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RETRACTED: Financial Inclusion, Technological Innovations, and Environmental Quality: Analyzing the Role of Green Openness

Mahmood Ahmad[1], Zahoor Ahmed[2,3], Yang Bai[1], Guitao Qiao[1], József Popp[4,5] and Judit Oláh[5,6]*

[1]*Business School, Shandong University of Technology, Zibo, China,* [2]*Department of Business Administration, Faculty of Management Sciences, ILMA University, Karachi, Pakistan,* [3]*Department of Economics, School of Business, AKFA University, Tashkent, Uzbekistan,* [4]*John von Neumann University, Hungarian National Bank—Research Center, Kecskemét, Hungary,* [5]*Department of Public Management and Governance, College of Business and Economics, University of Johannesburg, Johannesburg, South Africa,* [6]*Faculty of Economics and Business, University of Debrecen, Debrecen, Hungary*

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***Correspondence:**
József Popp
popp.jozsef@uni-neumann.hu

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Undoubtedly, financial inclusion (FIN) contributes to economic development by enabling individuals and businesses, particularly small and medium enterprises, to access financial services. Financial inclusion may also have environmental implications; however, limited studies have looked into the nexus between financial inclusion and environmental quality. Also, the possible impacts of technological innovation and green openness remain unexplored in this nexus. In this context, this article probes the relationship between financial inclusion, technological innovation, green openness, and CO_2 emissions in BRICS countries while controlling for economic growth and energy consumption. Using the panel times series data from 2004 to 2018, this study uses advanced econometric techniques for empirical analysis robust to cross-sectional dependency and slope heterogeneity. The empirical results unveiled that FIN contributes to environmental degradation in BRICS countries. In contrast, technological innovation and green openness pose mitigating effects on emissions, thus promoting environmental sustainability. Environmental degradation is evidenced to enhance due to rising economic growth and energy utilization. Financial inclusion, technological innovation, and green openness Granger cause CO_2 emissions, but not the other way around. Further, technological innovation, green openness, and financial inclusion Granger cause each other. Based on the empirical results, this study recommends that BRICS countries should promote technological innovation, green openness, and at the same time, integrate financial inclusion with environmental policies to achieve climate-related goals.

Keywords: financial inclusion, technological innovation, green openness, environmental quality, BRICS

Abbreviations: CD, Cross-sectional dependence; CO_2, Carbon dioxide; CUP-FM, Continuously updated fully modified; CUP-BC, Continuously updated bias-corrected; EC, Energy consumption; FIN, Financial inclusion; GDP, Economic growth; GOP, Green openness; TI, Technological innovations.

INTRODUCTION

In recent decades, scholars have focused on investigating the drivers of environmental deterioration. In this regard, the literature has reached a consensus that the combustion of fossil energy sources is the prime cause of anthropogenic emissions and consequent climate change. In addition, a plethora of environmental research indicated that economic development is largely responsible for massive energy consumption and environmental deterioration (Saboori et al., 2014; Kanat et al., 2021; Khan et al., 2021; Oláh et al., 2021). Apart from this, studies have unfolded some other determinants, such as financial development, technological innovation, urbanization, globalization, trade openness (Ahmed and Le, 2020; Can et al., 2020; Rafique et al., 2020; Saud et al., 2020), and tourism services (Uslu et al., 2020; Halaskova et al., 2021) among others.

Scholars have given a lot of attention to the effect of financial development on environmental quality because financial development is indispensable for funding cleaner energy projects, and generally, the role of financial development in environmental deterioration is multifaceted. This is because funding cleaner energy technologies projects can benefit the environment but disregarding the environmental impacts of financial investments can stimulate environmental problems (Ahmed et al., 2021). Interestingly, the study of Chibba (2009) introduced the concept of financial inclusion and stated that financial inclusion can play a key role in alleviating poverty. Finical inclusion indicates the inclusiveness of a financial system based on different aspects, such as access to banking services, banking penetration, and usage of a banking system. More precisely, it is defined as the capability to use a variety of financial services and products, such as payments, savings, insurance, remittances, credit, etc. to fulfill the financial needs in an affordable, responsible, and convenient manner (World Bank, 2021).

Theoretical arguments suggest that financial inclusion can enhance or alleviate environmental degradation. For instance, financial inclusion enables small and medium enterprises and individuals to avail financial products and services conveniently at an affordable cost, which makes investments in cleaner technologies more viable (Le et al., 2020; Metzker et al., 2021). Cleaner technologies promote both economic development and environmental sustainability (Jordaan et al., 2017); hence, financial inclusiveness can contribute to CO_2 reduction through this channel. Financial inclusiveness can also be critical for fulfilling the financial requirements of farmers in remote areas where credit constraints limit the usage of green energy, such as solar energy which is considered an affordable clean energy source with less environmental deterioration (IPA, 2017). Also, limiting credit constraints can pave the way towards investment in cleaner energy because credit constraints hinder investment in green energy (Baulch et al., 2018). Conversely, economic activity is predicted to be boosted by growing financial inclusion, which in turn can stimulate energy demand and CO_2 emissions (Qin et al., 2021). Additionally, access to more financial services promotes manufacturing and industrial activities, infrastructure development, and the use of household and other appliances (Ahmad et al., 2021b). Hence, financial inclusiveness is expected to boost environmental deterioration through these channels.

Against this backdrop, investigating financial inclusion, technological innovation, green openness, and CO_2 association is the main aim of this empirical study. it is also an important factor that not only promotes financial products and services but also increases energy efficiency and environmental sustainability. According to Agyekum et al. (2021), improving technological infrastructure boosts credit supply and enhances financial inclusion. Innovation is also critical in increasing productivity and economic progress (Kihombo et al., 2021). Evidently, innovation spurs technological advancement which reduces energy and emissions levels (Mensah et al., 2018) According to Kihombo et al. (2021), curtailing the negative externalities of growth and a high level of technological innovation are required to develop a low-carbon green economy. Hence, it is important to take into account innovation when modeling the effects of financial inclusion on CO_2 emissions.

Besides, Can et al. (2021b) presented the green openness index and suggested that green trade could help to reduce environmental degradation. Thus, we included the green openness index in the model, which consists of environmentally preferable (EP) and traditional environmental (TE) goods. TE goods, (such as pollution control equipment) offer solutions to diverse environmental problems while EP goods (such as solar cars) pose less threat to the environment than their alternatives. Green goods need low energy consumption in their production (Paramati et al., 2021). According to Can et al. (2021a), green trading is a viable solution to establish a green economy that might help in achieving carbon neutrality targets.

Exploring the environmental effects of financial inclusion (FIN), green openness, and technological innovation in the context of BRICS is vital because of the rapid economic progress and massive contribution to world economic growth and environmental deterioration by this country group. Brazil, Russia, India, China, and South Africa (BRICS) have a combined GDP of more than 23% of global GDP, and they contribute a massive 42% to global CO_2 emissions. In addition, the countries, such as China, India, Russia, and Brazil are included among the top seven nations based on their CO_2 emissions and environmental deterioration (Khan et al., 2020). The role of FIN is important in the context of BRICS because these nations strive to accomplish more development, and their financial sectors are required to offer various products and services to fulfill the growing financial requirements of individuals and businesses. In addition, the countries like China, India, and Russia are major players in global trade; hence, studying the potential environmental effects of financial inclusion and green trading in the context of BRICS is reasonable.

Based on this background, this article quantifies the environmental impacts of financial inclusion (FIN), green openness, and technological innovation. As per the best of the authors' knowledge, this is the first study that explores the relationship between financial inclusion, technological innovation, and CO_2 emissions in BRICS nations. Additionally, to empirically assess the influence of green trading on CO_2 emissions, this study includes the green openness index in the model. The authors have not found any empirical research that looked into the impact of green trading on CO_2 emissions in the BRICS economies. Furthermore, the study relied on reliable econometric approaches, such as CUP-FM and CUP-BC methods introduced by Bai et al. (2009), to get robust and reliable long-run findings. The Dumitrescu and Hurlin (2012) panel causality test is also applied to find the causal directions of the linkage between FIN, technological innovation, green openness, and CO_2 emissions.

The remainder of this article is organized as follows. *Literature Review Section* summarizes the literature review and identifies the literature gap. *Materials and Methods Section* provides the theoretical framework, model construction, data, and empirical methods. The empirical findings and discussion are presented in *Results and Discussion Section*. *Conclusion and Policy Implications Section* concludes this work and provides policy recommendations.

LITERATURE REVIEW

Indubitably, a vibrant financial sector can reduce poverty, contributes to economic development, and enhance climate resilience. In recent literature, some studies empirically evaluated the linkage between environmental sustainability and FIN but found contradictory outcomes. For instance, Le et al. (2020) used Driscoll–Kraay SEs for linear panel models to explore the relationship between FIN and environmental deterioration in 31 Asian countries over 2004–2014. Their results show that FIN, when combined with other control variables, such as urbanization, energy use, GDP, and FDI, fuels environmental degradation. Their results suggested that financial inclusion should be aligned with climate policies to nullify the adverse effect of financial inclusion on emissions. Using the GMM method, during the period 2004–2014, Renzhi and Baek (2020) investigated the influence of FIN on carbon emissions in 103 countries. Their findings demonstrated the inverted U-shaped association between FIN and emissions. They highlighted that a higher degree of FIN could curb environmental degradation. In the case of OECD countries, Hussain et al. (2021) studied the impact of FIN and infrastructure on ecological footprint. Their results unveil that FIN deteriorates the environmental quality by increasing ecological footprint while infrastructure is found to disrupt the environmental quality of OECD countries. Likewise, Rehman et al. (2022) examined the impact of FIN and CO_2 in 65 countries from 2004 to 2017 by including national governance to the model. Their results also support that FIN escalates environmental degradation. They further highlighted that national governance negatively and significantly moderates the relationship between FIN and CO_2 emissions.

Recently, Qin et al. (2021) employed panel quantile regression analysis to investigate the linkage between FIN and CO_2 emissions for seven emerging countries over 2004–2016. Their results suggested that FIN positively and significantly affects CO_2 emissions at the 25th and 50th quantiles; however, it does not influence CO_2 at 75th and 95th quantiles. They also suggested enhancing degrees of financial inclusivity to lower the adverse impact of the FIN on environmental quality. Likewise, Chaudhry et al. (2021) also studied the linkage between FIN and ecological footprint (EF) from 2004 to 2018 for 24 OIC member countries. Their study used the dynamic common correlated effects method and found that FIN is significantly and positively correlated with environmental degradation. On the contrary, Du et al. (2022) claimed that FIN improves the environmental quality of selected emerging countries as it is negatively connected with CO_2 emissions.

In the 21st century, countries worldwide are experiencing the Fourth Industrial Revolution wave, and technological innovation is considered one of the important elements to accomplish the SDGs. In this perspective, several studies revealed that technological innovation could be helpful to improve environmental quality, while some studies either found that technological innovation degrades environmental quality or does not affect emissions. For instance, Yii and Geetha (2017) explored the impact of technological innovation on environmental quality in the case of Malaysia. In the short run, their results indicated that innovation in technology is negatively associated with CO_2 emissions. While technological innovation poses an insignificant effect in the long term. Further, their results suggested promoting innovation without any postponement for the sake of economic and environmental sustainability. Henriques and Borowiecki (2017) observe the relation between technological innovation and environmental quality for Europe, North America, and Japan. They conclude that technological innovation mitigates environmental degradation. Further argues that energy transition and technological change have become important contributors to the decreasing levels of emissions in Europe during the last decade.

Lin and Zhu (2019) studied the association between renewable energy technologies and environmental quality in China. The linear regression model confirms that renewable technologies negatively impact CO_2 emissions, implying that renewable energy technologies promote a low-carbon society in China. Ahmad et al. (2020) analyzed the dynamic association between technological innovation and EF in 22 selected emerging countries and reported that technological innovation is the prime offsetting factor in footprint reduction. Wang et al. (2020) found that technological innovation promotes environmental sustainability and further recommended promoting innovation and clean energy use to achieve goals set by COP21 in the N-11 economies. Likewise, Guo et al. (2021) also confirmed the negative correlation between environmental degradation and technological innovation in China. They argued that technological innovation can help to achieve sustainable development goals (SDGs). Likewise, according to Sinha et al. (2020), technological innovation can help to achieve SDGs.

On the other hand, Samargandi (2017) revealed that technological innovation is futile in reducing CO_2 emissions in Saudi Arabia, which depicts that the innovation of technologies is not in the right direction to decrease environmental deterioration.

Further authors suggested that increasing technological progress, particularly in the production process, will reduce CO_2 emissions without harming economic growth. Recently, Adebayo et al. (2021) also found a similar outcome in Chile that technological change failed to decrease consumption-based carbon emissions. Chen and Lee (2020) revealed that technological innovation has no significant relationship with carbon emissions for the global sample. However, their group-wise analysis depicts that technological innovation in high-income countries effectively curbs CO_2 emissions. Besides, scholars have extensively examined the impact of trade on environmental quality. However, only one study is available that investigates the impact of green openness (trading green products) on environmental quality. For instance, Can et al. (2021a) studied the influence of green openness on CO_2 emission for the selected 31 OECD countries from 2007 to 2017. Their empirical results unveiled that green openness negatively affects CO_2 emissions, which portrays that green openness improves environmental quality.

Summing up this discussion, it can be concluded that limited investigations have looked into the effects of financial inclusion on CO_2 emission and illustrated inconsistent results. Besides, the linkage between technological innovation, green openness, financial inclusion, and CO_2 emissions remained unexplored. Further, the literature is silent on how green openness affects environmental quality in BRICS countries. Moreover, previous literature on financial inclusion and environmental quality nexus frequently overlooks cross-sectional dependence (CD) in panel data, resulting in unreliable estimates. As a result, there is a significant gap in the existing studies that must be tackled by using a more advanced estimating technique and examining the role of financial inclusion, technical innovation, green openness, and environmental quality.

MATERIALS AND METHODS

Theoretical Framework and Model Construction

The financial sector plays an important role in facilitating transactions, mobilization and utilization savings, and monitoring financial flows towards productive activities (Puatwoe and Piabuo, 2017). Financial development is inextricably linked to FIN, which fosters the development of financial sectors and institutions and contributes to GDP (Kim et al., 2018). However, the environmental impact of FIN in the literature has documented equivocal evidence. On the one hand, it is assumed that FIN can help to improve environmental quality. For instance, individuals and organizations can benefit from FIN by having easier access to financial services, which can help them implement environmentally friendly technologies. Moreover, improved access to financial services is particularly pertinent for the farmers and low-income households, where they may not have the accessibility of capital and credit facilities to invest in green energy technologies, such as solar and thermal small energy grids, which produce less expensive energy than fossil fuels with less pollution (IEA, 2019). On the other hand, easier access to finance boosts industrial and manufacturing activities, which in turn leads to higher energy use that may create more pollution. Increasing FIN can also speed up access to finance, allowing customers to buy energy-intensive appliances like air conditioners, automobiles, and refrigerators that can boost CO_2 (Wang et al., 2021). In this regard, financial inclusion brings a detrimental impact on environmental quality.

There is growing consensus that technological advancement significantly promotes FIN and environmental sustainability (Senyo and Osabutey, 2020; Ahmad et al., 2021a). Therefore, technological innovation is considered among the viable solutions to combat ecological deprivation and climate change. Endogenous growth theory and ecological modernization theory also support the notion that innovation may help countries achieve sustainable development without affecting the environment (Aghion et al., 1998; Buttel, 2000). However, some scholars believe that technology innovation is a two-edged sword that may increase or alleviate environmental damage. Recent advancements in technologies have made it easier for humans to access natural resources, causing more and more natural oil and mineral depletion. This has resulted in an imbalance of the ecosystem and an increase in environmental pollution.

Theoretically, openness to trade can affect the environmental quality through three main paths (i.e., scale, composition, and technique) (Antweiler et al., 2001). The scale effect refers to the increase in production level causing more environmental pollution. The composition effect specifies that the environmental impact of trade openness is influenced by the industry's structure. Depending on a country's environmental policies and resource abundance, this could be beneficial or detrimental. The technique effect specifies that an increase in income and advancement in technologies promote environmentally friendly production, which lessens environmental pollution (Managi et al., 2009).

Based on the theoretical framework, the model specification for this study is given as:

$$Co_{2_{it}} = \alpha_0 + \beta_1 FIN_{it} + \beta_2 TI_{it} + \beta_3 GOP_{it} + \beta_4 GDP_{it} + \beta_5 EC_{it} + \varepsilon_{it} \tag{1}$$

In **Eq. 1**, CO_2 is the dependent variable indicating carbon dioxide emissions per capita, whereas FIN, TI, GOP, GDP, and EC are the explanatory variables that denote financial inclusion, green openness, economic growth, and energy use, respectively. The symbol "i" characterizes the cross-sections, t indicates the time dimension, α and μ represent the constant and error term, respectively. Variables are converted to a logarithmic form before being used in the empirical analysis, except for financial inclusion because principal component analysis (PCA) is used to construct financial inclusion index.

Data

This article uses the annual data set from 2004 to 2018 for Brazil, Russia, India, China, and South Africa (BRICS). The duration of the research is based on data availability for key variables, such as CO_2 emissions and green openness. The

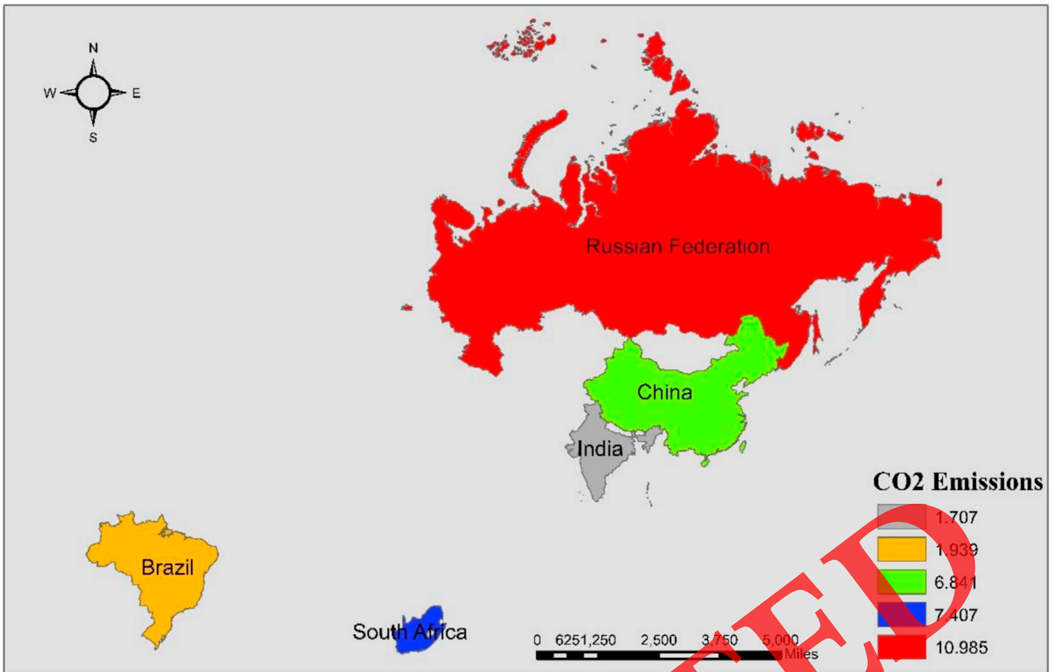

FIGURE 1 | CO_2 emission spatial distributions in BRICS countries for the year 2018. Data Source: IEA (2020).

TABLE 1 | Variable's description.

Variable	Symbol	Measurement	Source
Carbon emission	CO_2	Carbon dioxide emissions (tons per capita)	IEA
Financial Inclusion	FIN	It is an index based on (a) number of ATMs per 100,000 adults, (b) the number of branches of commercial banks, (c) number of commercial banks, (d) outstanding commercial bank loans (% of GDP), and (e) commercial banks' outstanding deposits (% of GDP)	IMF
Technological Innovation	TI	Patent applications (resident + non-resident)	WDI
Green openness	GOP	Green trade openness index	BASSRL
Economic growth	GDP	Per capita constant 2010$	WDI
Energy consumption	EC	kg of oil equivalent per capita	BP

Note. IEA, International Energy Agency; IMF, International Monetary Fund; WDI, World Development Indicators; BASSRL—BETA, akademi social science research lab; BP—BP, statistical renew of world energy.

selection of the starting period of 2004 is linked with financial inclusion data, and the period ended in 2018 is knotted with the data availability of CO_2. This study chooses CO_2 emission (tons per capita) for environmental quality, and its data is retrieved from the International Energy Agency. **Figure 1** depicts the distribution of CO_2 emissions in the BRICS countries indicating that the Russian federation is emitting very high emissions as compared to other panel countries. The five components of the financial inclusion (FI) index are produced through PCA based on five indicators. These elements include the number of ATMs per 100,000 adults, the number of branches of commercial banks, the number of commercial banks, outstanding deposits kept within commercial banks (% of GDP), and the outstanding loans from commercial banks (% of GDP). Technological innovation (TI) is defined as the patent applications of residents and non-resident, and its data is obtained from World Bank. The green openness index (GOP) is based on the country's import and export of green goods as a percentage of GDP. GOP index ranges between 0 and 100 and its higher values indicate greater green openness. GOP data is only available until 2016; therefore, linear interpolation is used to extend it until 2018. GOP index was introduced by Can et al. (2021b) and further improved by Can et al. (2021a). Economic growth (GDP) and energy consumption (EC) are measured by GDP per capita and per capita (kg of oil equivalent) respectively. The data and variables description is provided in **Table 1**.

Estimation Strategy

The empirical methodology of the study consists of seven steps described in **Figure 2**. The particulars of each step are provided in the subsequent subsections.

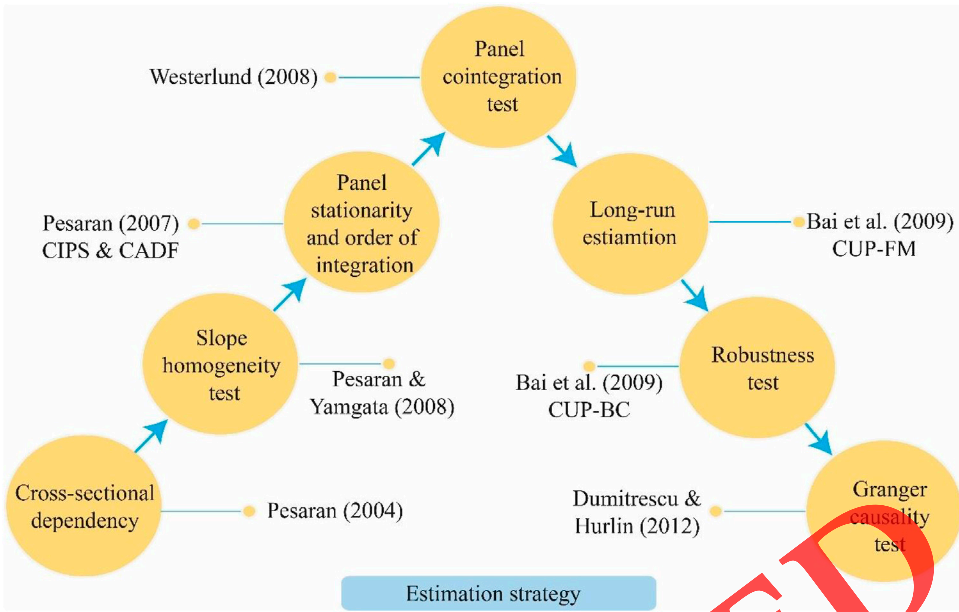

FIGURE 2 | Empirical estimation methods.

Cross-Sectional Dependence Test

In recent years, economies have been interrelated through several social, economic, and cultural channels. Therefore, the integration of economic development and the political system usually leads to interdependences, which could adversely affect the first-generation estimators' reliability. This study uses the (Pesaran, 2004) CD test to know about the possible interdependence in our data because this is necessary to choose suitable estimators for providing robust and reliable estimates. The test statistics for CD are given below.

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

Where $\hat{\rho}_{ij}$ represent the pair-wise residual correlation.

Slope Homogeneity Test

Further, the issue of slope heterogeneity may arise in panel data analysis because countries have varying rates of innovation and economic and demographic structure. Thus, to counter the issue of slope heterogeneity, the Pesaran and Yamagata (2008) method is used. The equation for this test can be written as:

$$\Delta_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}S-k\right) \qquad (3)$$

$$\Delta_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}S-k\right) \qquad (4)$$

Δ_{ASH} illustrates the adjusted delta tilde and Δ_{SH} indicates the delta tilde.

Panel Unit Root Tests

The conventional unit root test namely Fisher-ADF, Levin-Lin-Chu (LLC), Choi test, and Im, Pesaran, and Shin do not perform effectively in the presence of slope heterogeneity and CD. Therefore, in order to solve this problem, this article uses the second-generation unit root test of Pesaran (2007) (CIPS and CADF methods) to observe the stationary properties of the studied variables. The test equation is given as:

$$\Delta ZA_{i,t} = \varphi_i + \varphi_i X_{i,t-1} + \varphi_i \overline{ZA}_{t-1} + \sum_{l=0}^{p}\varphi_{il}\Delta\overline{ZA}_{t-1} + \sum_{l=0}^{p}\varphi_{il}\Delta ZA_{i,t-1} + \mu_{it} \qquad (5)$$

The averages of the cross-section are $\overline{ZA}_{t-1}$ and $\Delta\overline{ZA}_{t-1}$, respectively. The CIPS test statistics are as follows:

$$CIPS = \frac{1}{N}\sum_{i=1}^{n}CDF_i \qquad (6)$$

Panel Cointegration Tests

Before estimating the long-term parameters, the cointegration between the studied variables should be examined. We utilize a panel cointegration test developed by Westerlund (2008). This method has more power due to its flexibility to counter CD through common factors. It permits stationary regression in its assessment. The Durbin–Hausman can be given as follows:

$$DH_g = \sum_{i=1}^{n}S_i(\phi_i + \phi_i)^2\sum_{t=2}^{T}\hat{e}_{it-1}^2 \qquad (7)$$

TABLE 2 | Test results of CD.

Variable	Test stat	Prob	Corr	Abs(corr)
CO_2	4.272*	0.000	0.349	0.485
FIN	5.672*	0.000	0.463	0.530
TI	6.697*	0.000	0.547	0.547
GO	1.107	0.268	0.090	0.292
GDP	10.558*	0.000	0.862	0.862
EC	3.053*	0.002	0.249	0.743

*Note: The symbol * represents the 1% significance level.*

$$DH_p = S_n(\phi + \phi)^2 \sum_{i=1}^{n} \sum_{T=2}^{T} \hat{e}_{it-1}^2 \tag{8}$$

Long-Run Estimation

In the presence of FIN, technological innovation, and green openness, the Continuously Updated Fully Modified (CUP-FM) technique is used to investigate the long-run relationship between FIN and environmental quality. Furthermore, as a robustness test, this paper utilizes the Continuously Updated Bias-Corrected (CUP-BC) approach. These estimation methods perform better than conventional estimation techniques like DOLS, FMOLS, and DSUR. The FMOLS and DOLS provide robust results against the endogeneity and residual correlation problem but assume that cross-sections are independent. In contrast, DSUR can be used to counter the issue of CD but has limitations in not handling the serial correlation and endogeneity. Therefore, this article employs the CUP-BC and CUP-FM estimation techniques of Bai et al. (2009), which are robust to CD, slope heterogeneity, serial correlation, and endogeneity problem. The test equation can give as:

$$\widehat{B}cup, \widehat{F}cup = argmin \frac{1}{nT^2} \sum_{i=1}^{n} (y_i - x_i\beta)' M_F (y_i - x_i\beta) \tag{9}$$

Panel Granger Causality Test

Although the long-run estimation results provide significant information about the long-run effects of variables on CO_2, the causal relationship may also be important for policy measures. The current study uses the D and H (2012) causality test to examine the causal connection among variables. The test equation is given as.

$$G_{i,t} = \phi_i + \sum_{j=1}^{p} \lambda_i^j G_{i,t-j} + \sum_{j=1}^{p} \gamma_i^j T_{i,t-j} \tag{10}$$

RESULTS AND DISCUSSION

Before initiating the formal empirical analysis, we examine the CD and slope heterogeneity among the selected variables. **Table 2** depicts the outcome of the CD and rejects the null hypothesis of cross-sectional independence. The BRICS countries have a variety of economic and financial agreements, and they trade significantly with one another. Therefore, these countries are strongly interconnected, which is evident from the CD test results.

TABLE 3 | slope heterogeneity test results.

Test	Value	*p*-value
$\tilde{\Delta}$	3.996*	0.000
$\tilde{\Delta}_{adjusted}$	5.471*	0.000

*Note: The symbol * represents the 1% significance level.*

TABLE 4 | Panel unit root test results.

Variable	CADF		CIPS	
	Level	First-difference	Level	First-difference
CO_2	−1.397	−3.610*	−1.146	−2.403**
FIN	−2.002	−3.281*	−1.823	−3.045*
TI	−1.559	−3.087*	−1.289	−3.087*
GO	−1.098	−3.909*	−1.098	−3.909*
GDP	−1.502	−3.360*	−1.951	−3.753*
EC	−2.141	−3.427*	−1.857	−3.656*

*Note: The symbol * and ** represent 1 and 5% significance levels, respectively.*

TABLE 5 | Westerlund (2008) panel cointegration test.

	Value	*p*-value
DH_g	−2.018**	0.022
DH_p	−1.590***	0.056

*Note: The symbols ** and *** represent 5 and 10% significance levels, respectively.*

Despite strong integration, BRICS countries have a varying rate of technological innovation and demographic and economic structure that may lead to slope heterogeneity problems leading to biased estimates. In **Table 3**, the Pesaran and Yamagata (2008) test outcome indicates the presence of country-specific heterogeneity in our panel dataset of BRICS countries.

After checking the CD and slope heterogeneity, the stationary properties of the variables are investigated using CADF and CIPS tests. The outcomes in **Table 4** show that variables have unit root problems at the level; however, after taking the first difference, all variables became stationary.

After checking the stationarity properties, the panel cointegration test was used in this study, and the findings are exhibited in **Table 5**. The Westerlund (2008) cointegration test shows that the test results of the panel (DHp) and group (DHg) values are significant at the 5 and 10% level. Thus, the findings indicate the presence of a cointegration relationship among variables.

After performing these initial investigations, the CUP-FM and CUP-BC methods were used to estimate long-run elasticities in this study, and **Table 6** summarizes the findings. The coefficient of financial inclusion (FIN) is significant and presents a positive relationship with carbon emission. Numerically, a 1% raise in FI increases CO_2 emissions by 0.159% in the long run. This result shows that improved financial access in BRICS countries could enable citizens to purchase large-ticket products such as air

TABLE 6 | Long-run estimation results.

Variables	CUP-FM		CUP-BC	
	Coefficients	T Stats	Coefficients	T Stats
FIN	0.159*	2.815	0.165*	3.161
TI	−0.062**	−1.879	−0.070**	−2.277
GTO	−0.073*	−3.847	−0.061*	−3.621
GDP	0.174*	3.698	0.177*	4.071
EC	0.339*	6.469	0.355*	7.210

*Note: * and ** depict 1 and 5% significance level, respectively.*

conditioners, automobiles, and other electronic devices, which can raise energy demand resulting in environmental pollution. Our results portray that the FIN strategies seem ineffective in these countries and lack synergies between climate change policies and financial inclusion initiatives. Our findings coincide with that of Le et al. (2020); Hussain et al., 2021), Rehman et al. (2022), and Qin et al. (2021). However, these estimates contradict the result of Renzhi and Baek (2020) and Du et al. (2022) who claim that FIN can be used as a mitigating instrument to curb environmental degradation.

The results further indicate that technological innovation (TI) shows a negative relationship with carbon emissions. The significant negative coefficient unfolds that TI reduces CO_2 emissions in BRICS countries i.e., a 0.062% reduction in CO_2 emissions can be attained by a 1% increase in TI. This result suggests that technological innovation plays an important role in promoting environmental sustainability in BRICS countries. This is plausible because technological innovation creates a more sustainable industrial structure and improves environmental quality (Cheng et al., 2021). Our findings correspond to those of Ahmad et al. (2020), Danish and Ulucak (2021), and Erdogan (2021). However, these results are not in conformity with Santra (2017), who reported a positive connection between technological innovation and environmental degradation.

Similar to technological innovation, the coefficient of green openness (GTO) indicates a negative relationship with carbon emissions. Further, green trade decreases CO_2 emissions in the BRICS nations with an elasticity of 0.073, suggesting that increasing green trade by 1% will curb emissions by 0.073%. This implies that the import and export of green products seek less energy consumption and thereby exert minimal pressure on the environment. Additionally, it implies that international trade

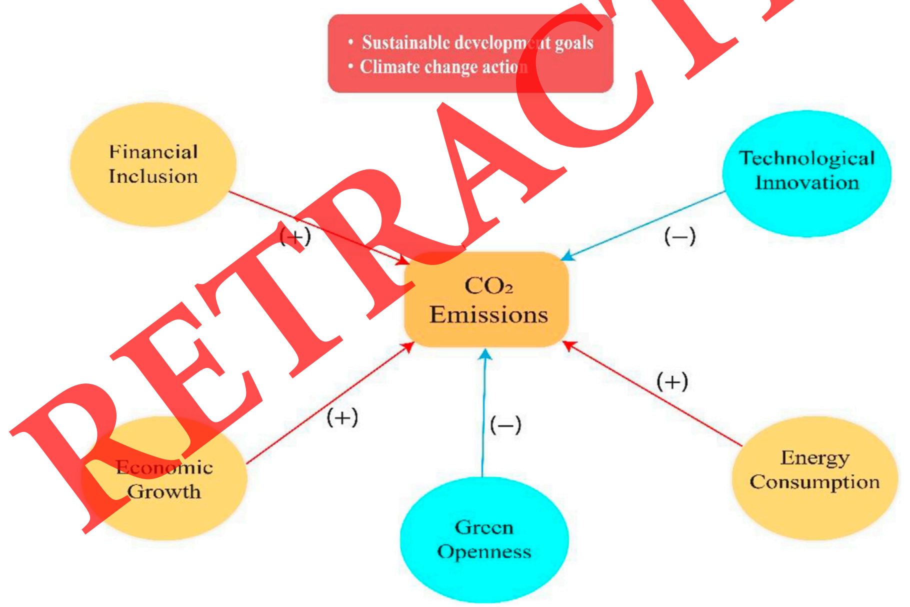

FIGURE 3 | Long-run results.

TABLE 7 | Panel Granger causality test results.

Variables	CO_2	FIN	TI	GTO	GDP	EC
CO_2	— —	3.121* (0.002)	2.282** (0.022)	1.932*** (0.053)	2.064** (0.039)	3.590* (0.000)
FIN	1.260 (0.208)	— —	9.563* (0.000)	2.316** (0.020)	7.474* (0.000)	1.137 (0.255)
TI	0.616 (0.538)	2.50** (0.012)	— —	2.639* (0.008)	2.500** (0.012)	1.450 (0.147)
GTO	1.052 (0.293)	2.140** (0.032)	3.590* (0.000)	— —	1.823*** (0.069)	1.579 (0.114)
GDP	2.359** (0.018)	3.313* (0.000)	3.268* (0.001)	5.244* (0.000)	— —	3.439* (0.000)
EC	1.801*** (0.072)	1.863*** (1.035)	1.741*** (0.082)	1.372 (0.170)	4.724* (0.000)	— —

*Note: *, **, and *** depict the significance level at 1, 5, and 10%, respectively. ( ) contain the P-values.*

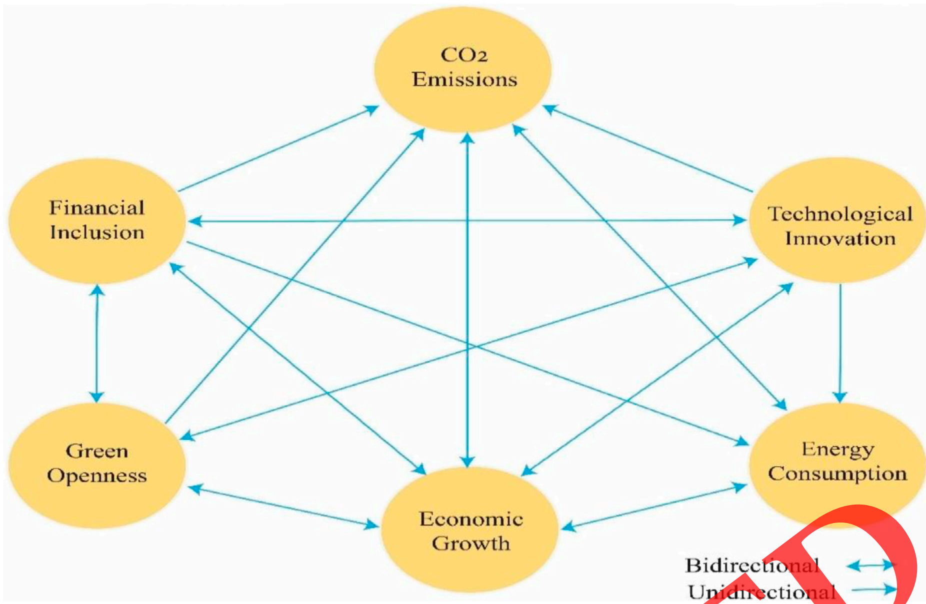

FIGURE 4 | Panel Granger causality results.

through green products contributes significantly to improving environmental quality in BRICS countries. As a result of this condition, the countries can enhance their green trade while protecting environmental quality. This finding supports the view of Can et al. (2021a), who document that green openness abates environmental degradation in OECD countries.

Further, the findings demonstrate that GDP poses a positive effect on environmental degradation. Statistically, a 0.174% increase in CO_2 emissions is caused by GDP. There are several main reasons for this result. Firstly, over the last two decades, the BRICS countries have experienced remarkable development, their per capita GDP (constant $) grew from US$ 5524.98 to US$ 8067.03 during 2004–2018. It portrays that economic expansion in BRICS countries is attained at the cost of environmental quality. Secondly, the prime reason for increasing emissions in BRICS countries is the reliance on conventional energy sources. This conclusion is similar to the findings given by Ahmed et al. (2021) for G7 countries, Ahmed et al. (2020) for China, and Shahbaz et al. (2013) for Indonesia. The results contradict the findings of Salahuddin et al. (2016), who indicated that GDP has no significant long-run and short-run impact on CO_2 emissions in OECD economies. Also, this result opposes the finding of Ozcan et al. (2020), who indicated a negative relationship between economic growth and CO_2 emissions.

Finally, in the BRICS countries, energy consumption (EC) was found to intensify CO_2 emissions. Numerically, a 1% expansion in EC can raise the CO_2 emissions by 0.339%. This means that energy use creates environmental pressure on the BRICS nations. These findings are reasonable because these nations depend on traditional energy sources to meet their increasing energy demand, and non-renewable energy (e.g., oil, coal, and gas) meets approximately 86 percent of total energy demand. These results coincide with earlier studies of (Rahman and Kashem, 2017) for Bangladesh and (Ulucak et al., 2020) for OECD economies. The long-run estimation results from CUP-FM and CUP-BC are graphically presented in **Figure 3**.

Following the long-run elasticity evaluation, the Dumitrescu and Hurlin (2012) panel Granger causality test is used. The outcomes in **Table 7** depict the unidirectional causal linkage running from financial inclusion, technological innovation, and green openness to CO_2 emissions. This means that any policy associated with financial inclusion, technological innovation, and green openness will have an impact on CO_2 emissions. The results depict that bidirectional causality exists between technological innovation and financial inclusion. Thus, an increase in technological innovation will also boot financial inclusion and vice versa. We also found bidirectional causality between green openness, technological innovation, and financial inclusion. The results further indicate the bidirectional causal association between energy use, economic growth, and CO_2 emissions. Economic growth, energy consumption, and emissions all have a strong link, according to these findings. Therefore, it will be challenging for BRICS countries to curb CO_2 emissions without affecting energy consumption and economic growth. The panel Granger causality results are given in **Figure 4**.

CONCLUSION AND POLICY IMPLICATIONS

During the last two decades, financial inclusion and technological innovation have dramatically augmented the accessibility and affordability of financial services and contributed to economic development; however, their environmental implications cannot be overlooked. Limited studies assess the relationship between financial inclusion and environmental degradation; however, research integrating financial inclusion and technological innovation in the same environmental policy framework is still scant. In this context, the impact of financial inclusion, technological innovations, green openness, GDP, and energy consumption on CO_2 emissions in BRICS countries is investigated. This study relied on advanced empirical estimation methods, such as CUP-FM and CUP-BC for long-run empirical estimation, which counter the issue of slope heterogeneity and CD. According to the empirical study, financial inclusion, economic growth, and energy consumption all increase CO_2 emissions. In contrast, technological innovation and green openness decrease CO_2 emissions. Further, according to the findings, economic development and energy consumption both intensify environmental degradation. The causal outcomes reveal that CO_2 emissions are caused by financial inclusion, technical innovation, and green openness, but not the other way around. Further, technological innovation, green openness, and financial inclusion Granger cause each other.

These results have significant policy implications for improving environmental quality in BRICS countries. Firstly, to address the negative impact of financial inclusion on CO_2 emissions, policymakers should integrate financial inclusion with climate change policies at the local, national, and regional levels. Further to reverse the trend, policymakers should expand the access and inclusiveness of green finance to individuals, micro, small and medium-sized enterprises in a more accurate direction, enabling them to adopt environmental sustainability actions.

Secondly, policies should be designed to increase the number of patents as technological innovation positively impacts environmental sustainability. Furthermore, the government should allocate more funds and offer subsidies and tax benefits to support research and development activities. Thirdly, to achieve carbon neutrality goals, policymakers should expand the market of ecologically beneficial products. To do this, inter-government long-term agreements on the trade of green products and reducing tariffs could be initiated for the betterment of environmental quality. Fourthly, since economic growth is found to be associated with environmental degradation, the BRICS countries should redesign their economic development policies. The BRCIS economies should adopt a sustainable production and consumption pattern that will aid in the achievement of the Sustainable Development Goals (SDG-8 and 13). Finally, energy consumption is a significant factor in environmental damage. This means that the existing energy consumption policies in BRICS countries need to be restructured. To fulfill the economic requirements, the BRICS countries rely significantly on fossil fuels and non-renewable energy. Notably, assisting various organizations in exploring clean energy sources and investing in clean energy innovation will be preferred options to achieve Sustainable Development Goals (SGD-7).

The scope of this article is limited to BRICS countries and only a limited number of variables are considered for a short period of 2004–2018. An in-depth study on the direct and indirect impact of financial inclusion on environmental quality can be conducted by adding its interaction terms with different variables. Also, the impact of financial inclusion on various environmental indicators can be studied and comparison can be made for interesting findings.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

MA: Conceptualization, data curation, formal analysis, visualization, writing original draft. ZA: Conceptualization, Writing original draft. YB: writing—review, and editing. GQ: writing—review and editing, supervision. JP: writing—review, and editing, funding acquisition. JO: supervision, project administration, writing—review, and editing.

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