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Influence of green financing, technology innovation, and trade openness on consumption-based carbon emissions in BRICS countries

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ABSTRACT

The study explores the dynamic effects of renewable energy investment (green financing), green technology, and trade openness on consumption-based (trade-adjusted) carbon emissions in BRICS economies from 2000 to 2020. The study employs the cross-section autoregressive distributed lag method for empirical estimation to address slope heterogeneity and cross-sectional dependency issues in panel data. The findings exhibit that green financing and sustainable technologies mitigate consumption-based carbon emissions in the long-run, while trade openness contributes to emissions in BRICS countries. The short-run outcomes are compatible with long-run; however, the magnitude of long-run estimates is larger than the short-run. Moreover, the error correction term reveals a significant negative coefficient value, endorsing the conversion towards steady-state equilibrium with a 37% yearly adjustment rate in case of any deviation from equilibrium. The robustness of results is confirmed through augmented mean group and common correlated effect mean group. These findings imply that BRICS countries should encourage financing in renewable energy projects and allocate R&D investment to promote the adaptation of sustainable technologies. In addition, sustainable and green trade policies would help to curb trade-adjusted pollution.

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1. Introduction

Over the last decade, the magnitude of trade activities has increased considerably in emerging economies because trade and integration help countries foster economic growth and better living standards. International trade serves as a bridge to close the gap between needed products and services and their availability. It indicates that trade openness aids economies that export the products that benefit from their lower opportunity cost and import products that they cannot manufacture or shortage as a result of climatic change from countries where they are available. This worldwide

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give-and-take involves the production and transportation of goods from one economy to another, where they are eventually consumed (Appiah et al., 2022; Yang, Su, et al., 2022; Xuefeng et al., 2022). In this way, the rising trade trend significantly affects the environment.

Prior literature on the trade-environment nexus can be classified into two categories. One category argued that the expansion of trade operations emerges the environmental degradation (Khan, Ali, et al., 2020; Hasanov et al., 2018). Through foreign trade, the countries compete with each other in terms of high-quality products at minimum cost; the higher demand for goods in the international market expands production activities. Thus, meeting the energy requirement during production has increased the use of non-renewable energy, resulting in carbo pollutants in the environment. On the flip side, the other category claimed that trade openness has a negative impact on carbon emissions (Zhang et al., 2017; Esmaeilpour Moghadam & Dehbashi, 2018). Trade could draw certain businesses to nations where knowledge spillovers encourage cleaner production and, as a result, a cleaner environment (Sarkodie & Strezov, 2019). Furthermore, international relations between countries and multinational firms have facilitated the transmission of technical advancements into underdeveloped countries, which has aided in the preservation of the environment in some way (Yang, Wang et al., 2022).

The countries must offset the connection between trade and CO_2 emissions, and now growing economies are shifting resources to efficient projects and adopting green technologies. Green innovation is a product and process innovation that incorporates energy-saving technologies, pollution control, waste recycling, and environmental management (Razzaq et al., 2021). Many research studies stated that green technologies effectively promote green growth while meeting environmental regulation standards (Wang et al., 2022; Shao et al., 2021). Thus, cost savings, enhanced productivity, and improved logistics are direct benefits, while indirect benefits include the improved image, health, safety, and customer relations of green innovation. In comparison, some studies indicated the negative or no consequences of using green technology on the environment (Khattak et al., 2020; Ali et al., 2016). Due to different economic stages, every economy has variant technological spillover effects; therefore, eco-friendly innovations positively influence high-income countries and have little impact on low-income countries.

The significance of green innovation has gained the attention of policymakers toward investment in renewable or clean sources. Green financing has developed as an important source of funding for environmental challenges. This cutting-edge technique of funding and handling environmental and growth-related issues prepares the ground for a global world where economies can prosper and grow while maintaining a friendly environment. It not only includes clean resources, but recycling, biomass processing, energy saving, waste management, and carbon-reducing technology are also part of this investment. Therefore, the accessibility of renewable energy resources may not be possible without investment from the government and private sectors (Chen et al., 2021).

However, there are two schools of thought regarding the relationship between green financing and carbon neutrality. One school of thought concluded that green investment is a valuable strategy for improving economic performance while ensuring environmental sustainability (Xiong & Sun, 2022; Lee & Min, 2015). Green financing is a cutting-edge technique for encouraging global sustainable development because the research and development in renewable energy replace traditional energy resources, improve energy efficiency, and preserves the environment from deterioration (Shen et al., 2021; Irfan et al., 2022). The other school stated that the influence of green financing has a negative or even no effect on the environment in the presence of inadequate investment and policies at government and business levels (Stucki, 2019; Nehler & Rasmussen, 2016). When any country bears a low cost of using conventional energy resources compared to the cost it bears on financing, there is a reluctance to invest in the investment of renewable energy. Further, direct gains of green investment are considered in terms of energy-saving costs. At the same time, indirect advantages are not included in green policies, such as producing more efficient products, emitting low carbon pollutants, optimum use of energy resources, and low repairing costs. Ignoring these benefits reduces the positive effects of green investment on the environment. Therefore, the relationship between them is still inconclusive.

Although many prior environment-related empirical studies have used simple or production-based carbon emissions, thus, less attention has been given to the consumption-based carbon emissions, which include not only the influence of trade but also includes emissions from the local consumption and production of foreign commodities (Hasanov et al., 2018; Liddle, 2018). As a result, CCE is a more reliable measure for addressing the whole carbon process, identifying carbon stock responsibility, and monitoring the performance of global efforts to reduce rising emissions levels (Khan, Ali, et al., 2020). In addition, many studies empirically investigate the green technology-environment and trade-environment nexus; however, very few studies analyzed the association between green financing and carbon neutrality. Thus, there is a lack of empirical evidence that explores the combined effects of green innovation, green financing, and trade openness on environmental pollution in the context of BRICS countries.

There are various reasons for the selection of BRICS countries in the study. Firstly, the BRICS nations are the fastest-growing economies globally, and the combined GDP of these countries is 22.45% of the world's total GDP (Hou et al., 2022). Secondly, the developed economies are establishing their industries or importing commodities from BRICS countries, causing consumption-based carbon emissions to rise, which is critical for environmental protection (Razzaq et al., 2021). Since these activities have significantly increased CO_2 emissions in BRICS, which totaled 14,759 billion tonnes in 2019, accounting for 43.19 percent of worldwide CO_2 emissions (Mngumi et al., 2022), therefore it is imperative to pay attention to the dominant elements of CO_2 emissions in the BRICS nations, which generate 2/3rd of the total CO_2 emissions. It not only puts pressure on global carbon emission reduction but also helps to promote the nations' long-term growth.

Against this background, this study examines the dynamic impacts of green financing, green technology, and trade openness on consumption-based carbon emissions (CCE) in BRICS economies using the panel data from 2000 to 2020. For analyzing the mitigating factors of green financing, green technology, and trade openness on carbon neutrality, CCE has been taken in the study as a proxy of environmental quality.

However, past studies mostly used production-based carbon emissions, which produced inconsistent results because it does not incorporate trade-related emissions. Therefore, CCE is more accurate in exploring environmental quality factors because the BRICS are export-oriented industries and economies. Moreover, for empirical analysis cross-sectional autoregressive distributed lag (CS-ARDL) method is employed, which is a more suitable and reliable estimation method than first-generation estimators. Lastly, the study used augmented mean group (AMG), and common correlated effect mean group (CCEMG) approaches to confirm the robustness of the results.

The remaining structure of the paper is summarized as follows: Section 2 indicates the literature review. Section 3 includes the data and methodology; section 4 represents empirical results and discussion. Section 5 highlights the conclusion and policy implications.

2. Literature review

This section shows the previous studies that have discussed the impacts of green innovation, green financing, and trade on the environment. The section consists of three parts: (1) link between green innovation and the environment, (2) interdependence between green financing and environment degradation (3) nexus between trade openness and environmental quality.

2.1. Green innovation-environment nexus

A large number of studies asserted that green innovation is a potential tool to eradicate carbon emissions from the environment. In the literature, there are two groups of studies about the nexus between green technology and environmental quality. One group argued that green innovation significantly enhances the environment's sustainability with economic growth (Wang et al., 2022; Shao et al., 2021) because green innovation refers to product or process that increase energy efficiency, protects the environment from degradation, shifts the use of non-renewable fuel sources to clean or renewable energy sources. Thus, it differs from conventional technology because it fosters economic growth and productivity without emitting emissions.

Wang et al. (2020) determined that green innovation is negatively associated with CO_2 emissions in G7 countries; thus, eco-friendly innovations are the ultimate solution for reducing CO_2 emissions due to the rising economic activities and export diversity. Similarly, using OECD countries' data, Ahmad et al. (2021) found that positive innovation mitigates CO_2 emissions. Thus, the study suggests encouraging green innovation through commercialization and reinforcing the policies of green innovation in the international market. Du et al. (2019) studied the impact of green innovation on CO_2 emissions by using data from 1996 to 2012 in 76 economies. The considered countries are divided into two groups: low-income and high-income. The findings reveal that green technology has a non-significant association with low-income countries and a substantial relationship with high-income countries. Razzaq et al. (2021) drew the link between green innovation, production, and consumption-based carbon emissions in BRICS countries from 1990 to 2017. They found that green innovation help in declining carbon emissions at higher emissions quantiles, whereas it does not play an effective role at lower emissions quantiles.

In contrast, the other group explored that green innovation has a negative or insignificant role in reducing environmental damage (Weina et al., 2016; Khattak et al., 2020). Technological spillover effects of green innovations for a particular country depend on the levels of economic development. Thus, it has substantial favorable effects for the developed nation while low potential impacts for the non-developed nation. Ali et al. (2016) investigated that technology innovation had an insignificant and inverse effect on CO_2 emissions in Malaysia from 1985 to 2012. Khattak et al. (2020) exposed that technological innovation failed to curb CO_2 emissions in BRICS countries from 1980 to 2016. Similarly, Yii and Geetha (2017) indicated in the case of Malaysia that technological innovation reduces CO_2 emissions in the short-run while, in the long-run, it has no impact on CO_2 emissions. The above studies show that the association between green innovation-environment nexus findings is inconclusive.

2.2. Green financing-environment nexus

Many studies have explored the direct association between green technology and carbon emissions. The significance of renewable or green energy sources in diminishing CO_2 emissions highlights the investment in this particular sector. However, the research studies on green financing and environmental degradation remain limited.

Some studies investigated that investment in green technology or green financing promotes environmental sustainability (Ahmed et al., 2021; Shen et al., 2021). Shahbaz et al. (2018) indicated that the increase in public investment in renewable energy development is influential in reducing environmental deterioration in France. Shen et al. (2021) analyzed that CO_2 emissions are inversely affected by the rise of green financing in 30 provinces of China from 1995 to 2017. Lee and Min (2015) conclude that green research and development has had a negative effect on CO_2 emissions from 2001 to 2010 in Japanese manufacturing firms. Mahesh and Shoba (2013) found that renewable energy investment has a great potential to mitigate CO_2 emissions in India. Similarly, Ahmed et al. (2021) show that more public investment in clean energy is effective in tackling the CO_2 emissions in Japan from 1974 to 2017. In addition, Xiong and Sun (2022) explored that green investment is essential for low CO_2 emissions by using the data of 34 Chinese provinces from 2003-to 2017.

However, some studies found that investment in green finance has a positive or negligible and mixed impact on CO_2 emissions (Stucki, 2019; Nehler & Rasmussen, 2016). Using the empirical data of China, Zhang et al., 2021 highlight that the impact of renewable energy investment on CO_2 emissions is unclear. In the initial and later stages of development, a rise in renewable energy investment also increases CO_2 emissions, while in the middle stage, it reduces CO_2 emissions. Thus, both variables have mixed findings that require more attention from scholars. Nehler and Rasmussen (2016) discovered that industrial enterprises emphasize green investment profitability over energy cost savings and that most green investment decisions do not take into account benefits other than energy, such as improved productivity, reduced emissions, enhanced product quality, efficient material utilization, and lower repairing and cleaning costs, which, if considered, would enhance green investment (Liu et al., 2022). As a consequence, the gains of green energy investment have declined. Therefore, the existing studies show mixed outcomes between these two concerning variables.

2.3. Trade openness-environment nexus

In this rapid era of development and globalization, the carbon emission impacts of trade have enormously increased; therefore, several studies focused on the role of trade on environmental quality. However, the existing findings concerning trade influences and the environment have been inconclusive.

Some studies found that trade openness positively affects CO_2 emissions through rising exports, and to meet the international demand for goods, the more local production of commodities requires energy consumption, which ultimately raises pollution (Dou et al., 2021; Hasanov et al., 2018). Mahmood et al. (2019) investigated the association between trade openness and CO_2 emissions in Tunisia from 1971 to 2014. The outcomes indicate that international trade is responsible for surging CO_2 emissions. Shahzad et al. (2017) analyzed the impact of trade activities on environmental degradation from 1971 to 2011 in Pakistan. The findings show that CO_2 emissions are directly affected by rising trading activities. Khan, Ali, et al. (2020) examined the nexus between trade and consumption-based carbon emissions in the case of nine oil-exporting economies. The study found that import is positive and exports have an insignificant influence on CO_2 emissions. Similarly, Fang et al. (2019) determined that environmental degradation is directly affected by the increase in trade on the panel dataset of 82 developing countries.

On the flip side, some prior studies found the beneficial effect of trade-related activities on carbon neutrality (Zhang et al., 2017; Dogan & Turkekul, 2016). The increasing trend of foreign trade enhances the competitiveness of commodities through the spillover effects of technology innovations in developing countries which substantially improve the environment. Moreover, through the bilateral trading reduction in exports of heavily polluted products, local demand for these polluted products meet by importing from the other country. Esmaeilpour Moghadam and Dehbashi (2018) explored the relationship between trade and environmental degradation in Iran from 1970 to 2011. The study's findings reveal that foreign trade helps reduce environmental pollution because Iran produces polluting commodities and imports these goods from China. Thus, through the bilateral trading reduction in exports of heavily polluted products, local demand for these polluted products meet by importing from the other country. Zhang et al. (2017) found the negative impact of trade openness on CO_2 emissions from 1971 to 2013 in 10 industrialized economies. The empirical findings highlight that products and services are easily mobile via international trade, particularly the transfer of technology, which diminishes the surplus capacity and CO_2 emissions in concerned countries.

However, (Sharma, 2011) analyzed the insignificant influence of trade on carbon neutrality by using the panel data of 69 countries over the period 1985–2005. The estimated results show that trade openness has no direct association with mitigating

Table 1. Variables of the study.

Symbols	Variables	Description	Measurement Unit	Source
CCE	Dependent	Consumption-based (trade-adjusted) carbon emissions	Metric Tons Per Capita	Global Carbon Atlas
GF	Independent	Investment in Renewable Energy Sectors	Million USD	IRENA
GI	Independent	Green Innovation	Eco patents % of total patents	OECD Statistics
TO	Independent	Trade Openness	Import + Export/GDP	WDI
GDP	Control	Economic Growth	GDP Per Capita (constant 2010 $)	WDI

carbon pollution. Thus, other measures are also necessary for achieving carbon neutrality. Therefore, the relationship between these two variables is ambiguous and must be explored.

3. Data methodology

3.1. Data sources

This study selects BRICS countries (Brazil, Russia, India, China, and South Africa) to explore the determinants of carbon neutrality by using the annual data from 2000 to 2020. In the data, consumption-based carbon emissions (CCE) are sourced from the GCA (2021) and are measured as metric tons per capita. The green financing (GF) data is taken from IRENA (2021), measured in a million USD. The green innovation (GI) data is collected from the (OECD Statistics, 2021) OECD and measured as eco patents % of total patents. However, trade openness (TO) is measured as import plus export/GDP, and economic growth (GDP) is per capita (constant 2010 $); thus, data of both variables are collected from WDI (2021). All the variables have different measurement units, thus transformed into logarithmic (Sun & Razzaq, 2022; Jin et al., 2021). The definitions, measurement units, and sources of the variables are mentioned in Table 1.

3.2. Model specification

The study investigates the impact of green finance, green innovation, and trade openness on CCE. For this study, we have adopted the empirical models of (Khan, Ali, et al., 2020; Dauda et al., 2021) and extended the model in the context of BRICS countries. The model specification of the study is as follows:

$$\mathrm{CCE}_{it} = \alpha_{it} + \beta_1 GF_{it} + \beta_2 GI_{it} + \beta_3 TO_{it} + \beta_4 GDP_{it} + \varepsilon_{it} \tag{1}$$

Equation (1) represents CCE as a dependent variable, whereas GF, GI, TO, and GDP are independent variables. Further, the coefficients of the variable are shown by β_s, α is a constant term and ε is a stochastic error term. The symbols t and $\boldsymbol{i}$ indicate the time period and cross-section identities.

3.3. Econometric techniques

Before applying the unit root test, it is imperative to check the cross-section dependence (CSD) and slope homogeneity because all the counties are heterogeneous in economic, demographic, social, and financial conditions. Therefore, ignoring the CSD and slope heterogeneity may provide inconsistent and biased results. Thus the study initially employs the CSD test presented by (Pesaran et al., 2004) and the slope homogeneity test given by (Pesaran & Yamagata, 2008).

After examining the CSD and heterogeneity of slope coefficients, the study determines the stationary properties of variables. Unlike the previous studies, the current study does not use the first generation unit root tests, for example, Levin et al. (2002) and Im et al. (2003), due to the inability to resolve the issues of CSD and heterogeneous slopes. Hence, the second-generation unit root test cross-section augmented IMPS developed by Pesaran (2007) is employed in the study for stationary analysis. Further, the study applied the Cross-sectional Augmented Dickey-Fuller (CADF) test, the first generation unit root test for unbiased results. Thus, both traditional and advanced unit root tests are employed in the study. Then to find the long-run cointegration among the variables, Westerlund's cointegration test (Westerlund, 2007) is applied because this test is more appropriate than the Pedroni and Kao cointegration tests due to the presence of CSD and slope heterogeneity.

For short and long-run estimations, the current study applied the cross-section autoregressive distributed lag (CS-ARDL) method presented by Chudik and Pesaran (2013); due to the supremacy of addressing the problems of CSD, endogeneity, and heterogeneity of slope parameters. Also, this approach deals with unobserved significant common factors, and ignoring these factors may provide misleading results. Therefore, the CS-ARDL method is more suitable than other estimation methods, such as Panel ordinary least square (POLS) and Panel ARDL. Lastly, the study checked the robustness of the model by using AMG presented by Eberhardt and Teal (2010) and the CCEMG estimator developed by Pesaran (2006).

4. Empirical results and discussion

4.1. Results of CSD and slope homogeneity test

The study first identifies CSD and slope homogeneity for empirical estimation before applying unit root tests. The results of CSD and slope homogeneity tests are shown in Table 2. The findings of the CSD test reject the null hypothesis of no CSD at a 1% significance level. Thus, the results highlight the presence of CSD in all the variables. The outcomes of the slope heterogeneity test reveal that all the parameters of variables are heterogeneous, implying that all the countries have different social, demographic, and economic conditions. Thus, slope heterogeneity lies in all the variables.

4.2. Results of unit root tests

The study checks the stationary condition of the concerned variables after determining the presence of CSD and slope heterogeneity. Thus, the CIPS and CADF unit

Table 2. CSD and Slope homogeneity test.

	CSD test	
Variables	F-Value	P-Value
CCE	34.215***	0.000
GF	27.850***	0.000
GI	23.934***	0.000
TO	33.146***	0.000
GDP	45.027***	0.000
Slope homogeneity test		
Test	Value	P-value
$\hat{\Delta}$	9.249***	0.000
$\hat{\Delta}_{\text{adjusted}}$	10.104***	0.000

Note: ***P < 1%, **P < 5% and *P < 10%.
Source: Author.

Table 3. CIPS & CADF unit root tests.

	CIPS		CADF	
Variables	I(0)	I(I)	I(0)	I(I)
CCE	−2.352	−4.115***	−2.126	−5.230***
GF	−1.755	−3.574***	−2.553	−3.972***
GI	−2.710	−3.781***	−2.845*	−5.648***
TO	−1.965	−3.520**	−2.070	−3.215***
GDP	−1.530	−4.149***	−1.716	−3.895***

Note: ***P < 1%, **P < 5% and *P < 10%.
Source: Author.

root tests are applied in the study because both unit root tests provide consistent results in the presence of CSD and slope heterogeneity. Table 3 shows the findings of CIPS and CADF tests which confirm that all the studied variables are stationary at first difference. Thus, all the variables are stable at I (I), which means that long-run cointegration may exist among all the variables.

4.3. Results of cointegration test

After applying the unit root test, the study examines the existence of long-run cointegration. Thus Westerlund's cointegration test is used, and its estimated results are mentioned in Table 4. The findings reveal that all the variables are co-integrated in the long run, as shown by the panel and group statistics values.

4.4. Results of CS-ARDL method

The study estimates the long and short-run findings of the CS-ARDL method after confirming the existence of long-run cointegration among the variables. The outcomes of long-run estimations are summarized in Table 5.

In the long run, the findings demonstrate that green financing is negative and significantly associated with CCE at a 5% significance level. Thus, the 1% rise in green financing tends to reduce CCE by 0.075%. Our findings are consistent with (Mngumi et al., 2022), who found that green finance reduces CO_2 emissions in BRICS countries, and contrary to the findings of (Stucki, 2019), who found that green investment

Table 4. Cointegration outcomes.

Statistics	Gt	Ga	Pt	Pa
Value	−6.745***	−8.563	−11.423***	−14.850**
P-value	0.000	0.610	0.000	0.015

Note: ***P < 1%, **P < 5% and *P < 10%.
Source: Author.

Table 5. Cross-sectional ARDL results.

	Long-Run			Short-Run		
Variables	Coeff.	t-stats	Sig.	Coeff.	t-stats	Prob.
ECT_{-1}	–	–	–	−0.372	−3.805	***
GF	−0.075	−2.530	**	−0.040	−2.317	**
GI	−0.274	−3.519	***	−0.068	−1.980	*
TO	0.476	2.536	**	0.375	3.010	***
GDP	0.695	4.740	***	0.532	3.218	***

Note: ***P < 1%, **P < 5% and *P < 10%.
Source: Author.

contributes to the CO_2 emissions in China due to the reluctance of high cost incurred on green financing. The second variable green innovation, is inversely related to CCE at a 10% significance level, which means that a 1% increase in green technology diminishes the CCE by 0.274%. The findings are identical to Wang et al. (2020), who argued that green technology significantly improves the environmental quality of G7 economies. These findings contrast with Ali et al. (2016), who found green innovation's opposite and insignificant impact on a sustainable environment in Malaysia. However, as the mitigating factors, in the long run, the coefficient of green innovation is greater in magnitude than the green financing coefficient, indicating that green innovation's positive effect on environmental quality is much higher. In comparison, the low parameter of green financing indicates the need for more investment in the research and development of green energy sources. Thus, public and private funds and investments promote green growth.

The third variable, trade openness, has a direct positive relationship with CCE. It shows that CCE rises by 0.476% when one percent increases in trade. The outcome is similar to Fang et al. (2019) for 82 countries where trading operations are responsible for environmental damage. The large coefficient of this variable shows that trade openness contributes to CCE in the long run, which indicates that BRICS economies are mostly export-oriented; thus, the results suggest that these countries should formulate sustainable foreign trading policies with other countries. The control variable GDP also significantly influences CCE by 0.695%. The results align with Khan, Ali, et al. (2020) because the increases in economic activities create more energy consumption in BRICS countries, producing pollution; thus, CCE is positively affected by GDP.

The short-run results of CS-ARDL are also mentioned in Table 5, which reveals that green innovation and green financing are negatively linked with CCE and help in decreasing CCE by 0.068% and 0.040%, respectively. Similarly, trade and GDP are positively related to CCE. Thus, a 1% rise in trade openness and GDP stimulated CCE by 0.375% and 0.532%, respectively. The estimations for the short run are similar to long-run findings. However, the magnitude of parameters is higher in the long

Table 6. Robustness estimators.

	CCEMG			AMG		
Variables	Coeff.	t-stats	Sig.	Coeff.	t-stats	Prob.
GF	−0.104	−2.850	***	−0.087	−2.756	**
GI	−0.268	−3.620	***	−0.262	−3.194	***
TO	0.430	2.403	**	0.415	2.875	***
GDP	0.564	4.212	***	0.524	4.738	***

Note: ***P < 1%, **P < 5% and *P < 10%.
Source: Author.

run compared to the short run, which implies that the sustainable long-term policy requires green financing, green technology, and trade openness to produce substantial effects. The coefficient of error correction term (ECT) is 0.372, which is significant and negative, showing that if any shock occurs in the short-run, then the model converges towards the long-run equilibrium with a 37.2% pace of adjustment. In addition, it also concludes that the estimated model is stable.

4.5. Results of robustness analysis

Finally, the study employed the CCEMG and AMG tests as robustness estimators to determine the reliability of the estimated results. The results are inserted in Table 6, confirming the negative association between green financing and CCE, with values of 0.104% and 0.087% for CCEMG and AMG, respectively. Similarly, green innovation and CCE are inversely related, with 0.268% by CCEMG and 0.262% by AMG. Further, the CCEMG and AMG also show a positive correlation between trade openness and CCE, with coefficient values of 0.430% and 0.415%, respectively. The finding of the control variable GDP is also positive with CCE. Therefore, both robustness tests endorsed findings attained from the CS-ARDL approach.

5. Conclusion and policy recommendations

The BRICS countries have become a well-known emblem of internationalism. These countries are projected to play a major role in global economic and social advancement but suffer from severe carbon pollution. From this perspective, the study examines the dynamic short and long-run influences of green innovation, green financing, and trade on CCE in BRICS economies. For empirical estimations, annual panel data is used from 2000 to 2020. At the initial stage, CSD and Slope heterogeneity tests are employed that confirm the CSD and heterogeneity in the slope parameters. After examining them, the study applied CIPS and CADF unit root tests to check the stationary properties of variables. The results of both unit root tests confirm that all the variables are integrated of order one. Then the long-run cointegration relationship of all variables is identified by using Westerlund's test. For the short and long-run estimates of the model CS-ARDL approach is used.

The long-run results show that green financing decreases CCE by 0.75%, while green innovation mitigates the CCE by 0.274%. Trade openness increases CCE by 0.476%. The GDP as a control variable also enhances the CCE by 0.695%. The short-run outcomes are identical to long-term results, and green financing and green innovation improve the environmental quality by 0.040% and 0.068%. In contrast, trade and economic expansion activities increase CCE by 0.375% and 0.532%, respectively. All the results obtained in the long run have a large magnitude than the short-run results. This indicates that these factors have substantial long-term effects on environmental degradation. The error correction term is also significantly negative at 37.2% and shows the long-run stability of the model. Similar results are also endorsed by CCEMG and AMG estimators and offer the following policy recommendations.

1. The outcome of green innovation suggests that green technology is imperious for BRICS countries and shifting the non-renewable energy resources to green or clean energy resources and products, which are more efficient for sustainable development without degrading the environment. The current results highlight the importance of allocating substantial resources to the development of renewable energy sources to decrease existing overdependence on fossil fuels. As a result, encouraging and implementing environmental technologies in the industry, residence, and transportation can assist in lowering emissions at the source.
2. The findings of green financing demonstrate that shared infrastructure is urgently needed in BRICS nations to improve research and development cooperation, broaden collaboration and planning, enhance combined effort for green innovation, encourage personal interactions, enable green technology transmission, maintain a full functioning system (research-academic-enterprise), and launch research, technology, and enterprise-focused initiatives. As a result, the government should promote a green growth goal by increasing R&D budgetary allocation, leading to high eco-innovation and, as a result, resource preservation and emission reduction.
3. The economic growth of BRICS countries largely depends on trade, and the result of trade openness has a larger positive effect on CCE. It recommends that the BRICS countries formulate sustainable foreign trading policies with other trading partners. It should introduce and implement strict carbon tax policies on the polluted goods manufactured in BRICS and exported to other importing countries.
4. Furthermore, to minimize the negative effects of trade openness in BRICS nations, more industries with environmentally friendly production processes must be targeted, as this will increase knowledge spillovers from clean technology into various sectors of the economy. Host countries should increase their absorptive capacity mechanisms for an effective and successful know-how spillover process.
5. The positive association of GDP with CCE in BRICS countries shows the requirement for alternative energy exploration and exchange policies (e.g., wind, solar, and biofuels) through joint investments in the renewable energy industry. Policymakers should assess the strategies of partner countries before adopting developmental and green policies to accomplish sustainable development goals.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

Ahmad, M., Khan, Z., Rahman, Z. U., Khattak, S. I., & Khan, Z. U. (2021). Can innovation shocks determine CO2 emissions (CO2e) in the OECD economies? A new perspective. *Economics of Innovation and New Technology*, *30*(1), 89–109. https://doi.org/10.1080/10438599.2019.1684643

Ahmed, Z., Cary, M., Shahbaz, M., & Vo, X. V. (2021, June). Asymmetric nexus between economic policy uncertainty, renewable energy technology budgets, and environmental sustainability: Evidence from the United States. *Journal of Cleaner Production*, *313*, 127723. https://doi.org/10.1016/j.jclepro.2021.127723

Ali, W., Abdullah, A., & Azam, M. (2016). The dynamic linkage between technological innovation and carbon dioxide emissions in Malaysia: An autoregressive distributed lagged bound approach. *International Journal of Energy Economics and Policy*, *6*(3), 389–400.

Appiah, K., Worae, T. A., Yeboah, B., & Yeboah, M. (2022). The causal nexus between trade openness and environmental pollution in selected emerging economies. *Ecological Indicators*, *138*, 108872. https://doi.org/10.1016/j.ecolind.2022.108872

Chen, F., Jiang, G., & Kitila, G. M. (2021). Trade openness and CO2 emissions: The heterogeneous and mediating effects for the belt and road countries. *Sustainability (Switzerland)*, *13*(4), 1958–1916. https://doi.org/10.3390/su13041958

Chudik, A., & Pesaran, M. H. (2013). *Federal Reserve Bank of Dallas Globalization and Monetary Policy Institute Large Panel Data Models with Cross-Sectional* Dependence: 153.

Dauda, L., Long, X., Mensah, C. N., Salman, M., Boamah, K. B., Ampon-Wireko, S., & Kofi Dogbe, C. S. (2021). Innovation, trade openness and CO2 emissions in selected countries in Africa. *Journal of Cleaner Production*, *281*, 125143. https://doi.org/10.1016/j.jclepro.2020.125143

Dogan, E., & Turkekul, B. (2016). CO2 emissions, real output, energy consumption, trade, urbanization and financial development: Testing the EKC hypothesis for the USA. *Environmental Science and Pollution Research International*, *23*(2), 1203–1213. https://doi.org/10.1007/s11356-015-5323-8

Dou, Y., Zhao, J., Malik, M. N., & Dong, K. (2021). Assessing the impact of trade openness on CO2 emissions: Evidence from China-Japan-ROK FTA countries. *Journal of Environmental Management*, *296*, 113241. https://doi.org/10.1016/j.jenvman.2021.113241

Du, K., Li, P., & Yan, Z. (2019, April). Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data. *Technological Forecasting and Social Change*, *146*, 297–303. https://doi.org/10.1016/j.techfore.2019.06.010

Eberhardt, M., & Teal, F. (2010). Department of economics discussion paper series productivity analysis in global manufacturing production productivity analysis in. *Working Paper*, *515*, 1–32.

Esmaeilpour Moghadam, H., & Dehbashi, V. (2018). The impact of financial development and trade on environmental quality in Iran. *Empirical Economics*, *54*(4), 1777–1799. https://doi.org/10.1007/s00181-017-1266-x

Fang, J., Gozgor, G., Lu, Z., & Wu, W. (2019). Effects of the export product quality on carbon dioxide emissions: Evidence from developing economies. *Environmental Science and Pollution Research International*, *26*(12), 12181–12193. https://doi.org/10.1007/s11356-019-04513-7

GCA. (2021). Global Carbon Atlas. http://www.globalcarbonatlas.org/en/CO2-emissions. Accessed date: 2 June 2022

Hasanov, F. J., Liddle, B., & Mikayilov, J. I. (2018). The impact of international trade on CO2 emissions in oil exporting countries: Territory vs consumption emissions accounting. *Energy Economics*, *74*, 343–350. https://doi.org/10.1016/j.eneco.2018.06.004

Hou, D., Chan, K. C., Dong, M., & Q, Y. (2022). The impact of economic policy uncertainty on a frm's green behavior: Evidence from China. *Research in International Business and Finance Journal*, *59*(C), 101544. https://doi.org/10.1016/j.ribaf.2021.101544

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics*, *115*(1), 53–74. https://doi.org/10.1016/S0304-4076(03)00092-7

IRENA. (2021). International Renewable Energy Agency. Retrieved June 2022, from https://www.irena.org/

Irfan, M., Razzaq, A., Sharif, A., & Yang, X. (2022). Influence mechanism between green finance and green innovation: Exploring regional policy intervention effects in China. *Technological Forecasting and Social Change*, *182*, 121882. https://doi.org/10.1016/j.techfore.2022.121882

Jin, C., Razzaq, A., Saleem, F., & Sinha, A. (2021). Asymmetric effects of eco-innovation and human capital development in realizing environmental sustainability in China: Evidence from quantile ARDL framework. *Economic Research-Ekonomska Istraživanja*, *35*, 1–24.

Khan, Z., Ali, M., Jinyu, L., Shahbaz, M., & Siqun, Y. (2020). Consumption-based carbon emissions and trade nexus: Evidence from nine oil exporting countries. *Energy Economics*, *89*, 104806. https://doi.org/10.1016/j.eneco.2020.104806

Khattak, S. I., Ahmad, M., Khan, Z. U., & Khan, A. (2020). Exploring the impact of innovation, renewable energy consumption, and income on CO2 emissions: new evidence from the BRICS economies. *Environmental Science and Pollution Research*, *27*(12), 13866–13881. https://doi.org/10.1007/s11356-020-07876-4

Lee, K. H., & Min, B. (2015). Green R&D for eco-innovation and its impact on carbon emissions and firm performance. *Journal of Cleaner Production*, *108*, 534–542. https://doi.org/10.1016/j.jclepro.2015.05.114

Levin, A., Lin, C. F., & Chu, C. S. J. (2002). Unit root tests in panel data: Asymptotic and finite-sample properties. *Journal of Econometrics*, *108*(1), 1–24. https://doi.org/10.1016/S0304-4076(01)00098-7

Liddle, B. (2018). Consumption-based accounting and the trade-carbon emissions nexus. *Energy Economics*, *69*, 71–78. https://doi.org/10.1016/j.eneco.2017.11.004

Liu, X., Razzaq, A., Shahzad, M., & Irfan, M. (2022). Technological changes, financial development and ecological consequences: A comparative study of developed and developing economies. *Technological Forecasting and Social Change*, *184*, 122004. https://doi.org/10.1016/j.techfore.2022.122004

Mahesh, A., & Jasmin, K. S. (2013). Role of renewable energy investment in India: An alternative to CO_2 mitigation. *Renewable and Sustainable Energy Reviews*, *26*, 414–424. https://doi.org/10.1016/j.rser.2013.05.069

Mahmood, H., Maalel, N., & Zarrad, O. (2019). Trade openness and CO2 emissions: Evidence from Tunisia. *Sustainability (Switzerland)*, *11*(12), 3295. https://doi.org/10.3390/su10023295

Mngumi, F., Shaorong, S., Shair, F., & Waqas, M. (2022). Does green finance mitigate the effects of climate variability: Role of renewable energy investment and infrastructure. *Environmental Science and Pollution Research*, *29*, 0123456789. https://doi.org/10.1007/s11356-022-19839-y

Nehler, T., & Rasmussen, J. (2016). How do firms consider non-energy benefits? Empirical findings on energy-efficiency investments in Swedish industry. *Journal of Cleaner Production*, *113*, 472–482. https://doi.org/10.1016/j.jclepro.2015.11.070

OECD Statistics. (2021). Organization Economic Cooperation Development. Retrieved 2 June, 2022, from https://stats.oecd.org/

Pesaran, M. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics*, *22*(2), 265–312.

Pesaran, M. H. (2006). Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica*, *74*(4), 967–1012. https://doi.org/10.1111/j.1468-0262.2006.00692.x

Pesaran, M. H., Schuermann, T., & Weiner, S. M. (2004). Modeling regional interdependences using a global error-correcting macroeconometric model. *Journal of Business & Economic Statistics*, *22*(2), 129–162. https://doi.org/10.1198/073500104000000019

Pesaran, M. H., & Yamagata, T. (2008). Testing slope homogeneity in large panels. *Journal of Econometrics*, *142*(1), 50–93. https://doi.org/10.1016/j.jeconom.2007.05.010

Razzaq, A., Fatima, T., & Murshed, M. (2021). Asymmetric effects of tourism development and green innovation on economic growth and carbon emissions in top 10 GDP countries. *Journal of Environmental Planning and Management*, 1–30. https://doi.org/10.1080/09640568.2021.1990029

Razzaq, A., Sharif, A., Najmi, A., Tseng, M. L., & Lim, M. K. (2021). Dynamic and causality interrelationships from municipal solid waste recycling to economic growth, carbon emissions and energy efficiency using a novel bootstrapping autoregressive distributed lag. *Resources, Conservation and Recycling*, *166*, 105372. https://doi.org/10.1016/j.resconrec.2020.105372

Razzaq, A., Wang, Y., Chupradit, S., Suksatan, W., & Shahzad, F. (2021, April). Asymmetric inter-linkages between green technology innovation and consumption-based carbon emissions in BRICS countries using quantile-on-quantile framework. *Technology in Society*, *66*, 101656. https://doi.org/10.1016/j.techsoc.2021.101656

Sarkodie, S. A., & Strezov, V. (2019). Effect of foreign direct investments, economic development and energy consumption on greenhouse gas emissions in developing countries. *The Science of the Total Environment*, *646*, 862–871. https://doi.org/10.1016/j.scitotenv.2018.07.365

Shahbaz, M., Nasir, M. A., & Roubaud, D. (2018). Environmental degradation in France: The effects of FDI, financial development, and energy innovations. *Energy Economics*, *74*, 843–857. https://doi.org/10.1016/j.eneco.2018.07.020

Shahzad, S. J. H., Kumar, R. R., Zakaria, M., & Hurr, M. (2017). Carbon emission, energy consumption, trade openness and financial development in Pakistan: A revisit. *Renewable and Sustainable Energy Reviews*, *70*, 185–192. https://doi.org/10.1016/j.rser.2016.11.042

Shao, X., Zhong, Y., Liu, W., Li, R., & Y., M. (2021). Modeling the effect of green technology innovation and renewable energy on carbon neutrality in N-11 countries? Evidence from advance panel estimations. *Journal of Environmental Management*, *296*, 113189. https://doi.org/10.1016/j.jenvman.2021.113189

Sharma, S. S. (2011). Determinants of carbon dioxide emissions: Empirical evidence from 69 countries. *Applied Energy*, *88*(1), 376–382. https://doi.org/10.1016/j.apenergy.2010.07.022

Shen, Y., Su, Z. W., Malik, M. Y., Umar, M., Khan, Z., & Khan, M. (2021). Does green investment, financial development and natural resources rent limit carbon emissions? A provincial panel analysis of China. *The Science of the Total Environment*, *755*(2), 142538. https://doi.org/10.1016/j.scitotenv.2020.142538

Stucki, T. (2019). Which firms benefit from investments in green energy technologies? – The effect of energy costs. *Research Policy*, *48*(3), 546–555. https://doi.org/10.1016/j.respol.2018.09.010

Sun, Y., & Razzaq, A. (2022). Composite fiscal decentralisation and green innovation: Imperative strategy for institutional reforms and sustainable development in OECD countries. *Sustainable Development*, *30*(5), 944–957. https://doi.org/10.1002/sd.2292

Wang, L., Chang, H. L., Rizvi, S. K. A., & Sari, A. (2020). Are eco-innovation and export diversification mutually exclusive to control carbon emissions in G-7 countries? *Journal of Environmental Management*, *270*, 110829. https://doi.org/10.1016/j.jenvman.2020.110829

Wang, F., Rani, T., & Razzaq, A. (2022). Environmental impact of fiscal decentralization, green technology innovation and institution's efficiency in developed countries using advance panel modelling. *Energy & Environment*, 0958305X2210747. https://doi.org/10.1177/0958305X221074727

Weina, D., Gilli, M., Mazzanti, M., & Nicolli, F. (2016). Green inventions and greenhouse gas emission dynamics: A close examination of provincial Italian data. *Environmental Economics and Policy Studies*, *18*(2), 247–263. https://doi.org/10.1007/s10018-015-0126-1

Westerlund, J. (2007). Testing for error correction in panel data. *Oxford Bulletin of Economics and Statistics*, *69*(6), 709–748. https://doi.org/10.1111/j.1468-0084.2007.00477.x

WDI. (2021). World Development Indicators. Retrieved 1 June, 2022, from https://data.worldbank.org/country.

Xiong, Q., & Sun, D. (2022). Influence analysis of green finance development impact on carbon emissions: An exploratory study based on fsQCA. *Environmental Science and Pollution Research*, 0123456789. https://doi.org/10.1007/s11356-021-18351-z

Xuefeng, Z., Razzaq, A., Gokmenoglu, K. K., & Rehman, F. U. (2022). Time varying interdependency between COVID-19, tourism market, oil prices, and sustainable climate in United States: Evidence from advance wavelet coherence approach. *Economic Research-Ekonomska Istraživanja*, *35*(1), 3337–3359. https://doi.org/10.1080/1331677X.2021.1992642

Yang, X., Su, X., Ran, Q., Ren, S., Chen, B., Wang, W., & Wang, J. (2022). Assessing the impact of energy internet and energy misallocation on carbon emissions: New insights from. *Environmental Science and Pollution Research International*, *29*(16), 23436–23460.

Yang, X., Wang, J., Cao, J., Ren, S., Ran, Q., & Wu, H. (2022). The spatial spillover effect of urban sprawl and fiscal decentralization on air pollution: Evidence from 269 cities in China. *Empirical Economics*, *63*(2), 847–875. https://doi.org/10.1007/s00181-021-02151-y

Yii, K. J., & Geetha, C. (2017). The nexus between technology innovation and CO2 emissions in Malaysia: Evidence from granger causality test. *Energy Procedia*. *105*, 3118–3124. https://doi.org/10.1016/j.egypro.2017.03.654

Zhang, S., Liu, X., & Bae, J. (2017). Does trade openness affect CO2 emissions: Evidence from ten newly industrialized countries? *Environmental Science and Pollution Research International*, *24*(21), 17616–17625. https://doi.org/10.1007/s11356-017-9392-8

Zhang, M., Yang, Z., Liu, L., & Zhou, D. (2021). Impact of renewable energy investment on carbon emissions in China - An empirical study using a nonparametric additive regression model. *The Science of the Total Environment*, *785*, 147109. https://doi.org/10.1016/j.scitotenv.2021.147109