, in line with these findings, it can be said that technological progress can help the BRICS nations to overcome the adverse environmental impacts faced by these nations due to relying heavily on unclean energy resources. Among the two possible mechanisms through which technology can impose these favorable environmental outcomes include (a) new technologies can help to make more productive use of energy so that the undue waste of energy can be curbed and, therefore, its reserve can be conserved; consequently, the growth in the rate of energy-related CO_2 emissions can be contained; and (b) improved technologies can drive energy diversification by scaling up the share of modern and cleaner energy resources in the total energy consumption levels of the BRICS nations. Besides, technological limitation/backwardness has often been highlighted as a major inhibitor of renewable energy adoption (Murshed 2020); accordingly, developing new technologies can be assumed to help in facilitating the supply of low-cost renewable energy within the BRICS countries. On the other hand, the failure of technological innovation to jointly contribute to lowering of CO_2 emission growth rates further indicates that since the BRICS nations are predominantly fossil fuel-dependent, providing finance to private sectors is likely to surge the demand for dirty energy which, in turn, is most likely to trigger a rise in the rate of discharge of CO_2 emissions into the atmosphere.

Conclusions and policy recommendations

The BRICS nations are striving for simultaneously improving their economic and environmental conditions by respectively boosting their per capita economic growth rates and mitigating the discharge rates of per capita CO_2 emissions in tandem. Besides, from the point of view of attaining the SDG by 2030, it is essential for these emerging nations to sustain their annual rise and decline in economic growth and CO_2 emission rates, respectively, in the future. Hence, this study aimed to juxtapose the impacts of financial development, energy use, and technological innovation on the annual rates of per capita economic growth and CO_2 emissions in the context of the BRICS nations considering the study period from 1990 to 2020. The econometric methodology involved in estimating these impacts was designed to account for the panel data problems concerning cross-sectional dependence, heterogeneous slope coefficients, and, more importantly, endogenous covariates. The key results from the analysis firstly affirmed long-run cointegrating associations among the variables of concern. Secondly, the causality analysis revealed unidirectional causal influences of primary energy consumption and technological innovation on per capita economic growth rate and from financial development and technological innovation to per capita CO_2 emissions growth rate. More importantly, the causality analysis led to the identification of two bidirectional causalities between financial development and economic growth rate and between primary energy use and CO_2 emission rate.

The presence of these reverse causalities verified that the financial development and primary energy consumption variables are endogenous covariates within the economic growth rate and CO_2 emission growth rate models, respectively. As a result, to control for endogeneity issues within the regression analysis, as well as accounting for cross-sectional dependence and heterogeneity of slope coefficients, the DCCE-IV technique was employed. This advanced technique considers the lagged levels of the other explanatory variables in the respective model as IV for treating the corresponding endogenous covariate. The results from the DCCE-IV regression analysis discovered that in the long run, financial development, primary energy consumption, and technological innovation boost the annual per capita economic growth rates in the BRICS countries. In addition, technological innovation was evidenced to indirectly boost the economic growth rate further by jointly stimulating higher economic growth rate with greater financial development and primary energy use. These findings verified the moderating roles of technological innovation on the financial development–economic growth rate and energy consumption-economic growth rate relationships. On the other hand, financial development and primary energy consumption were observed to surge the annual per capita CO_2 emission rates, while technological innovation was found to reduce the emission growth rates. Besides, technological innovation was also evidenced to indirectly contribute to reducing the annual rate of discharge of CO_2 emissions by jointly reducing emissions rates with primary energy use. Consequently, this finding once again verified another moderating effect of technological innovation on the energy consumption-CO_2 emission growth rate nexus. Considering these major analytical outcomes, we recommend some important policies that can facilitate the attainment of the SDG agenda from the perspectives of emerging market economies.

Firstly, regarding policies concerning sustainable economic growth, it is essential for the government to further enhance the share of private sector credit in their respective GDP so that private investors do not find it difficult to expand their output levels due to financial constraints. In this regard, reducing the difficulties in availing of private loans and provision of low-interest loans can be expected to substantially scale up private investment levels to surge the rate of economic growth in the future. At the same time, the introduction of new credit schemes with flexible repayment arrangements is also important in incentivizing private investments further. On the other hand, since the energy led-economic growth hypothesis was verified in this study, ensuring a reliable supply of energy, electricity in particular, is important from the point of view of attaining sustainable economic growth. However, since ensuring energy supply reliability is not easy for the context of emerging nations, it is pertinent for the concerned governments to identify the loopholes through which energy is wasted at present in order to reduce current energy consumption and rather conserve energy for future consumption. In this regard, efficient monitoring and penalizing of energy theft can be an option since often the poor institutional quality in emerging nations triggers the theft of electricity; moreover, often the stolen electricity is also not full-fledgedly utilized for boosting the national income growth rate. More importantly, it is of utmost importance for the emerging nations to achieve technological progress so that the latest technologies can significantly improve factor productivity to further expedite economic growth rates. Besides, new technologies should ideally be aimed at digitalizing the financial system so that private sector loan availability can be enhanced further; moreover, new technologies should also help in discovering techniques that can ensure more productive use of energy. As a result, these policies can be assumed to comprehensively stimulate higher technological innovation-led economic growth in the emerging economies.

Secondly, regarding policies concerning environmental sustainability, the financial sector policies need to adhere to the environmental guidelines so that the financial sector is not held responsible for a surge in the future annual CO_2 emission rate. Therefore, it is necessary that preferential treatment is given to potential borrowers who are committed to investing in green projects; these loans should be made available at relatively lower rates of interest compared with the relatively higher interests charged on dirty loans. Moreover, the loan repayment period for green loans should be comparatively longer than the corresponding repayment periods for dirty loans. Furthermore, the financial sector should redirect funds from dirty to green industries so that the development of this sector does not harm the environment. On the other hand, since the energy sector is found to be responsible for deteriorating the environment in emerging nations, energy portfolio diversification, especially by replacing unclean with clean energy resources, is of paramount importance for these nations. In addition, ensuring better management of energy demand by reducing the level of energy wasted and minimizing electricity distribution and transmission losses can also be considered as a major energy sector reform that can be conducive to ensuring environmental sustainability in the future. Lastly, in respect of technological innovation-led environmental improvement, it is ideal for emerging nations to invest in research and development for enhancing the rate at which energy is consumed. This is important because the latest technologies are often thought of as pre-requisites for achieving energy innovation which, in turn, can be expected to persistently curb the annual CO_2 emission rates in these countries. In addition, technological innovation-led energy diversification is also essential for the traditionally unclean energy-reliant emerging nations to undergo clean energy transition within their respective energy sector. Consequently, these policies can be anticipated to help the emerging nations contain their energy use-related greenhouse gas emissions to a large extent.

Insufficient data availability has limited the size of the country sample whereby we could only focus on the BRICS nations but not on other emerging nations across the globe. As a result, data variation within the sample, due to the limited sample size, has been low which could have had an impact on the findings. Therefore, to address this limitation, future studies can try to focus on the other emerging nations as well to check the robustness of the findings across different samples of emerging nations. Besides, predicting country-specific outcomes can also be considered in order to propose heterogeneous policies for the individual emerging nations.

Author contribution PM conceptualized and wrote the original draft. MSA conducted the econometric analysis, generated the graphical illustrations, and reviewed and edited the final draft. KA and HM contributed to the methodology section. MM conceptualized the study, wrote the original draft, compiled the literature review, analyzed the findings, recommended the policy implications, and reviewed and edited the final draft. DP provided computational support and contributed to the revision.

Data availability Data sources are duly mentioned.

Declarations

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