Technology in Society 70 (2022) 102037

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Can technological innovation, foreign direct investment and natural resources ease some burden for the BRICS economies within current industrial era?

Bright Akwasi Gyamfi [a], Divine Q. Agozie [b], Festus Victor Bekun [c,d,e,*]

[a] Economic and Finance Application and Research Center, İstanbul Ticaret University, Turkey
[b] University of Ghana, Business School, Department of Operations and Management Information Systems, Ghana
[c] Faculty of Economics Administrative and Social Sciences, Istanbul Gelisim University, Istanbul, Turkey
[d] Adnan Kassar School of Business, Department of Economics, Lebanese American University, Beirut, Lebanon
[e] Department of Economic Security, South Ural State University, 76, Lenin Aven., Chelyabinsk, 454080, Russia

ARTICLE INFO

Keywords:
Environmental sustainability
Industrialization
Technological innovation
Carbon-reduction
Panel econometrics
BRICS economies

ABSTRACT

Economic advancement has tended to affect the processes of industrialization, which has increased the value of exploited natural resources via the application of technology. Intensive use of natural resources via total reserves, technological innovation, foreign direct investment (FDI), and renewable energy can have an impact on the environment. Considering this, the present study investigates the nexus between industrialization, total reserves, inflows of FDI, technical innovation, renewable and natural resources, and CO_2 emissions in the case of BRICS. To this end, annual frequency data for BRICS from 1990 to 2019 are employed in panel framework. The study employs a battery of econometric techniques, namely the Augmented Mean Group (AMG), Common Correlated Effects Mean Group (CCEMG), and Driscoll-Kraay estimators to explore the underlined relationship. The cointegration results based on Westerlund, J. (2007) show that there exists a long-run equilibrium relationship between the study outlined variables over the investigated period. From the empirical analysis, technological innovation and renewable energy both reduce CO_2 emissions while industrial value-added, natural resources, FDI and total reserves contribute to the degradation of the environment. Additionally, the interaction between industrial value-added and technological innovation also has negative impact on the BRICS countries' environment. Based on these outcomes, the BRICS economies are enjoined to pursue green technology growth without compromise for environmental quality in the bloc. Finally, numerous significant policy ramifications for protecting environmental quality in BRICS economies have been proposed in the concluding section.

1. Introduction

The debate on sustainable development goals (SDGs) and the nature of economic and social developments presents a greater need to extend the existing arguments and new trends on green growth. Due to growing variations in atmospheric conditions and global warming concerns there are perceived threats to human existence, prosperity, and natural resource security [2]. Abbasi et al. [3]; for example, report that the global greenhouse gas emission is composed of 75% of carbon dioxide, and this is a consequence of the current global warming and anthropogenic climate consequences faced by the world. An increase in greenhouse gas (GHG) emission drives global warming [4,5]. Likewise micro and macro-economic engagements such as increased demand for energy, natural resource exploitation, inefficient production and urban pollution trends contribute to generating more CO_2 which worsens the issue of atmospheric pollution and environmental degradation [3,6]. Relative to greenhouse gas and environmental pollution assessment, much of the literature shows significant concentration on carbon dioxide since it contributes the most to GHG [7]. Indeed, the share of carbon emission in the atmosphere is substantially high and has been linked with the occurrence of events such as rising sea levels, high temperatures, droughts, and fast-melting glaciers [8].

Industrial expansion is globally highlighted to be at the core of pollutant emissions and has two broad effects [9] Thus, although industrialization contributes positively to the economic growth of an economy (like GDP growth) – the economic expansion effect, it is also a

* Corresponding author. Faculty of Economics Administrative and Social Sciences, Istanbul Gelisim University, Istanbul, Turkey.
E-mail addresses: bagyamfi@ticaret.edu.tr (B.A. Gyamfi), dagozie@ug.edu.gh (D.Q. Agozie), fbekun@gelisim.edu.tr (F.V. Bekun).

https://doi.org/10.1016/j.techsoc.2022.102037
Received 18 February 2022; Received in revised form 13 June 2022; Accepted 13 June 2022
Available online 16 June 2022

significant pollution source to the environment (environmental quality effect) [10]. This assertion holds true especially for emerging or industrializing countries like the BRICS bloc, who rely largely on nonrenewable energy sources and energy inefficient technologies ([4,5,11–14]). This is contrary to developed industrialized economies which operate more advanced production methods and efficient technology that reduce the harmful ecological effects [4,5,7]. By implication, technological innovations in industrialization may play a significant role relevant to environmental quality. This is endorsed by the fact that, at the inception of industrialization, industrial activities contribute negative consequences to the environment, whereas, at later stages, efficient technology utilization expands and industrial production improves environmental quality as well as drives the facilitation of efficient production methods that mitigate adverse environmental consequences (Adedoyin et al., 2021; [2].

Moreover, consistent with industrialization is the phenomenon of financial development, which could impact economic growth and the environmental sustainability [15]. However, this assertion is not found to be entirely true for environmental quality objectives. Financial development can drive the process of industrialization to explore cleaner and efficient energy sources and sustainable consumption [16], or otherwise drive the vast exploitation of natural resources due to increased capacity and investment inflows which subsequently increases the occurrence of adverse consequences on the environment [17]. For example, natural resource depletion due to industrialization increases deforestation and mining, surface soil destruction, etc., which impact air quality and worsens global warming [17]. Thus, natural resource use, although crucial for industrialization, at the same time is a culprit for environmental pollution [18]. This consideration amplifies the need for deeper understanding into environmental quality factors like natural resource utilization, financial development, and industrialization [2].

It is shown that economic expansion drives urban population growth, and demand for energy [19]; however, they are reported to have negative impact on environmental quality, as such suggesting a path for decision-makers and policy experts to consider toward improving environmental quality [4,5]. Several examinations exist on the role of these factors, including other pertinent factors like renewable energy, natural resources use, industrialization and economic expansion, on environmental quality [4,19–22] but few have sought to discern their effect on ecological footprints, which is a crucial determinant of environmental quality [2]. This study seeks to contribute to this issue gap, by attempting to extend the literature on these relationships, especially where a litany of mixed observations exists on this issue [2]. Particularly, it endeavors to explore the diverse role of urbanization, technological innovation, foreign direct investments, renewable energy, and natural resource utilization on environmental quality among BRICS bloc of countries.

Many findings suggest mixed conclusions on the diverse complementary roles of financial development, urbanization, natural resource use, renewable energy, and technological innovation on environmental quality. According to Usman and Balsalobre-Lorente, [2]; this observation highlights the need for further empirical evidence from other contexts to improve the reliability of assessments of these factors (financing of economic development, natural resources use, technological innovation, clean energy utilization and urbanization) on ecological consequences like CO_2 emissions. As a key contribution to literature, this study extends its assessment to verify the effect of industrial value added as direct impact of industrial growth, a relationship nascently considered crucial to environmental quality [2]. To this end, the present study draws strength from the trade-off between anthropogenic human induced activities and economic growth, which has been popularized in the energy and environmental literature as the Environmental Kuznets curve (EKC) hypothesis. For our study case, a linear version is fitted, i.e., in a carbon-income function to rationalize the study variables industrial value added, technological innovation, natural resources, foreign direct investment, interaction between industrial value added and technological innovation. The intuition for the variables' selection is in line with the drive for climate change mitigation (UNSDG-13) and quest for sustainable production and consumption (UNSDG-12). The present study focuses on BRICS, a fast-emerging bloc, to explore the outlined study variables for the pursuit of environmental sustainability.

Another contribution of this study to literature is that it sets out to provide evidence of a verification of the effect of economic expansion on environmental quality. Some studies assert that environmental quality is higher in economies with greater organized financial systems and markets [7,23,24]. However, emerging evidence in recent literature purports that structured financial markets and systems impact environmental quality in both positive and negative directions as well as in both structured and unstructured economy types [7,19,25]. For instance, Usman et al. [7]; showed that financial systems are crucial for impacting environmental quality, but highly structured financial systems attract foreign investment inflows, which increases economic activity in diverse modes, and may worsen environmental quality. In addition, where more FDIs drive more research into efficiency and technological innovation, it is likely to increase the quality of the environment through efficient production methods [7]. However, where financial investments mainly drive economic expansion through resource exploitation and income expansion, like in many emerging economies, there is a greater likelihood of worsening environment quality [26]. Therefore, it is assumed that financial investments will increase environmental quality through efficient economic expansion activities or increase adverse consequences on environmental quality through CO_2 emissions from expanded production [7]. Based on the above analysis, this study utilized the BRICS economics cross-sectional data to answer the following hypotheses:

Hypothesis1. (H_1): Doe technological innovation mitigates emission in the BRICS countries?

Hypothesis2. (H_2): Does FDI mitigates ecological degradation in the BRICS countries?

Hypothesis3. (H_3): Does natural resources in the BRICS enhance environmental damage?

Hypothesis3 (H_3): Does industrial value added is a tool to mitigate emission in the BRICS economics?

In answering these hypotheses, this current study, although seeking to examine certain relationships already observed in literature, differs significantly from extant works in the following ways: first, this study exists among few to have nascently extended the relationship between determinants of economic expansion (i.e., natural resource utilization, urbanization, technological innovation, financial investment inflows) and industrial value added and carbon dioxide emissions in emerging industrialized blocs like the BRICS. This kind of extension was first considered for newly industrialized countries (NIC) against ecological footprints in Usman and Balsalobre-Lorente [2], and is now being attempted in BRICS nations. In our opinion, as countries strive to become more industrialized and attain greater economic influence, the need to achieve the global sustainable development goals must be kept in sight. Thus, it is imperative to discern the impact of industrialization and economic expansion activities of emerging industrialized economies.

Secondly, the story of ecological footprints alone may not provide an expanded view; this study, as such diverts its focus toward the influence of isolated industrialization factors and economic development on CO_2 emissions; it departs from extant works that have focused on ecological footprints. Additionally, emerging industrialized nations like the BRICS are on the path to establishing benchmarks for executing ways to attain and comply with global sustainable development goals [4,5], thus it is more important to understand how their mix of economic development factors and industrialization are being employed to impact environmental quality.

Lastly, from a methodological standpoint, this examination differs from its peers in the literature which have mainly employed first-generation estimation techniques. This study considers cross-sectional dependencies and homogeneity, cointegration tests and second-generation stationarity tests, like Westerlund cointegration techniques, and AMG estimator to assess long-run effects, to resolve issues of the reliance between SH (slope homogeneity) and cross-sectional units.

2. Review of literature and hypothesis development

2.1. Technological innovation and environmental quality

Recent technological innovations provide several avenues to improve on environmental quality. Foremost, they facilitate reliability, accuracy, transparency, and the power to harness insights from the deluge of data generated by environmental stakeholders [9]. Recent technologies like big data technologies, blockchains, mobile and computing devices offer a broad scope for application across multiple sectors including financial and non-financial areas like environmental economics. These characteristics have made them more attractive as well as the fast pace of decentralization they come with [27]. However, some scholars believe consequential effects of technological advances on environmental sustainability need constant appraisal, as it is still unclear whether technological advances in their full adoption positively drive sustainable development practices [28–31]. For instance, from the supply chain context, Saberi et al. [30] identifies that technological innovations like blockchains can support supply chain sustainability through design and production of green products. Sharma et al. [31]; in endorsement conclude that technological advances in supply chains drive reduction of pollutant emissions.

Anthropogenic activities in pursuant of industrialization and economic expansion still remain a central source of reasons exacerbating poor environmental quality; therefore, it remains a crucial area needing more examination by sustainability scholars. Fu et al. [32] agree that technological innovations have advanced significant transformations for industrialization and energy utilization, which act as an apparatus for reducing aggregate emissions at all levels of production. However, the idea of distributed technological advances is confusing as in certain industrial settings it has negatively impacted environmental quality, hence requiring further deliberation [9]. Some scholars also show in the literature that the functioning of some technological innovation relative to green development practices is susceptible to different interpretations and new developments [9,30,32,33]. Therefore, it is hypothesized that:

H1. : Technological innovation mitigates carbon emission in the BRICS bloc of countries

2.2. FDI and environmental quality

Socioeconomic engagements of people have resulted to many adverse ecological consequences, like extinction of species, natural resources depletion, drastic changes to the weather and ecological deprivation [34]. Economic development is driven by industrialization, which also has many consequential effects on the environment.

Several extant works have assessed various factors to determine their effect on environmental quality, particularly financial development, manifested in foreign direct investment inflows [26]. Yang et al. [26] position that this factor is among the few that have seen the most consideration among factors for analyzing environmental quality. With a well-structured financial sector, production units can attract financing to expand production and natural resource depletion and subsequent demand for clean energy [35]. Thus, financial investment inflows can drive industrialization, which may consequentially drive greater pollution and environmental degradation [36,37]. However, foreign direct investment (FDI) inflow, particularly, is observed to reduce carbon footprints and increase economic growth [7]. It is also shown in extant studies that adverse environmental consequences emanate from non-renewable energy utilization and economic expansion, whereas trade openness and clean energy consumption through increased foreign direct investment can control the negative environmental consequences. Khan et al. [22] revealed a causal relationship between foreign direct investment inflows, trade openness and clean energy use among upper-middle-income states. Whereas evidence from selected European countries revealed causalities between FDI inflows, technological development, urbanization and bio energy and greenhouse gas emissions. Among Asian and American countries, increased clean energy use and foreign direct investments mitigate environmental pollution (Fernandes & Reddy, 2020).

In China, Lahiani [38] also observed a positive role of FDI on environmental quality. In the case of Turkey, between 1986 and 2018, Godil et al. (2020) present evidence of a positive effect of FDI (foreign direct investment), on environmental quality. These conclusions indicate that financial development through foreign direct investments will facilitate environmental quality through enhancement of efficiency and reduced non-renewable energy consumption. Drawing on the aforementioned, this examination proposes that:

H2. : FDI will mitigate environmental degradation in the BRICS countries

2.3. Natural resources and environmental quality

Sustaining quality environments and resource utilization have gained much prominence in recent years, particularly among scholars, policy experts and state stakeholders. Economic expansion activities are crucially linked to environmental degradation and climate change consequences. Economic growth drives industrialization and urbanization, which deepens the exploitation of natural resources. Many economic growth activities one way or the other diminish natural resources available through overexploitation and waste generation beyond the capacity of the environment. Thus, discerning the relationship between economic expansion, environmental degradation and natural resource utilization is relevant for policy formulation and development of clean energy generation and reliance. Recently, Khan et al. [4,5], exploring the link between natural resource utilization, tourism development, demand for energy and environmental quality in the BRI (Belt & Road) initiative, revealed that poor environmental quality is underlined by natural resource utilization in the region. Between 1995 and 2015, Sun et al. (30) examined the association between natural resources, tourism development, energy use and environmental quality and found that natural resources sustainability significantly impacts negative environmental quality. Further Ulucak and Khan [39] in studying the causal relationship between energy utilization, urbanization, natural resources, and environmental degradation among selected emerging industrialized economies showed that natural resources rent, urbanization and energy consumption mitigate environmental degradation. This is mainly through recycling, value-addition, and reprocessing of materials to reduce natural resources utilization. Zafar et al. [40]; in a similar study, showed that environmental quality is favorably associated with natural resources conservation. However, opposed to these findings, Ahmed et al. [41] found a negative impact of natural resources rent on environmental quality. To this end, it is believed that the true effect of natural resources on environmental quality would depend on the extent of positive and negative effects found on the various comparisons across contexts. Based on the above assertion, this study speculates that:

H3. : Natural resources utilization in the BRICS drives environmental damage

2.4. Industrial value-added and environmental quality

The utilization and ease of access to natural resources are crucial to industrialization, which underpins human development and economic development of countries. The importance of the relationship of industry-value added and environmental quality cannot be ignored as this nexus underlines crucial aspects of daily life, including food production, construction and transportation [42]. Scholars like Wackernagel and Galli [43] propose that, in order for a productive system to remain competitive, there must be sufficient consideration for environmental stability and its industrial output in order to sustainably utilize scarce resources. Environmental quality policies and industrial operations are intricately interwoven; hence, industrial value-added presents new opportunities to drive sustainable industrialization. However, this crucial relationship between environmental quality and industrial value-added has been nascently explored. Therefore, we presume that:

H4. : Industrial value added improves environmental quality in BRICS nations

2.5. Renewable energy and environmental quality

The current and most deliberated trend on the energy consumption scene is the debate on the effect of renewable energy on quality environment [44]. A surging number of studies continue to investigate the role of renewable in economic growth and environmental quality, which is currently the most absorbing topic of research in the environmental and energy economics [45]. It is indicated that the net effect of economic expansion on environmental pollution is still undetermined and could either be positive or negative (Shahbaz et al., 2013). In essence, the effect being positive hinges on the logic that economies can gain more from globalization, which will drive efficiency and competitiveness. Such economies can develop or even import green technologies from other economies, which will reduce carbon pollution, hence improve environmental quality. Subsequently, the negative effect is seen from the fact that trade from globalization increases industrialization, which ultimately drives greater carbon emissions. A study on emerging economies by Jebli et al. (2019) showed that globalization and trade negatively affect environmental quality and renewable energy facilitates quality environments. Similarly, Halicioglu [46]; Tiwari et al. [47]; Balsalobre-Lorente et al. [18] and Gasimli et al. [48] all variously present evidence from India, Turkey, Sri Lanka, and selected EU statesto support the negative effect of trade and positive impact of renewable energy on the environment. Thus, to achieve the green transformation targeted by countries and global international bodies like the UN, there is an urgent need for the development of renewable energy technologies and policy based on new evidence across countries to hasten the transition to renewable energy and effectively combat climate change and environmental pollution. Therefore, inferring from the aforementioned, it is observed that energy demand, natural resources use, industrialization, technological advancements and financial development have been steadily examined to be increasing in many contexts including emerging industrialized ones. However, reports on their impact on environmental quality, except for economic development which has consistently been observed to negatively impact environmental quality, others such as natural resource utilization, industrialization process (industrial value added), technological innovation, financial investments, clean energy consumption, and urbanization have all shown mixed effects (Gyamfi et al., 2020). These inconsistencies in their roles as factors of environmental quality deepen the need for further examinations to better perceive the convergence of these effects to attain sufficient soundness and reliable conclusions on how these factors impact environmental quality relative to CO_2 emissions.

3. Data and methodology

As a means of achieving the present study goal for the case of BRICS countries, which are comprised of Brazil, Russia, India, China, and South Africa, worthy of mention is that four of the highlighted BRICS blocs are listed as leading newly industrialized economies (NICs) during the period 1990 to 2019 due to availability of data. With the exception of renewable energy and CO_2 emissions, which were obtained from the British Petroleum [49] database, all of the data for this investigation were derived from the World Development Indicators [13]. The choice of these coefficients is in accordance with the 2030 Sustainable Development Goals (SDGs). Table 1 below present more details on the coefficients utilized for this estimation.

3.1. Economic structure

The following analytical framework, which is built on past works by Ulucak and Khan [39]; Pata et al. [25]; Usman et al. [7] and Usman and Balsalobre-Lorente [2]; is used to investigate the influence of industrial value-added (IVA), technological innovation (TI), natural resources (NRU), renewable energy (REU), foreign direct investment (FDI) and total reserves (TRS) on CO_2 emissions in Eq. (1) as follows:

$$\mathrm{LCO2}_{it} = \beta_0 + \beta_1 LIVA_{it} + \beta_2 LTI_{it} + \beta_3 LNRU_{it} + \beta_4 LREU_{it} + \beta_5 FDI_{it} + \beta_6 \mathrm{LTRS}_{it} + \varepsilon_{it} \tag{1}$$

where CO_2, IVA, TI, NR, REU, FDI, and TRS are coefficients stated above. Moreover, $\beta_1 \ldots\ldots \beta_6$ stands for the coefficients of the regressors while I and t represent nations and timeframe, respectively. Moreover, all the coefficients have been log-transformed except FDI. In an attempt to contribute to the investigation by providing further ideas, we have developed a model which is presented as:

$$\mathrm{LCO2}_{it} = \beta_0 + \beta_1 LIVA_{it} + \beta_2 LTI_{it} + \beta_3 LNRU_{it} + \beta_4 LREU_{it} + \beta_5 FDI_{it} + \beta_6 \mathrm{LTRS}_{it} + \beta_7 \mathrm{LIVALTI}_{it} + \varepsilon_{it} \tag{2}$$

The interaction between industrial-value added and technological innovation indicate how advanced implementation for technological innovation in industrialization (4th industrial revolution) has impacted on the environment. In order to give a clear perspective to the study method sequences, Fig. 1 highlights the step-by step flow of process with the use of robust and state-of-the-art econometrics for ample policy construction (see Fig. 2).

3.2. Methodology

3.2.1. Cross-sectional dependence and slope heterogeneity tests

With more worldwide globalization and less trade restrictions, cross-sectional dependency (CD) in panel regression is more probable to appear in the contemporary period. Ignoring the CD dilemma and asserting CD can result in estimates that are erroneous, biased, and incorrect. The Pesaran [50] CD, Pesaran [51] scaled LM and Breusch and

Table 1
Description of variables.

Name of Indicator	Abbreviation	Proxy/Scale of Measurement	Source
Carbon Dioxide Emissions Per Capita	CO_2	Measured in metric tonnes	[49]
Industrial value added	IVA	Including construction (constant 2010 US$)	[13]
Technologic Innovation	TI	Internet users (per 100 people)	[13]
Natural resources	NRU	Total natural resource rent (% of GDP)	[13]
Renewable Energy	REU	Renewable energy consumption (% of total final energy consumption)	[49]
Foreign Direct Investment	FDI	% of real GDP	[13]
Total Reserves	TRS	Current US dollar	[13].
Interaction term	IVA*TI	Industrial value added*technological innovation	

Source: Authors compilation

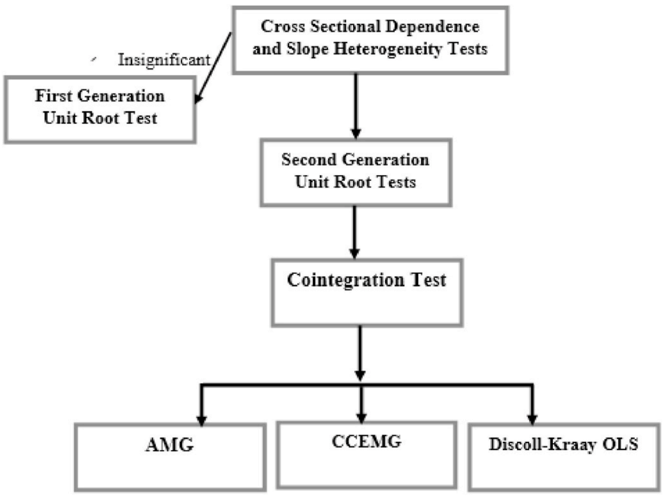

Fig. 1. Methodological sequence.

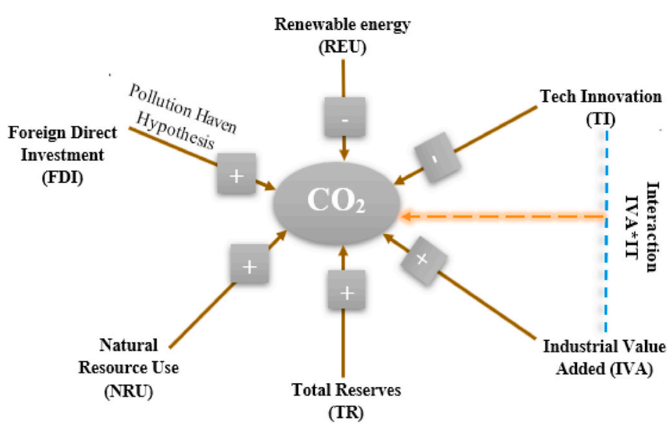

Fig. 2. Graphical presentation of empirical analysis.

Pagan Breusch and Pagan [52] approaches test are used to determine CD in this research. Similarly, assuming a homogeneous slope coefficient without evaluating for heterogeneity might result in misleading estimator results. As a consequence, Pesaran and Yamagata [53] developed an improved version of Swamy's (1970) slope heterogeneity test (SH). It is crucial to check for the presence of CD and SH before obtaining the stationarity properties of variables. The following are the SH test equations:

$$\widetilde{\Delta}_{SH} = (N)^{\frac{1}{2}}(2k)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - k\right) \quad [3]$$

$$\widetilde{\Delta}_{ASH} = (N)^{\frac{1}{2}}\left(\frac{2k(T-k-1)}{T+1}\right)^{-\frac{1}{2}}\left(\frac{1}{N}\widetilde{S} - 2k\right) \quad [4]$$

where delta tilde and adjusted delta tilde are shown by $\widetilde{\Delta}_{SH}$ and $\widetilde{\Delta}_{ASH}$.

3.2.2. Panel unit root tests

In the next stage we assess the unit root properties of the variables. Therefore, the current paper relies on ADF and Pesaran's [50] cross-sectional augmented IPS and ADF tests, which are also known as the CADF and CIPS tests. The CADF test equation looks like this;

$$\Delta Y_{i,t} = \gamma_i + \gamma_i Y_{i,t-1} + \gamma_i \overline{X}_{t-1} + \sum_{l=0}^{p} \gamma_{il} \Delta \overline{Y_{t-l}} + \sum_{l=1}^{p} \gamma_{il} \Delta Y_{i,t-l} + \varepsilon_{it} \quad [5]$$

where $\Delta\overline{Y_{t-l}}$ and $\overline{Y}_{t-1}$ represent the first differences and lagged averages.

Equation (6) also displays the CIPS test statistic calculated by averaging each CADF.

$$\widehat{\mathrm{CIPS}} = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{CADF_i} \quad [6]$$

Equation (6) produces the CIPS, which is derived from Equation (5). Since the 1st generation unit root tests generate inconsistent results, especially when there is CD in the data, these 2nd generation unit root tests have lately been employed.

3.2.3. Panel cointegration test

The current paper uses the Westerlund [1] cointegration test as well as Koa cointegration to capture the long-run interconnectedness between CO_2 emissions and the independent variables. Unlike the first generation cointegration, this technique takes into account CD and slope heterogeneity. The test is depicted as follows:

$$\alpha i(L)\Delta y_{it} = y2_{it} + \beta_i(y_{it} - 1 - ά_i \mathrm{x_{it}}) + \lambda_i(\mathrm{L})\mathrm{v_{it}} + \eta_i \quad [7]$$

where. $\delta_{1i} = \beta_i(1)\widehat{\vartheta}_{21} - \beta_i\lambda_{1i} + \beta_i\widehat{\vartheta}2_i \mathrm{and} y2_i = -\beta_i\lambda 2_i$

The following are the test statistics for the Westerlund cointegration:

$$G_t = \frac{1}{N}\sum_{i-1}^{N}\frac{ά_i}{SE(ά_i)} \quad [8]$$

$$G_\alpha = \frac{1}{N}\sum_{i-1}^{N}\frac{\mathrm{T}ά_i}{ά_i(1)} \quad [9]$$

$$P_T = \frac{ά}{SE(ά)} \quad [10]$$

$$P_\alpha = \mathrm{T}ά \quad [11]$$

The group means statistics, comprising $\mathrm{G_a}$ and $\mathrm{G_t}$, are shown in Equations (8) and (9). Panel statistics, comprising $\mathrm{P_a}$ and $\mathrm{P_t}$, are represented by Equations (10) and (11).

3.2.4. Parameter estimation using Augmented Mean Group (AMG) estimator

Following the circumstances surrounding the results in Section 4.2, the panel estimators for the study should consequently take into cognizance the concerns on the cross-sectional dependence. Hence, weapplied three robust techniques that are designed to accommodate the latter concern for the study, the Augmented Mean Group (AMG), Common Correlated Effects Mean Group (CCEMG), and Driscoll-Kraay as proposed by Driscoll and Kraay [54] and extended by Kapetanios et al. [55]. These methods offer the unusual capacity to account for cross-sectional dependence as well as slope heterogeneity and give more robust outcomes than other techniques [56–58]. They can sustain a unique path because of the way commonly affected impacts are handled. The CCEMG addresses the influence of the variables, whereas for AMG these impacts represent a single continuous change that can be compensated for by deducting it from the dependent variable. Thus, the motivation for battery of estimation techniques like AMG, CCEMG offers robust estimates coefficients and results for ample policy construction. The Augmented Mean Group (AMG) heterogeneous panel estimator of Eberhardt and Bond [59] as well as Eberhardt and Teal [60] were utilized in the study following the expression in Equation-12:

$$\Delta Y_{it} = \alpha_i + \beta_i \Delta X_{it} + \sum_{t=1}^{T} \pi_t D_t + \varphi_i UCF_t + \mu_{it} \quad (12)$$

The OLS method of the difference is applied to the AMG technique. This is shown in Equation (13) whereas φ_i symbolises the projected slope parameters of X_{it} coefficient in Equation-12.

$$\text{AMG} = \frac{1}{N}\sum_{i=1}^{N}\varphi_i \quad (13)$$

4. Empirical outcomes and interpretation

From the empirical outcome, individual time series are examined first for cross-sectional dependence utilizing the Breusch-Pagan LM test, the Pesaran scaled LM test, and the Pesaran CD test which is shown in Table 2. It is demonstrated by the cross-sectional association analysis that the null assumption of no cross-sectional connection is rejected for all three procedures tested for all the variables at the one percent level of significance. This implies that the panel unit root analysis must consider the connection among cross-sectional individuals. However, the Pesaran & Yamagata [53], SH test is also significant at 1%. This means that, in each of the BRICS countries, a shock appears to be conveyed to other states within the panel. The results continue to prove the absence of multicollinearity as well as serial autocorrelation among the datasets. Hence, the CIPS unit root test of Pesaran [50]; and IPS unit root techniques are reported in Table 3 to support this conclusion for the variables in the study, and the panel cointegration analysis is presented in Table 4. The CIPS, and IPS results validate that all variables are stationary after difference.

Subsequently, the outcome of the Westerlund [1] cointegration test shown in Table 4 traces a long-run equilibrium relationship between the highlighted variables in the panel analysis. The conclusion was supported by the evidence of rejecting the null hypothesis.

4.1. Panel estimation results

From Table 5, the utilized methods (i.e., AMG, CCEMG and Driscoll-Kraay OLS) show relatively close outcomes, with slight variations mainly noted in relations to the scales of the assessed variables and their equivalent level of statistical significance. However, Table 5 shows that industrial value-added has a positively and significant effect on the CO2 emission in all the three techniques utilized for the BRICS countries. From the outcome, it was observed that a percent change in industrial value-added will increase emission by 0.210% for the AMG, 0.122% for the CCEMG and 0.155% for the Driscoll-Kraay for the BRICS countries which affirms the finding of Usman and Balsalobre-Lorente [2]. The fast growth in human activity has an impact on global emissions and is unquestionably dangerous; moreover, the industrialization cycle has an impact on many of our day-to-day activities. A rise in industrial operations, energy usage, and ecological pollution as a consequence of individual behaviors leads to an increase globally in heating rates and climatic variability [61]. It has been found in the literature [62] that a rise in industrial production can be promoted when the energy sector moves from low to high production levels. The rapid expansion of industrial activity, particularly in the BRICS, has fueled tremendous GDP growth while simultaneously increasing nonrenewable energy utilization and carbon emissions by orders of magnitude. There is little discussion of the relationship connecting natural resources, financial deepening, and countries' CO_2 emissions among the BRICS countries. This is especially true in the areas of fuel and coal use, as well as hazardous waste connected with other non-renewable energy sources. Increases in the carbon impact, which might be controversial, frequently serve to stimulate domestic industrial prosperity. A variety of creative strategies may be used to create a dynamic industrialization structure with a minimal environmental imprint, all of which are environmentally friendly [63].

Moreover, due to the sheer amount of economic activity in BRICS economics, the bloc's refining and manufacturing sectors generate significant pollution, resulting in the degradation of environmental sustainability. Furthermore, the findings show that technological innovation is negatively significantly connected to CO_2 emission for the BRICS nations, which affirms the findings of Al-mulali et al. [64]; Latif et al. [58]; Zhang et al. [14]; Nguyen et al. [65] and Chien et al. [66]. However, the outcomes of the research lend credence to the replacement impact of the ICT–energy nexus, which explains how technological innovation can help to reduce carbon dioxide emissions. In addition, internet purchasing decreases the need for transportation, which results in less pollution as a result. The internet shopping experience also provides consumers with the opportunity to sell their second-hand products online; therefore, reducing waste and emissions. Li et al. [67] point out

Table 3
Panel IPS and CIPS unit root test.

VARIABLES	CIPS		IPS	
	I(1)		I(1)	
	C	C&T	C	C&T
LCO_2	−4.359a	−5.431a	−4.204a	−2.889a
LIVA	−5.410a	−5.468a	−4.901a	−3.929a
LTI	−4.344a	−4.423a	−4.329a	−3.239a
LREU	−4.883a	−4.841a	−4.208a	−2.621a
LTNU	−5.187a	−5.223a	−8.378a	−7.418a
FDI	−4.497a	−4.670a	−7.035a	−6.132a
LTRS	−3.865a	−4.333a	−4.938a	−5.181a

NOTE: a<0.01, b < 0.05, c < 0.10 represents statistical rejection level at 1% and 10% respectively.

Table 4
Westerlund cointegration techniques.

Statistics	Westerlund technique		
	Value	Z- Value	p-value
Gτ	−1.753a	−1.475	(0.000)
Gα	−6.147a	−2.067	(0.001)
Pτ	−2.921b	−1.535	(0.038)
Pα	−4.644b	−1.370	(0.015)

NOTE: a<0.01, b < 0.05, c < 0.10. represents statistical rejection level at 1%, 5% and 10% respectively.

Table 2
Cross-sectional dependency (CD) and Slope Homogeneity (SH) Examinations.

Model	Pesaran CD Test	p-value	Pesaran LM Test	p-value	Breuch-Pagan LM	p-value
LCO_2	215.1614a	(0.000)	44.7574a	(0.000)	14.6168a	(0.000)
LIVA	54.1419a	(0.000)	8.6562a	(0.000)	3.6070a	(0.000)
LTI	40.2243a	(0.000)	5.6403a	(0.000)	−2.476b	(0.013)
LREU	196.0994a	(0.000)	40.4950a	(0.000)	13.9519a	(0.000)
LTNU	97.1919a	(0.000)	18.3786a	(0.000)	2.2691b	(0.000)
FDI	21.0255a	(0.000)	1.3473a	(0.008)	−2.4865b	(0.000)
LTRS	211.184a	(0.000)	43.868a	(0.000)	14.501a	(0.000)
Slope Homogeneity (SH)						
	COEFFICIENT	p-value				
SH ($\tilde{\Delta}$ test)	4.7550a	(0.0011)				
SH ($\tilde{\Delta}$ adj test)	3.1092a	(0.0032)				

NOTE: a<0.01 represents statistical rejection level at 1%.

Table 5
AMG, CCEMG and Driscoll-Kraay estimation.

Variables	AMG	CCEMG	Driscoll-Kraay
LIVA	0.210c	0.122a	0.155a
p-value	(0.051)	(0.000)	(0.009)
LTI	−0.057c	−0.007a	−0.677a
p-value	(0.083)	(0.002)	(0.000)
LREU	−1.130a	−1.710a	−1.512a
p-value	(0.000)	(0.000)	(0.000)
LTNU	0.012b	0.015c	0.025a
p-value	(0.041)	(0.080)	(0.002)
FDI	0.001a	0.006b	0.018a
p-value	(0.002)	(0.038)	(0.002)
LTRS	0.034c	0.018b	0.275a
LIVA*LTI	−0.05b	−0.03b	−0.110b
***P*-value**	(0.041)	(0.038)	(0.013)
p-value	(0.055)	(0.047)	(0.000)
CONS.	3.328a	3.618a	1.110b
p-value	(0.000)	(0.000)	(0.032)
F-STAT	–	–	111.95a
p-value	–	–	(0.000)
R^2	–	–	0.839
ADJ R^2	–	–	0.832
Wald test	94.53a	15600.63a	
***P*-value**	(0.000)	(0.000)	
No. regressors	6	6	6
No. of group	5	5	5

NOTE: a<0.01, b < 0.05, c < 0.10 represents statistical rejection level at 1%,5% and 10% respectively.

that the more sophisticated the modern technology of the 4IR is, the fewer resources are utilized which our findings are in accordance with. This suggests that technical innovation has the potential to conserve resources while also increasing production efficiency. In contrast to Salahuddin and Alam [68]; who discovered that utilizing technology can result in the generation of waste and hazardous emissions, the findings of this study are contradictory. ICT equipment necessitates a higher level of power consumption, resulting in a rise in demand.

Nevertheless, a negative but significant (at $p < 0.01$) relationship is observed between renewable energy and CO_2 emission. This is an indication that transition to more conservative or environmentally friendly energy sources guarantees improvements on the environment. We find this consistent with findings from some prior studies (see Refs. [69–73]. Given that clean energy technology makes use of the purest and greenest forms of energy that are both durable and meet the demands of both the present and the future, it is an effective means of reducing CO_2 emission.

The outcome acquired from natural resources, on the other hand, is found to have a positive and statistically significant link with ecological degradation. This verifies the findings of Ahmed et al. [41]; Ahmad [74, 75]; and Onifade et al. [76] who found that natural resources promote pollutants in the BRICS economics. These countries have a significant quantity of revenue that may be used for both export and domestic consumption. This discovery, on the other hand, lends weight to the notion that the obtained energy from natural resources within these countries has never been profitable. Excessive reliance on natural resources contributes to the loss of biocapacity, which is the capacity of living organisms to reproduce [77]. Furthermore, considering the vital significance of the BRICS economics, the usage and growth of agricultural resources encourage deforestation, which increases pollution. Aside from that, several countries make use of their natural resources (coal, petroleum, and natural gas) to meet their energy requirements. It has been claimed that the abundance of resources would enable a country to become more self-sufficient by reducing energy importation and depending on domestic energy generation with fewer pollution levels [41].

Moreover, FDI was seen to also have positive impact on the ecology for the BRICS economics. There are other elements that contribute to the appeal of FDI, such as availability to cheaper labor, proximity to the sector, and less stringent policies in terms of controlling the abuses of overseas investors, that make this outcome more likely. This serves as a reminder that economies in the BRICS economics are continuing developing in their economic operations and growth while paying little attention to the health of their ecology. This supported the position of some critics of foreign direct investment, particularly those concerned with the long-term viability of underdeveloped nations. This observation lends credibility to the notion of a pollution haven (PHH). This validates the results of Sarkodie and Strezov (2019), Udemba [78]; Gyamfi et al. (2021a) and Agboola et al. [79].

Again, the result shows that total reserves enhance pollution for the BRICS countries, which is in line with the finding of Usman and Balsalobre-Lorente [2]. Nevertheless, since the positive impact of total reserves on supporting CO_2 emission levels would result in significant increases in environmental degradation, national and international strategies to enhance total reserves will need to be recast in order to reduce unanticipated fiscal and monetary crises as well as environmental damage. Following the observations of this study, it is clear that we must encourage greener energy and the use of innovative energy sources such as wind, hydroelectric, and solar power. We also need to promote bioenergy, which is one of the most promising solutions for a greener way of life in the BRICS emerging economies. Funding for greener energy endeavors through public-private partnerships (PPPs) would relieve some of the hardship on BRICS authorities, as many of these nations' governmental bodies are constrained by financing constraints and their financial industries are not established enough to undergo these developments on their own [80].

Lastly, the interaction between industrialization value-added and technological innovation shows a negative impact on the BRICS environments. Industrialization, along with technical development, has had a detrimental impact on the environment that has persisted to this day. Industrial gains stemming from technological application in main operations have indirectly led to increased living conditions, despite the fact that the negative aspects of technology are increasingly prominent. Environmental contamination, on the other hand, occurs as a result of poor technology administration and an absence of effective control mechanisms. The advancement of technology has resulted in the manufacture of more machinery, weaponry, and vehicles in recent years. Demand for enhanced facilities is stimulated by increased consumption, which, in turn, impacts the supply of high-quality goods that are key contributors to industrialization as a result of the use of improved technology. In such situations, the importance of technology is related to the gratification of human desires, despite increasing contamination of the environment because of increased output in the manufacturing and processing sectors, weapons testing, and the widespread use of automobiles such as autos. Technology has resulted in a continuous degradation of the environment, with air pollution, water pollution, and noise pollution being the most significant components. Large-scale industrial emissions of gases into the atmosphere, such as carbon dioxide (CO_2), generate air pollution, which, in turn, has had a devastating impact on the ecosystem. Another environmental concern is the discharge of waste into rivers and water systems by factories and other organizations, which causes water pollution and other environmental problems. Similarly, a significant amount of noise pollution from weapons testing and usage, companies in their everyday manufacturing operations, and cars is a contributing factor to environmental degradation [81].

5. Conclusion and policy direction

Following the UN-SDG-13 crusade to reduce climate change impact, this study explores this topical issue by investigating the effect industrial value-added, technological innovation, natural resources, renewable energy, FDI, and total reserves on CO_2 emission for the BRICS economies from 1990 to 2018. This study leverages on second-generational modeling methodology that corrects for cross-sectional dependency and heterogeneity to achieve the soundness of empirical findings. To this end, we used Augmented Mean Group, Common Correlated Effects Mean Group estimator and Driscoll-Kraay. The Westerlund cointegration analysis affirms the existence of a long-run bond between the studies' highlighted variables. The outcome from the estimation shows that industrial value-added, natural resources, FDI and total reserves have positive impact on the environment while technological innovation and renewable energy have negative impact on the environment of the BRICS economics. For the interaction term, the interaction between industrial value-added and technological innovation also has negative impact on the BRICS countries environment.

5.1. Policy recommendations

This study further highlighted policy prescriptions given the study outcomes. The policy suggestion includes:

- ➢ It is necessary for authorities, centralized agencies, and lawmakers in these nations to reduce the rate of expansion of industrialization activity, especially in the case of production enterprises that emit significant quantities of carbon dioxide into the atmosphere. As a result of this procedure, the growing harmful effects of industrialization on the environment will be reduced. Authorities must also define the environmental laws and regulations that apply to polluting industrial facilities. To safeguard ecological integrity through current technology, research and development (R & D) organizations in the private and public sector are required. In addition, industrial waste should be promoted as an energy source to lower emission levels. Cleaning up the energy sector by bringing in greener energy infrastructure such as petroleum-efficient small and large-scale technology will minimize the environmental spillovers. Environmental laws and guidelines should be enacted to protect unnecessary energy consumption and to encourage the use of green technologies as a percentage of total energy production. This will have a positive impact on the economy, the climate, and the social setting. Using Pigovian taxation and tariffs on imports of dirty and conventional equity, it is possible to provide attractive schemes for greener and more advanced types of mechanical equipment to be used in these countries; this would incentivize local funders to invest their assets in sustainable power technologies. Strategies for environmental mitigation must be enacted in order to give economic incentives to the finance industry.
- ➢ The BRICS countries should have a commitment to build technological innovation in order to lower the production of pollutant, having a general objective of reducing poverty and increasing wealth. BRICS countries should increase the usage of information and communication technology (ICT) as a way to raise the understanding of the value of ecological growth and climate change within their economics. In this way, technological innovation can be considered as tools and strategies for tracking the status of the ecosystem and evaluating the effects of human activity and the ecosystems and environmental assets strategies and interventions enforced. This policy should concentrate on the most polluting industries such as travel, industry, and buildings. In the field of manufacturing, ICT can be used to maximize capital usage in industrial development operations, conserve electricity, and boost efficiency. There should be a comprehensive plan for BRICS to leverage emerging technology to improve quality of transportation. ICT could perhaps be utilized for economic and environmental purposes.
- ➢ It is unclear if foreign direct investment (FDI) has been advantageous to the economy of the region in the short, medium, or long term. BRICS nations have reaped the benefits of FDI in dirty oil and multi-domain energy in recent years. It is important that these acts are tied to greater social, economic, environmental, and democratic goals. It is important for the BRICS to encourage the effective use of renewable energy for financial and commercial advantage. Companies in these nations must be encouraged to adopt new technology in order to improve the efficiency and effectiveness of their present operations and procedures. According to the findings of the study, FDI has a favorable impact on the stability of the environment. Renewable energy legislation should be implemented instead of depending on the existing energy sector in order to establish a long-term energy business. As a consequence of this decision, new employment opportunities will be created, energy stability will be improved, income progress will be increased, a positive export sector will be formed, and environmental protection will be improved [82].

5.2. Limitation and future recommendation of the study

Due to the lack of data available, it is not possible to incorporate institutional actions and traditional indicators into the CO_2 emission equation for BRICS at this time. These variables may have varying degrees of influence on the environment and the economy. Cultural events and institutional factors (as measured by political, socioeconomic, and economic data) have a great deal of potential to play a significant role in a country's total reserves, economic expansion, natural resources, financial deepening, technical development, and the effective operation of its human capital. Furthermore, recent research does not evaluate the environmental Kuznets curve (EKC) of CO_2 emissions in the BRICS countries in conjunction with the factors that have been studied. Another major limitation of this study is the lack of available data. However, the preliminary model might be enhanced by including more demographic factors for gender categorization and household composition in addition to those already included. In addition, the findings may be employed to broaden comparable studies (particularly with these variables) for both emerging and established economies, in which future academics will be able to regulate these restrictions.

Credit author statement

Bright Akwasi Gyamfi: Conceptualization; Formal analysis; Methodology; **Divine Q. Agozie:** Validation; Visualization; Data curation; Writing – original draft; Investigation, **Festus Victor Bekun:** Writing – original draft; Writing, Validation; Visualization; Supervision, and Corresponding.

Appendix Table 1

Descriptive statistics and correlation matrix analysis

	LCO_2	LIVA	LTI	LREU	LTN	LTRS	LIVA*LTI
Mean	−0.796	3.131	3.708	4.059	−0.082	22.614	36.358
Median	−0.497	3.155	3.642	4.017	0.111	22.386	34.915
Maximum	0.606	3.438	4.425	4.545	1.960	26.745	56.700
Minimum	−3.005	2.538	2.602	3.548	−2.343	19.926	8.895
Std. Dev.	0.840	0.223	0.455	0.275	0.965	1.705	10.610
Skewness	−0.553	−0.802	−0.189	0.235	−0.579	0.848	−0.278

(continued on next page)

(*continued*)

	LCO_2	LIVA	LTI	LREU	LTN	LTRS	LIVA*LTI
Kurtosis	2.370	2.893	2.101	2.156	2.667	2.999	2.565
Jarque-Bera	9.122	14.547	5.348	5.249	8.173	16.205	6.405
LCO_2	1						
LIVA	0.533	1					
LTI	0.027	0.017	1				
LREU	−0.801	−0.542	−0.330	1			
LTN	0.185	−0.162	0.566	−0.276	1		
LTRS	0.764	0.391	0.442	−0.725	0.519	1	
LIVA*LTI	−0.684	0.849	0.179	0.088	−0.012	0.939	1

References

[1] J. Westerlund, Testing for error correction in panel data, Oxf. Bull. Econ. Stat. 69 (6) (2007) 709–748.
[2] M. Usman, D. Balsalobre-Lorente, Environmental concern in the era of industrialization: can financial development, renewable energy and natural resources alleviate some load? Energy Pol. 162 (2022), 112780.
[3] K.R. Abbasi, K. Hussain, A.M. Haddad, A. Salman, I. Ozturk, The role of financial development and technological innovation towards sustainable development in Pakistan: fresh insights from consumption and territory-based emissions, Technol. Forecast. Soc. Change 176 (2021), 121444.
[4] N.H. Khan, Y. Ju, Z. Latif, K. Khan, Nexus between carbon emission, financial development, and access to electricity: incorporating the role of natural resources and population growth, J. Publ. Aff. 21 (1) (2021), e2131.
[5] S.A.R. Khan, D.I. Godil, M.U. Quddoos, Z. Yu, M.H. Akhtar, Z. Liang, Investigating the nexus between energy, economic growth, and environmental quality: a road map for the sustainable development, Sustain. Dev. 29 (5) (2021) 835–846.
[6] S.A.R. Khan, D.I. Godil, Z. Yu, F. Abbas, M.A. Shamim, Adoption of renewable energy sources, low-carbon initiatives, and advanced logistical infrastructure—an step toward integrated global progress, Sustain. Dev. 30 (1) (2022) 275–288, 567-580.
[7] A. Usman, I. Ozturk, S. Ullah, A. Hassan, Does ICT have symmetric or asymmetric effects on CO2 emissions? Evidence from selected Asian economies, Technol. Soc. 67 (2021), 101692.
[8] UNFCCC, UN Climate Change Annual Report of 2017. United Nations Framework Convention on Climate Change (UNFCCC), 2017. Bonn, Germany, https://unfccc.int/resou rce/annualreport/.
[9] S.A.R. Khan, D.I. Godil, C.J.C. Jabbour, S. Shujaat, A. Razzaq, Z. Yu, Green data analytics, blockchain technology for sustainable development, and sustainable supply chain practices: evidence from small and medium enterprises, Ann. Oper. Res. (2021) 1–25.
[10] N. Carvalho, O. Chaim, E. Cazarini, M. Gerolamo, Manufacturing in the fourth industrial revolution: a positive prospect in sustainable manufacturing, Procedia Manuf. 21 (2018) 671–678.
[11] X. Liu, Z. Latif, D. Xiong, M. Yang, S. Latif, K.U. Wara, The nexus among globalization, ICT and economic growth: an empirical analysis, J. Inf. Proc. Syst. 17 (6) (2021) 1044–1056.
[12] Z. Nasrollahi, M.S. Hashemi, S. Bameri, V.M. Taghvaee, Environmental pollution, economic growth, population, industrialization, and technology in weak and strong sustainability: using STIRPAT model, Environ. Dev. Sustain. 22 (2) (2020) 1105–1122.
[13] World Development Indicators (WDI), WDI - Home (worldbank.Org), 2020.
[14] J. Zhang, B. Wang, Z. Latif, Towards cross-regional sustainable development: the nexus between information and communication technology, energy consumption, and CO 2 emissions, Sustain. Dev. 27 (5) (2019) 990–1000.
[15] A. Tamazian, B.B. Rao, Do economic, financial and institutional developments matter for environmental degradation? Evidence from transitional economies, Energy Econ. 32 (1) (2010) 137–145.
[16] J. Wang, K. Dong, What drives environmental degradation? Evidence from 14 Sub-Saharan African countries, Sci. Total Environ. 656 (2019) 165–173.
[17] S.A. Sarkodie, The invisible hand and EKC hypothesis: what are the drivers of environmental degradation and pollution in Africa? Environ. Sci. Pollut. Control Ser. 25 (22) (2018) 21993–22022.
[18] D. Balsalobre-Lorente, M. Shahbaz, D. Roubaud, S. Farhani, How economic growth, renewable electricity and natural resources contribute to CO2 emissions? Energy Pol. 113 (2018) 356–367.
[19] A.A. Alola, F.V. Bekun, S.A. Sarkodie, Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe, Sci. Total Environ. 685 (2019) 702–709.
[20] K.U. Ehigiamusoe, H.H. Lean, Effects of energy consumption, economic growth, and financial development on carbon emissions: evidence from heterogeneous income groups, Environ. Sci. Pollut. Control Ser. 26 (22) (2019) 22611–22624.
[21] M.S. Hossain, Panel estimation for CO2 emissions, energy consumption, economic growth, trade openness and urbanization of newly industrialized countries, Energy Pol. 39 (11) (2011) 6991–6999.
[22] M.T.I. Khan, M.R. Yaseen, Q. Ali, Dynamic relationship between financial development, energy consumption, trade and greenhouse gas: comparison of upper middle income countries from Asia, Europe, Africa and America, J. Clean. Prod. 161 (2017).
[23] I. Ozturk, A. Acaravci, The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey, Energy Econ. 36 (2013) 262–267.
[24] E.G. Popkova, P. De Bernardi, Y.G. Tyurina, B.S. Sergi, A theory of digital technology advancement to address the grand challenges of sustainable development, Technol. Soc. 68 (2022), 101831.
[25] U.K. Pata, M. Aydin, I. Haouas, Are natural resources abundance and human development a solution for environmental pressure? Evidence from top ten countries with the largest ecological footprint, Resour. Pol. 70 (2021), 101923.
[26] B. Yang, A. Jahanger, M. Usman, M.A. Khan, The dynamic linkage between globalization, financial development, energy utilization, and environmental sustainability in GCC countries, Environ. Sci. Pollut. Control Ser. 28 (13) (2021) 16568–16588.
[27] U. Awan, Steering for sustainable development goals: a typology of sustainable innovation, in: Industry, Innovation, and Infrastructure, Springer International Publishing, Cham, 2021, pp. 1026–1036.
[28] M.Z. Chishti, A. Sinha, Do the shocks in technological and financial innovation influence the environmental quality? Evidence from BRICS economies, Technol. Soc. 68 (2022), 101828.
[29] M. Kouhizadeh, J. Sarkis, Q. Zhu, At the nexus of blockchain technology, the circular economy, and product deletion, Appl. Sci. 9 (8) (2019) 1712.
[30] S. Saberi, M. Kouhizadeh, J. Sarkis, L. Shen, Blockchain technology and its relationships to sustainable supply chain management, Int. J. Prod. Res. 57 (7) (2019) 2117–2135.
[31] R. Sharma, C.J.C. Jabbour, A.B.L. de Sousa Jabbour, Sustainable manufacturing and industry 4.0: what we know and what we don't, J. Enterprise Inf. Manag. 34 (1) (2020) 230–266, https://doi.org/10.1108/JEIM-01-2020-0024.
[32] B. Fu, Z. Shu, X. Liu, Blockchain enhanced emission trading framework in fashion apparel manufacturing industry, Sustainability 10 (4) (2018) 1105.
[33] A. Razzaq, Y. Wang, S. Chupradit, W. Suksatan, F. Shahzad, Asymmetric inter-linkages between green technology innovation and consumption-based carbon emissions in BRICS countries using quantile-on-quantile framework, Technol. Soc. 66 (2021), 101656.
[34] R. Ulucak, F. Bilgili, A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries, J. Clean. Prod. 188 (2018) 144–157.
[35] M.A. Baloch, J. Zhang, K. Iqbal, Z. Iqbal, The effect of financial development on ecological footprint in BRI countries: evidence from panel data estimation, Environ. Sci. Pollut. Control Ser. 26 (6) (2019) 6199–6208.
[36] A.O. Acheampong, Modelling for insight: does financial development improve environmental quality? Energy Econ. 83 (2019) 156–179.
[37] A. Omri, S. Daly, C. Rault, A. Chaibi, Financial development, environmental quality, trade and economic growth: what causes what in MENA countries, Energy Econ. 48 (2015) 242–252.
[38] A. Lahiani, Is financial development good for the environment? An asymmetric analysis with CO 2 emissions in China, Environ. Sci. Pollut. Control Ser. 27 (8) (2020) 7901–7909.
[39] R. Ulucak, S.U.D. Khan, Determinants of the ecological footprint: role of renewable energy, natural resources, and urbanization, Sustain. Cities Soc. 54 (2020), 101996.
[40] M.W. Zafar, S.A.H. Zaidi, N.R. Khan, F.M. Mirza, F. Hou, S.A.A. Kirmani, The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: the case of the United States, Resour. Pol. 63 (2019), 101428.
[41] Z. Ahmed, M.M. Asghar, M.N. Malik, K. Nawaz, Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China, Resour. Pol. 67 (2020), 101677.
[42] GFN, Sector Analysis, 2019 global footprint network, https://www.footprintnetwork.org/our-work/sector-analysis/.
[43] M. Wackernagel, A. Galli, Ecological footprint: economic performance and resource constraints, Global Dialog. 14 (1) (2012) 13.
[44] S.A.R. Khan, C. Jian, Y. Zhang, H. Golpîra, A. Kumar, A. Sharif, Environmental, social, and economic growth indicators spur logistics performance: from the perspective of South Asian Association for Regional Cooperation countries, J. Clean. Prod. 214 (2019) 1011–1023.

[45] M.M. Rahman, Do population density, economic growth, energy use and exports adversely affect environmental quality in Asian populous countries? Renew. Sustain. Energy Rev. 77 (2017) 506–514.
[46] F. Halicioglu, An econometric study of CO2 emissions, energy consumption, income, and foreign trade in Turkey, Energy Pol. 37 (3) (2009) 1156–1164.
[47] A.K. Tiwari, M. Shahbaz, Q.M.A. Hye, The environmental Kuznets curve and the role of coal consumption in India: cointegration and causality analysis in an open economy, Renew. Sustain. Energy Rev. 18 (2013) 519–527.
[48] O. Gasimli, I.U. Haq, S.K. Naradda Gamage, F. Shihadeh, P.S.K. Rajapakshe, M. Shafiq, Energy, trade, urbanization and environmental degradation nexus in Sri Lanka: bounds testing approach, Energies 12 (9) (2019) 1655.
[49] BP, BP Statistical Review of World Energy 2020, 2020. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energyeconomics/statistical-review/bp-stats-review-2020- full-report.pdf.
[50] M.H. Pesaran, A simple panel unit root test in the presence of cross-section dependence, J. Appl. Econ. 22 (2) (2007) 265–312.
[51] M.H. Pesaran, Testing weak cross-sectional dependence in large panels, Econom. Rev. 34 (6–10) (2015) 1089–1117.
[52] T.S. Breusch, A.R. Pagan, The Lagrange multiplier test and its applications to model specification in econometrics, Rev. Econ. Stud. 47 (1) (1980) 239–253.
[53] M.H. Pesaran, T. Yamagata, Testing slope homogeneity in large panels, J. Econom. 142 (1) (2008) 50–93, https://doi.org/10.1016/j.jeconom.2007.05.010.
[54] J.C. Driscoll, A.C. Kraay, Consistent covariance matrix estimation with spatially dependent panel data, Rev. Econ. Stat. 80 (4) (1998) 549–560.
[55] G. Kapetanios, M.H. Pesaran, T. Yamagata, Panels with nonstationary multifactor error structures, J. Econ. 160 (2011) 326–348.
[56] F.V. Bekun, B.A. Gyamfi, S.T. Onifade, M.O. Agboola, Beyond the environmental Kuznets Curve in E7 economies: accounting for the combined impacts of institutional quality and renewables, J. Clean. Prod. 314 (2021), 127924.
[57] F.V. Bekun, F.F. Adedoyin, M.U. Etokakpan, B.A. Gyamfi, Exploring the tourism-CO2 emissions-real income nexus in E7 countries: accounting for the role of institutional quality, J. Policy Res. Tour. Leis. Events 14 (1) (2022) 1–19.
[58] Z. Latif, S. Latif, L. Ximei, Z.H. Pathan, S. Salam, Z. Jianqiu, The dynamics of ICT, foreign direct investment, globalization and economic growth: panel estimation robust to heterogeneity and cross-sectional dependence, Telematics Inf. 35 (2) (2018) 318–328.
[59] M. Eberhardt, S. Bond, Cross-section dependence in nonstationary panel models: a novel estimator, Munich Person. RePEc Arch. (2009). http://mpra.ub.uni-muenchen.de/17692/.
[60] M. Eberhardt, F. Teal, Productivity Analysis in Global Manufacturing Production, Department of Economics, University of Oxford, 2010. Discussion Paper 515, http://www.economics.ox.ac.uk/research/WP/pdf/paper515.pdf.
[61] B. Xiao, D. Niu, H. Wu, Exploring the impact of determining factors behind CO2 emissions in China: a CGE appraisal, Sci. Total Environ. 581 (2017) 559–572.
[62] Z. Cheng, L. Li, J. Liu, H. Zhang, Total-factor carbon emission efficiency of China's provincial industrial sector and its dynamic evolution, Renew. Sustain. Energy Rev. 94 (2018) 330–339.
[63] R. Wang, X. Zheng, H. Wang, Y. Shan, Emission drivers of cities at different industrialization phases in China, J. Environ. Manag. 250 (2019), 109494.
[64] U. Al-mulali, I. Ozturk, H.H. Lean, The influence of economic growth, urbanization, trade openness, financial development, and renewable energy on pollution in Europe, Nat. Hazards (2015) 621–644.
[65] T.T. Nguyen, T.A.T. Pham, H.T.X. Tram, Role of information and communication technologies and innovation in driving carbon emissions and economic growth in selected G-20 countries, J. Environ. Manag. 261 (2020), 110162.
[66] F. Chien, A. Anwar, C.C. Hsu, A. Sharif, A. Razzaq, A. Sinha, The role of information and communication technology in encountering environmental degradation: proposing an SDG framework for the BRICS countries, Technol. Soc. 65 (2021), 101587.
[67] G. Li, Y. Hou, A. Wu, Fourth Industrial Revolution: technological drivers, impacts and coping methods, Chin. Geogr. Sci. 27 (4) (2017) 626–637.
[68] M. Salahuddin, K. Alam, Information and Communication Technology, electricity consumption and economic growth in OECD countries: a panel data analysis, Int. J. Electr. Power Energy Syst. 76 (2016) 185–193.
[69] R. Bamidele, I. Ozturk, B.A. Gyamfi, F.V. Bekun, Tourism-induced pollution emission amidst energy mix: evidence from Nigeria, Environ. Sci. Pollut. Control Ser. (2021) 1–10.
[70] K. Dong, R. Sun, G. Hochman, Do natural gas and renewable energy consumption lead to less CO2emission? Empirical evidence from a panel of BRICS countries, Energy 141 (2017) 1466–1478.
[71] B.A. Gyamfi, T.S. Adebayo, U. Ogbolime, Towards a sustainable consumption approach: the effect of trade flow and clean energy on consumption-based carbon emissions in the Sub-Saharan African countries, Environ. Sci. Pollut. Control Ser. (2022) 1–14.
[72] M. Sebri, O. Ben-Salha, On the causal dynamics between economic growth, renewable energy consumption, CO2 emissions and trade openness: fresh evidence from BRICS countries, Renew. Sustain. Energy Rev. 39 (2014) 14–23.
[73] Y.S. Steve, A.B. Murad, B.A. Gyamfi, F.V. Bekun, G. Uzuner, Renewable energy consumption a panacea for sustainable economic growth: panel causality analysis for African blocs, Int. J. Green Energy (2021) 1–10.
[74] M. Ahmad, Non-linear dynamics of innovation activities over the business cycles: empirical evidence from OECD economies, Technol. Soc. 67 (2021), 101721.
[75] B.A. Gyamfi, M.A. Bein, E.N. Udemba, F.V. Bekun, Investigating the pollution haven hypothesis in oil and non-oil sub-Saharan Africa countries: evidence from quantile regression technique, Resour. Pol. 73 (2021), 102119.
[76] S.T. Onifade, B.A. Gyamfi, I. Haouas, F.V. Bekun, Re-examining the roles of economic globalization and natural resources consequences on environmental degradation in E7 economies: are human capital and urbanization essential components? Resour. Pol. 74 (2021), 102435.
[77] F.V. Bekun, A.A. Alola, S.A. Sarkodie, Toward a sustainable environment: nexus between CO2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries, Sci. Total Environ. 657 (2019) 1023–1029.
[78] E.N. Udemba, Mediation of foreign direct investment and agriculture towards ecological footprint: a shift from single perspective to a more inclusive perspective for India, Environ. Sci. Pollut. Control Ser. 27 (21) (2020) 26817–26834.
[79] P.O. Agboola, M. Hossain, B.A. Gyamfi, F.V. Bekun, Environmental consequences of foreign direct investment influx and conventional energy consumption: evidence from dynamic ARDL simulation for Turkey, Environ. Sci. Pollut. Control Ser. (2022) 1–14.
[80] M. Moner-Girona, M. Solano-Peralta, M. Lazopoulou, E.K. Ackom, X. Vallve, S. Szabó, Electrification of Sub-Saharan Africa through PV/hybrid mini-grids: reducing the gap between current business models and on-site experience, Renew. Sustain. Energy Rev. 91 (2018) 1148–1161.
[81] J. Ausubel, A. Sladovich, Technological Advancement, National Academic publishers, Washington DC, US, 1999.
[82] J. Domac, K. Richards, S. Risovic, Socio-economic drivers in implementing bioenergy projects, Biomass Bioenergy 28 (2) (2005) 97–106.