Resources Policy 92 (2024) 105022

Contents lists available at ScienceDirect

Resources Policy

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

Influence of fintech, natural resources, and energy transition on environmental degradation of BRICS countries: Moderating role of human capital

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ARTICLE INFO

Keywords:
Natural resources
Financial technologies
Digitalization
Energy transition
Environmental degradation

ABSTRACT

The rapid pace of economic development experienced by the BRICS countries is accompanied by increased carbon (CO_2) emissions resulting from the excessive use of energy and natural resources. However, the emergence of recent technologies has led to the offering of efficient production methods with improved financing channels. This study analyzes the role of financial technologies, digitalization, natural resources, energy transition, and energy innovations on CO_2 emissions. It also tests the moderating effect of human capital in BRICS countries from 1995 to 2021. Initially, Augmented Mean Group (AMG) estimation approach is applied to conduct empirical analysis. Due to asymmetric data distribution and non-linear relationships among variables, the Method of Moments Quantile Regression (MMQR) approach is also applied to estimate the effect of the variables across different quantiles of CO_2 emission. The findings indicate that digitalization, financial technologies, energy transition, energy innovations, and natural resources reduce CO_2 emission, whereas human capital increases it. However, the moderating effect of human capital on the association between digitalization, energy transition, and CO_2 emission is significant and positive, indicating that human capital strengthens the negative impact of these factors on environmental degradation. Human capital does not significantly moderate the relationship of natural resources, financial technologies, and renewable energy innovations with CO_2 emissions.

1. Introduction

Environmental degradation has become a major challenge for sustainable development and human life. One of the main causes of this rising environmental degradation is the excessive release of greenhouse gases (GHG) in the climate, which causes various negative climate issues. CO_2 emission (CE) has the highest proportion of GHG emissions and corresponds to environmental degradation. With the start of the industrial revolution, CE increased by about 50% in tandem with economic growth, worsening the state of the environment. CE level continuously rises into the atmosphere, which has had far-reaching effects like flooding, drought, strong storms, glaciers melting, and increasing sea levels, all of which result in environmental degradation (Chien et al., 2021).

Economic activities are also associated with the increased level of urbanization and modernization of society, leading to over-extraction and over-utilization of natural resources (NR), intensifying environmental pollution issues. NR extraction and consumption are associated with water and air pollution and unfavorable environmental effects. It is known that mining, chain saw activities, and deforestation negatively

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https://doi.org/10.1016/j.resourpol.2024.105022
Received 20 November 2023; Received in revised form 6 April 2024; Accepted 18 April 2024
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impact biodiversity and cause serious soil, air, water contamination, etc (Nathaniel et al., 2021). However, some studies also contend that having a significant amount of NR is advantageous since it allows governments to replace extremely polluting petroleum, coal, natural gas, etc. Therefore, NR can aid in slowing down the increase of CE.

The United Nations (UN) emphasizes the significance of adaption and mitigation efforts to combat the devastation of climate extremes. The transition from fossil fuel to renewable energy resources helps realize these objectives because the massive use of fossil fuel-based energy resources is the main reason for environmental degradation (Y. Liu et al., 2023). Energy transition (ET) refers to shifting energy consumption from fossil fuel-based to environmentally friendly and clean energy sources. The growing concerns about energy security have greatly heightened the urgency of ET. Direct electrification supply, increasing green hydrogen, and energy efficiency would help promote ET. Undeniably, significant commitments to promote ET and reduce environmental degradation require increasing research and development and innovation efforts, particularly when governments consider ecological issues. This compels scholars and decision-makers to create new technologies and establish frameworks to handle the intricate relationships between energy infrastructure and environmental degradation. In this regard, there are increased investments in renewable energy technologies (RETECH) in advanced and emerging countries. RETECH improves the technological level in the renewable energy sector and promotes renewable energy consumption. Renewable energy is acknowledged as the energy for the future to curb CE and therefore, the massive renewable energy use can improve energy security and efficiency and curb climate change. For this reason, RETECH is frequently regarded as an affordable means of achieving zero-carbon societies (Lin and Zhu, 2019).

In the current era of the Industrial Revolution, the role of financial technologies (FT) and digitalization (DIG) in environmental degradation has been researched extensively for their impact on environmental sustainability. Academics have highlighted that FT advancements have the potential to revolutionize sustainable investing and green finance. FT supports the allocation of capital effectively towards environmentally friendly projects, encourages renewable energy consumption, and promotes sustainable practices by businesses through utilizing data analytics and digital platforms (Xu and Ullah, 2023). However, theoretically, the relationship of FT with CE is diverse and complicated. Four different theories explain the relationship between FT and CE. First, direct effect proposes that FT facilitates using durable products such as laptops, phones, tablets, and other e-commerce-related items, which require more energy to operate and increase environmental degradation (Z. Liu et al., 2023). The wealth effect hypothesizes that the FT industry can raise individuals' incomes by enhancing economic activities and employment opportunities in non-fungible tokens and crypto-currency areas. These sectors increase the energy demand, which damages the environmental quality. According to the business effect, FT facilitates and promotes new business models that can grow business spending, jobs, and volumes, increasing energy consumption. The substitution effect proposes that FT facilitates access to environmental technologies and energy-efficient initiatives help reduce energy use and environmental degradation (Tao et al., 2022).

In the meantime, digitalization (DIG) has accelerated in recent years and changed how people, businesses, and consumers behave, operate, and interact globally. This phenomenon is related to the advancement of mobile phone and internet technologies, which produce new processes, products, additional organizational complexities, market mechanisms, and technological advents. These technologies have increasingly penetrated the world economy, and almost all aspects of life are influenced by them, including social, economic, ecological, and political aspects (Li et al., 2023). The theoretical arguments about the role of DIG in environmental sustainability are inconsistent in the literature. On the one hand, integrating DIG with manufacturing technologies curbs CE by optimizing production processes (Pan et al., 2023). The "de-materialization impact," which shifts the economy's focus from physical to information resources, is another result of DIG contributing to improved environmental quality. Also, dematerialization reduces vehicle movement because people switch to online trading, e-commerce, distance learning, and virtual meetings. There is increased production efficiency through DIG-related products, reduced production cost, and cheaper product production. Consequently, the overall demand for products rises, worsening the state of the environment. Several studies report that DIG has benefited the environment by aiding in developing eco-friendly technologies. In addition to controlling the risks associated with the environment, DIG can foresee these hazards.

On the other hand, the application of DIG drives up energy consumption directly, especially non-renewable, and therefore, the energy consumption-related CE can go up simultaneously. Improvements in energy efficiency brought about by DIG use may potentially have the unintended consequence of creating a rebound effect, which would cause energy consumption to increase further and result in increased CE. In addition, the theoretical framework proposed by Kunkel and &Matthess (2020) classifies the environmental impacts of DIG into direct and indirect effects. The direct effect proposes that DIG is associated with a rise in energy use and the consumption of resources in the life cycle, which reduces environmental sustainability. On the other hand, the indirect effect indicates that DIG adoption impacts product structure, production scale, and process efficiency, which positively affects environmental sustainability. Thus a non-linear relationship is found between DIG and environmental sustainability according to these effects, leading to ambiguous findings and necessitating further investigation.

The importance of human capital (HC) in environmental quality has received the attention of researchers. Several advantages of the investment in HC, including labor productivity, higher growth, etc., have been reported along with several social externalities, including a lower rate of crime, more democratic participation and better and improved health. At the micro-level, many channels declared that the relationship between HC and CE is negative. First, more well-educated and qualified professionals facilitate the dispersion and innovation of climate change technologies during production. Firms with higher HC levels are likely to have long-term sustainable production. The firms that have more HC follow strict environmental pollution regulations. They have a lower likelihood of breaking environmental standards(Ahmed and Wang, 2019).On the macro level, HC affects CE through three channels: technology, physical capital, and income, making the relationship more complicated. The first "income effect" channel suggests that economic growth is mediatory in the relationship between HC and CE. HC promotes labour productivity and economic growth. Second, endogenous growth theory hypothesizes that HC catalyses technological innovations and promotes research and development expenditures (Romer, 1990). Technological innovations increase production efficiency and lead to energy sector transformation by increasing the supply of green and clean energy sources, reducing CE. Third, HC formation complements the investment in physical capital, promoting technology capital. Technology capital might turn out to use energy more efficiently, which could aid in lowering energy intensity and encouraging designs for energy use that are far greener and more environmentally friendly (Zhang et al., 2021).

Based on the above background, the present study estimates the role of FT, NR, DIG, ET, RETECH and HC on environmental degradation under the STIRPAT framework in BRICS countries (Brazil, India, Russia, China, and South Africa) from 1995 to 2020. There are several reasons for selecting BRICS economies. Over the years, these economies have enjoyed rapid growth and collectively account for 21 % of global GDP. Moreover, India, Russia, and China are among the top CE emitters globally. BRICS countries have 42 percent of the global population, consuming approximately 40 percent of energy and emitting about 43 percent of total CE, causing serious health and environmental challenges. A clear picture of the inter-temporal trends in CE levels shown in Fig. 1 reveals that the total volume of CE annually by the BRICS

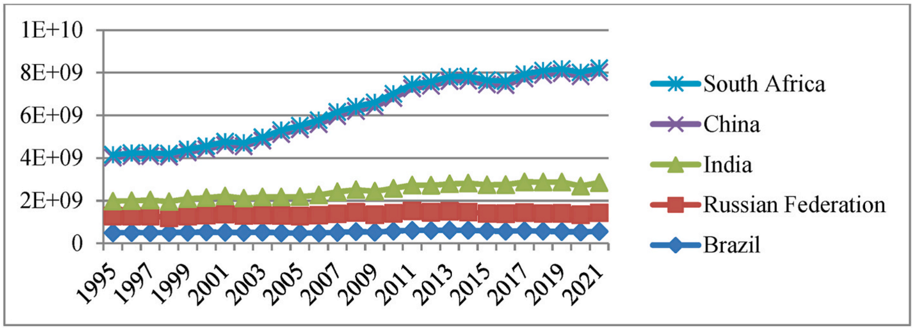

Fig. 1. Carbon Emission in individual BRICS countries (1995–2021).

countries has increased progressively from 1995 to 2021, and the cumulative annual CE in these countries increased by approximately 6.4% annually. Thus, the statistical trend evaluation supports the mounting concerns about climate change caused by CE across the BRICS countries.

As mentioned above, the BRICS countries are experiencing rapid economic development primarily because of the rise in industrialization, which requires more NR extraction and the ever-rising energy demand. Fig. 2 reveals the ever-increasing demand for NR extraction in BRICS countries over the 1995 to 2021 period. This depletion of NR over the past three decades is the main reason for the loss of bio-capacity value and increased environmental degradation. More unfortunate is the over-dependence of these nations on conventional non-renewable energy resources. It clarifies that the BRICS countries have failed to grow their renewable energy industries undergoing ET. Therefore, the average share of renewable energy in the total energy consumption in BRICS economies is very low, as shown in Fig. 3.Even more alarming is that the countries have increased their reliance on fossil fuels over time instead of decreasing it. Since it is impossible to cut the use of NR and energy use, as these are the most important factors of production in the manufacturing sector, the BRICS countries must adopt innovative approaches to transition to sustainable energy and advance environmental sustainability (Shan et al., 2024).

Thus, efficient strategies are required in the BRICS economies to address the rising demand for fossil fuels and environmental concerns. Out of these strategies, the adoption of cost-cutting and green technologies has been emphasized heavily at several BRICS summits in recent years. However, except in China, the progress in green technologies, particularly in renewable energy technologies, has been very slow in most of the BRICS countries shown in Fig. 4 therefore, these innovations are not contributing significantly to reducing CE in BRICS.

According to recent statistics, the expansion of DIG in BRICS countries has spurred industrial upgrading and financial growth, posing a significant negative effect on energy consumption. The FT sector penetration in BRICS has constantly increased over the last two decades, as shown in Fig. 5. FT can potentially accelerate the BRICS countries' transition to a new environmentally friendly banking sector using smart management techniques and industrial automation to support CE reduction. However, strengthening HC is key to achieving sustainable EG and adopting technological advancements. HC is regarded as one of the primary factors in changing a country's energy mix by supporting the advancement of technology capabilities, innovative energy transformation processes that prioritise the green economy, and the effective management of energy resources. HC aids in minimising fossil fuel energy consumption in the production process. The development of HC has also contributed to the emergence of a more qualified labour force and the renewal of the talent capable of using RETECH, FT, and DIG in the manufacturing of goods and services.

Interestingly, the mechanism through which HC influences the effect of these variables on CE is not yet known. Therefore, the main purpose of this research is to estimate the effect of FT, ET, RETECH, DIG, and NR under the moderating role of HC on CE in BRICS economies. Particularly in developing countries like BRICS, HC can be hypothesized to make these countries capable of using environmentally sustainable and efficient NR consumption and adoption of technological advancements in all sectors. As a result, it is reasonable to expect these factors to impact the environmental quality in BRICS countries simultaneously.

The study aims to contribute to the existing literature in the following prominent ways: First, the current study accompanies those few existing studies that tried to estimate the effect of FT and NR on CE in BRICS countries. In addition to FT and NR, the study also considers

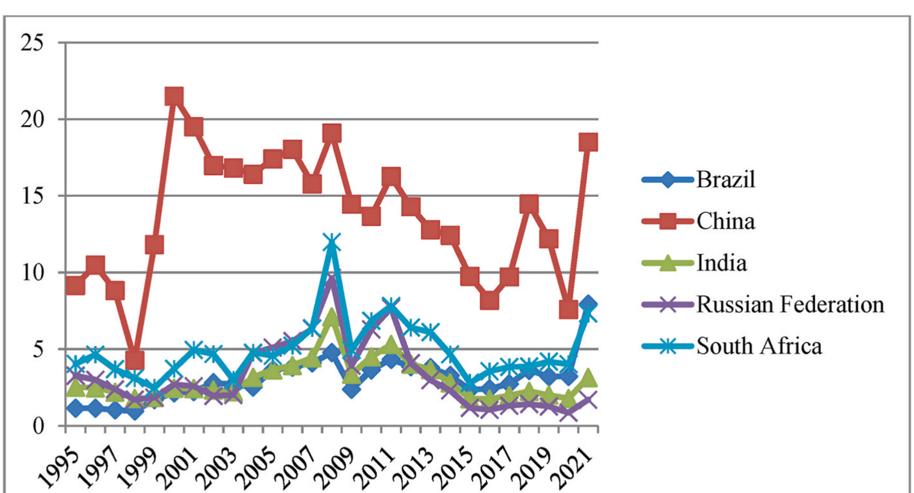

Fig. 2. Nr consumption in BRICS over (1995–2021).

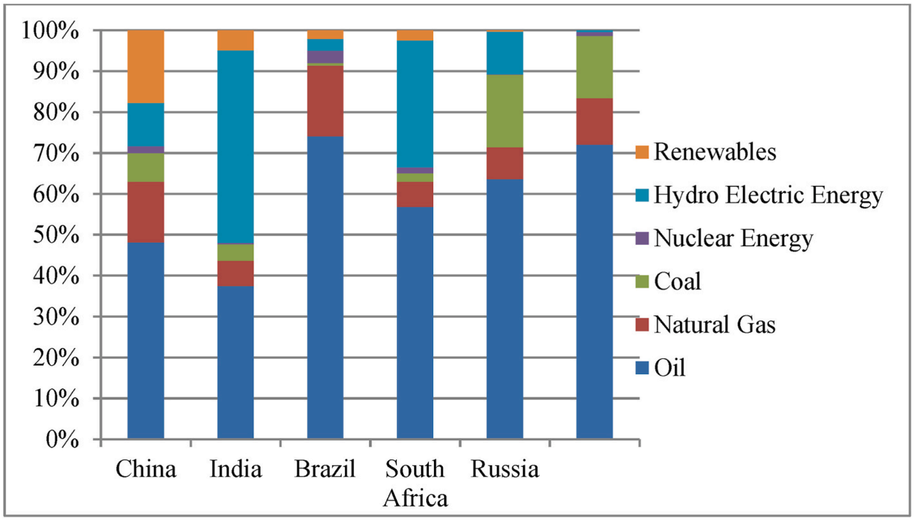

Fig. 3. Share of renewable and non-renewable sources in total energy in BRICS (2021).

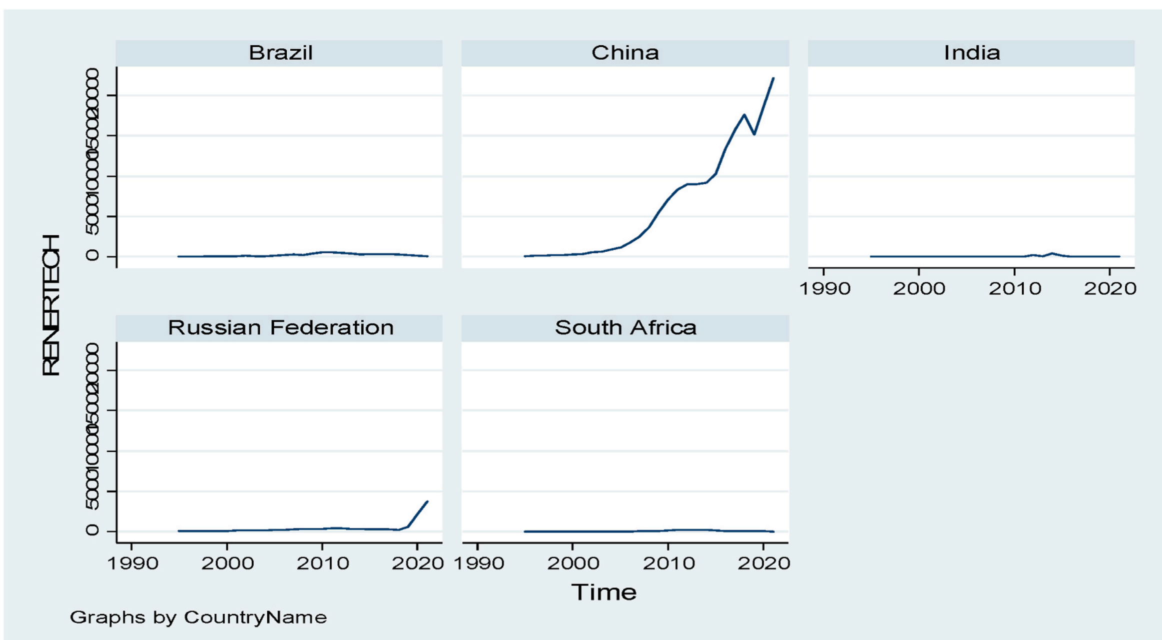

Fig. 4. Retech adoption in BRICS countries (1990–2021).

the effect of HC, ET, RETECH, and DIG on CE in BRICS countries, which, to our best knowledge, has not been studied before in BRICS countries context. Second, previously, the role of FT, NR, ET, RETECH, and DIG were estimated independently on CE in different countries, but the moderating effect of HC on relationship between FT, NR, ET, RETECH, DIG and CE is not explored yet. The present study contributes to the literature by estimating the joint impacts of FT, DIG, NR, RETECH, ET, and HC on CE in BRICS economies. Third, the study applies AMG estimation to address the issues of slope heterogeneity and cross-sectional dependence (CSD) present in the data. The study also contributes to the body of knowledge by employing the nonlinear panel estimation technique, namely MMQR to conduct empirical analysis, as non-parametric and asymmetric techniques are not commonly used to study the role of studied variables in CE. MMQR can deal with the issues of endogeneity, heterogeneity, and the presence of outliers in data series, enabling the BRICS countries to identify the effect of FT, NR, ET, RETECH, HC, and DIG at different quantiles of CE.

The study is organized in the following order: Section 2 reviews existing literature. Data and methodology are provided in Section 3. Section 4 gives results and discussions. The conclusion of the study and policy implications are given in section 5.

2. Review of the literature

The driving factors of CE are diverse and complicated. Researchers all around the world conducted different studies on these important determinants and proposed diverse strategies for CE mitigation according to their findings The most common theoretical model explaining the important determinants of environmental quality is the Stochastic Impression on Regression, Population, Affluence, and Technology (STIRPAT) framework proposed by Dietz and Rosa (1994). To explain the environmental challenges, this framework emphasizes three main factors, population, wealth, and technology. To fulfill the study objectives, the study takes theoretical support from the STIRPAT framework

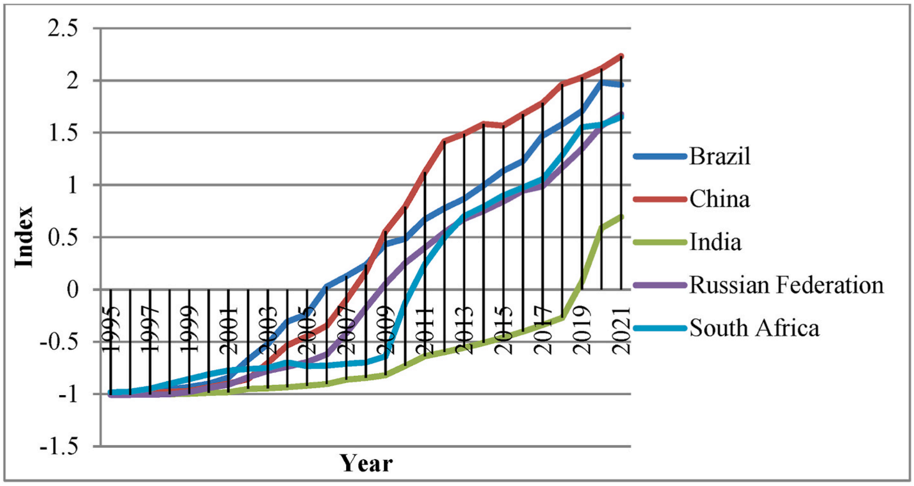

Fig. 5. FT Penetration in BRICS over the 1995 to 2021 period.

to validate the theoretical relationship among the study variables. It aims to explore the effect of DIG, FT, ET, NR, and RETECH on CE in the presence of HC.

Using the STIRPAT framework, the researchers have previously explored the relationship of the abovementioned variables with environmental quality or degradation. We divide the available literature into three strands for review as follows.

2.1. Financial technologies and environmental degradation

Literature witnessed a significant number of studies on the FT and CE nexus. Researchers have tried to study the effect of FT on CE promotion or reduction; however, inconclusive research studies on the association between FT and CE are available. J. Xu et al. (2023) analyzed the nexus between FT and CE in the case of Chinese provinces from 2011 to 2020. FT was found to impact CE negatively in China. Similarly, Udeagha and &Muchapondwa (2023b) also attempted to estimate the FT contribution to achieving the carbon neutrality target for the 2000 to 2018 period. CS-ARDL technique was used, which showed the positive contribution of FT in achieving the carbon neutrality target. FMOLS estimation was used to indicate the negative relationship between FT and CE. In the case of India, Nenavath and Mishra (2023) analyzed the moderating role of FT in CE and green finance relationship for the period 2010–2020. FT was found to have a positive moderating effect on the negative relationship between green finance and CE. However, in contrast to the studies mentioned above, Guo and Yin (2023) found the opposite results in their study for China while analyzing the nexus between FT and CE. NARDL findings indicated that FT promoted CE via both positive and negative shocks. Likewise, DİLEK and &Furuncu (2019) found that FT in terms of Bitcoins and blockchain technologies promoted energy use and increased CE level. Mora et al. (2018) concluded that bitcoin and cryptocurrencies are energy-hungry and blameworthy for enhancing CE globally.

2.2. Natural resources and environmental degradation

NR has a significant role in environmental degradation; therefore, the number of studies on the subject matter has significantly increased. The effect of NR on environmental quality/degradation can be positive or negative, and the association between NR and environmental degradation is found to be ambiguous in the literature. Khan et al. (2020) estimated the nexus between NR and CE by considering a panel of BRI countries over the 1990 to 2016 period and using System and Difference GMM estimation. According to their findings, NR had a positive impact on CE. Thus, the study concluded that NR is detrimental to environmental quality. Similarly for BRI countries, Hussain et al. (2020) reached similar conclusions while exploring the relationship between NR and CE from 1990 to 2014. AMG and CCEMG analyses were conducted in the study, revealing NR's positive role in CE promotion.

On the other hand, some researchers have reported the positive contribution of NR towards reducing CE. Balsalobre-Lorente et al. (2018) analyzed the relationship of NR with CE in 5 EU countries for the 1985 to 2016 period. The findings uncovered the negative effect of NR on CE. More so, Nathaniel (2021) evaluated the dynamic NR effect on the ecological footprint in ASEAN from 1990 to 2016. According to the findings of the Augmented Mean Group estimator, NR was found to impact the ecological footprint negatively. Sun et al. (2021) studied the association between NR and environmental sustainability from 1995 to 2015. The study outcomes revealed NR's negative effect on environmental sustainability.

2.3. Human capital and environmental degradation

In recent decades, the relationship between HC and environmental quality has occupied the research's central position as a subject matter. Although several research studies have discussed the positive role of HC in environmental performance, several researchers have concluded that HC can harm the atmospheric or environmental quality. For instance, Rahman et al. (2021) estimated the effect of HC on CE by taking a panel of newly industrialized countries over 1979 to 2017 period. The negative association between HC and CE was observed using second generation panel estimations. In this way, the researchers have concluded that HC positively promotes environmental sustainability. In addition, a negative moderating effect of HC was observed in the relationship between internet use and CE. In the case of BRICS countries, X. Li and &Ullah (2022) estimated the role of HC in CE for 1991 to 2019 period, applying the NARDL panel estimation approach indicated that positive shocks in education reduced CE, whereas negative shocks in education increased CE. Likewise, in the case of Central Asian States, Isiksal et al. (2022) also studied the effect of HC in CE for the 1995 to 2018 period. Pooled Mean Group estimation revealed a significant negative effect of HC on CE.

In contrast, in the case of BRICS countries estimated the role of HC on CE but no significant effect of HC was found on CE in AMG, CCEMG, and AMG estimations. Similarly, P. Li and &Ouyang (2019) explored the effect of HC on CE in China using ARDL analysis. The N-shaped relationship was present between HC and CE, i.e., CE first increased then decreased and again increased with a rise in HC. In a study for China, Sarkodie et al. (2020) researched the effect of HC on CE for 1961 to 2016 period and concluded that HC was conducive for CE escalation.

2.4. Digitalization and environmental degradation

Researchers have widely explored the impact of the digital economy on the sustainable environment and development with the advent of digital technology worldwide. However, researchers cannot find a definite conclusion regarding the role of DIG on environmental sustainability/quality. For instance, considering individual BRICS countries' data, Yang et al. (2021) researched the role of DIG in CE. The ARDL estimation approach was applied, indicating that DIG had positively contributed to promoting environmental sustainability by reducing CE. Thus, they concluded that DIG helps reduce the issues related to global warming. Similar evidence was also provided by X. Li et al. (2021), who considered the data for 190 countries from 2005 to 2006 to estimate the role of the digital economy on CE. The basic Fixed Effects model revealed the inverted U-shaped association between digital economy and CE. Similar evidence was also given by the earlier estimation of (Kwilinski et al., 2023) for EU countries. The study estimated the DIG and CE nexus from 2006 to 2020. According to the findings of the Panel panel-corrected standard Error approach, DIG was found to reduce CE.

In contrast, some studies report opposite conclusions and blame DIG for increasing CE. Like, (Higón et al., 2017) estimated DIG's effect on CE in a global panel of 142 countries. According to the findings of OLS, Pooled OLS, and Driscoll-Kraay standard errors, DIG positively contributed to promoting CE. Asongu et al. (2018) analyzed the role of DIG in CE in Sub-Saharan African countries using the GMM estimation approach. No significant impact of DIG was found to have on CE in the selected countries.

2.5. Energy transition and environmental degradation

Contrary to above-mentioned factors, the role of ET in CE is still under research. Only a few studies have previously explored the role of ET in CE or any environmental degradation indicator. Tang et al. (2022) analyzed the impact of ET on the ecological footprints in BRICS economies from 1992 to 2018 applying CUP FM and CUP BC estimation. The results showed that ET reduced ecological footprints. Bouyghrissi et al. (2022) analyzed the relationship between renewable energy consumption and CE in Morocco from 1980 to 2017. Using ARDL estimation, the study found that renewable energy consumption reduces CE in Morocco. On the other hand, some researchers depict the opposite story. Yu-Ke et al. (2022) analyzed the data for 42 environmentally polluted countries over the 1995 to 2019 period to understand the effect of renewable energy on industrial and transport-based CE. Their study found an inverted U-shaped association between renewable energy and CE. That is, renewable energy first increased and later decreased CE. Jebli and Youssef (2017) estimated the effect of ET on CE in North American countries, and their findings revealed that ET increased the level of CE in the selected countries in the long run. Likewise for Malaysia, Raihan and &Tuspekova (2022) concluded that ET had a negative but insignificant impact on CE.

2.6. Renewable energy innovations and environmental degradation

The association between RETECH and environmental degradation is still under research compared to the massive empirical evidence available regarding the role of environmental innovations and environmental degradation. Some of these limited studies have concluded that RETECH is a blessing for promoting atmospheric quality. Shahbaz et al. (2018) estimated the effect of energy innovations on CE in France from 1955 to 2016 using the Bootstrapping ARDL Bound Cointegration approach. The study's results indicated the negative impact of energy innovations on CE. For 17 OECD countries, Balsalobre-Lorente et al. (2019) also analyzed the effect of energy innovations on GHG emissions and concluded that energy innovations reduced environmental pollution in OECD countries. In continuation, Bai et al. (2020) considered the data from Chinese provinces from 2000 to 2015 to study the relationship between RETECH and CE. The panel Fixed Effects Model was used in the study to indicate that RETECH reduced CE in China. However, in contrast to earlier conclusions, the study of Pata et al. (2023) in the USA found that RETECH had no significant impact on CE in Augmented ARDL estimation.

2.7. Research gap

The literature review reveals that studies have mainly focused on the role of NR, FT, DIG, and HC in environmental degradation, but the findings remain inconclusive. According to our knowledge, no empirical study exists trying to explore the moderating effect of HC on the relationship between NR, ET, RETECH, FT, DIG, and CE. The current study is aimed at filling this research gap by estimating the moderating effect of HC on the relationship between NR, FT, DIG, RETECH, ET, and CE in BRICS countries.

3. Data and employed methodology

3.1. Model Construction

This study intends to investigate the impact of FT, NR, ET, RETECH, and DIG on CE under the moderating effect of HC over the 1995 to 2021 period in BRICS economies. Theoretically, the study uses the STIRPAT model to construct the models. The basic form of this framework is expressed as:

$$I_i = \alpha P_i^{\beta} A_i^{\gamma} T_i^{\delta} \varepsilon_i \tag{1}$$

Where I represents environmental impacts, P, A, and T denote population, affluence, and technology, respectively. The STIRPAT framework allows every coefficient to be estimated and the proper decomposition of parameters so that several other influencing factors can be added to the model according to the characteristics of each study. In addition to examining the basic science of environmental change, the STIRPAT model identifies the variables that might respond most positively to policy.

In the present study, we measured I by CE, P by urban population, A by economic growth, and T by DIG, FT, and RETECH. Due to the flexible nature of the STIRPAT model, NR, ET, and HC are added to the STIRPAT model to specify the study model. Thus, the baseline model of the study is specified as.

3.1.1. Model 1: baseline model

$$\mathrm{CO_{2it}} = \mathrm{f\ (NR, FT, DIG, HC, RETECH, ET, URB, GDP)} \tag{2}$$

In econometric form, the model can be written as:

$$CO_{2it} = \alpha_0 + \beta_1 FT_{it} + \beta_2 NR_{it} + \beta_3 DIG_{it} + \beta_4 HC_{it} + \beta_5 ET_{it} + \beta_6 RETECH_{it} + \beta_6 GDP_{it} + \quad \beta_7 URB_{it} + \mu_{it} \tag{3}$$

After introducing HC into the model as a moderator, the model takes the following form.

3.1.2. Model 2: Moderation effect model

$$CO_{2it} = \alpha_0 + \beta_1 FT_{it} + \beta_2 NR_{it} + \beta_3 DIG_{it} + \beta_4 HC_{it} + \beta_5 ET_{it} + \beta_6 RETECH_{it} + \beta_6 GDP_{it} + \quad \beta_7 URB_{it} + \beta_7\ HC * FT_{it} + \beta_7\ HC * NR_{it} + \beta_7\ HC * DIG_{it} + \varepsilon_{it} \tag{4}$$

Where i and t refer to cross-section and period, CO_2 denotes CO_2 emission, NR shows natural resources, FT refers to financial technologies, HC represents human capital, DIG shows digitalization, *GDP economic growth*, *URB is urbanization and* μ_{it} is the error term.

Following Table 1 gives measurements of the variables and their data sources.

3.2. Applied methodologies

3.2.1. AMG regression

The study applies the AMG estimation Bond and &Eberhardt (2013) proposed for empirical estimation. The main reason for selecting the AMG approach is that the findings of AMG are more robust in the presence of CSD, heterogeneity, and non-stationarity within the panel data. It measures explicit parameter estimates for the unobserved common factors, which show a dynamic common process as the meaningful construct. AMG estimation approach is independent of the non stationarity characteristic of the panel data. The unknown standard dynamic effects are estimated using a two-step process in AMG estimation, which also allows CSD to include the value for the conventional dynamic effect.

$$\Delta y_{it} = a_{1i} + \beta_i \Delta x_{it} + \varphi_i f_t + \sum_{t=2}^{T} \tau_t DUMMY_t + \varepsilon_{it} \tag{5}$$

Where Δ is the operator, τ denotes time dummy parameters known as the standard dynamic procedure. The second step adds an explicit factor or variable for every group member in the regression model (group-specific). The explanatory variable is subtracted from the AMG estimator to force the application of the unit parameter. It also averages the parameters of the model throughout the panel. Every regression that includes the time-invariant fixed effect intercept is added.

$$AMG = N^{-1} \sum_{i=1}^{N} \widetilde{\beta}_i \tag{6}$$

where $\widetilde{\beta}_i$ is the coefficient estimation in the below equation.

$$\Delta y_{it} = a_{1i} + \beta_i \Delta x_{it} + \varphi_i f_t + \sum_{t=2}^{T} \tau_t DUMMY_t + \varepsilon_{it} \tag{7}$$

3.2.2. MMQR regression

The quantile regression analysis examines the heterogeneous and distributional effects at every quantile. Machado and Silva (2019) proposed an enhanced version of quantile regression known as MMQR, which also considers fixed effects. This method efficiently calculates the impact of covariance of factors using conditional heterogeneity. This approach is also effective when the model is rooted in individual effects and contains endogenous explanatory factors. Since MMQR can consider the non-normality of the data as well as the non-linear relationship among the variables, it holds its superiority over other non-linear approaches such as "NARDL" by deriving the benchmark values from the data, by keeping fixed effects equal to zero instead of explaining the nonlinear features exogenously. These facts make the MMQR robust and more legit, especially in generating asymmetrical links and non-linear relationships and addressing outlier presences, heterogeneity, and endogeneity issues. The conditional quantiles of the location and scale variation model Qy(|X) are shown as follows:

$$\dot{Y}_{it} = \dot{\alpha}_i + X_{it} \varnothing + \left(ƛ_i + Z_{it}^{'}\psi\right) \ddot{U}_{it} \tag{8}$$

In equation (8), þ (ƛi + Ƶ′it $\psi > 0$) = 1 shows probability, whereas (ƛ, F, J, α̇) ′ is calculated based on coefficients. (ƛi, α̇i), = 1 – n represents the fixed effects whereas Ƶ represents k vector modules of Ẍ. The evident variations are shown in the following equation (9).

$$Z_j = Z_j\left(\ddot{X}\right).j = 1\ to, k \tag{9}$$

Where time-period and in, Ẍ′$_{it}$ andÜ$_{it}$are distributed identically. Ü$_{it}$ shows standard momentum condition orthogonal to series Ẍ′$_{it}$. equation (9) can be alternatively written as follows:

$$Q_y\ (\delta!\ \ddot{X}'it) = (\lambda_i q(\delta) + \dot{\alpha}_i) + Z_{it}^{'} + \ddot{X}_{it}\rho\bar{\varrho}q(\delta) \tag{10}$$

In equation (10), Ẍ, represents the vector of all variables i.e., CO_2, FT, ET, RETECH, NR, HC, GDP, URB. Qy (d| Ẍ′$_{it}$) represents the quantile distribution of Ẏ$_{it}$. The dependent variable constrains the position of the independent variable. α̇i (**δ**)≡ ƛi q (**δ**) + α̇i; denotes scalar which shows fixed effects **δ'** in quantiles at distinct i. Individual sample quantiles are denoted by q(**δ**) achieved by solving the following optimization;

$$Min_q = \sum_i \sum t\eta\delta\, q\left(R_{it} - \left(\lambda_i + Z_{it}^{'}\gamma\right)\right) \tag{11}$$

ṅ0 (Ȑ) = TȐÎ (Ȑ > 0) + (**δ**– 1) ȐÎ and (Ȑ < 0) is the calculated operator.

4. Results and discussions

Descriptive or summary statistics of data series are reported in Table 2. We can see that RETECH has the highest mean and standard deviation among all data series, whereas DIG has the lowest values for mean and standard deviation. Moreover, highly significant statistics of the J-B test reveal that data is not normally distributed.

Moreover, the relationship between the dependent and independent variables is shown graphically in Fig. 6. The charts indicate a non-linear relationship between the dependent and all independent variables. Therefore, the MMQR method is the most appropriate or suitable to

Table 1
Variables of the study and data sources.

Series	Proxy	Source	Literature Support
Human Capital	Human Capital Index	Penn World	Hassan et al. (2019)
Financial Technologies	Index comprising of Fixed Broad Band subscription and Mobile cellular subscription (both per 100 people) and Individuals using Internet (% of population)	WDI	S. S. Xu et al. (2023).
Renewable Energy Innovations	Climate change mitigation technologies related to renewable energy generation	OECD	You et al. (2022)
Natural resources	Natural resource Rents (as percent of GDP)	WDI	Hanif et al. (2022)
CO_2 emission	CO_2 emission (metric ton per capita)	WDI	Hanif et al. (2022)
Digitalization	Digital Trade [ICT related exports (% of total exports) + ICT related imports (% of total imports)]	WDI	Shahbaz et al. (2022)
Energy Transition	Ratio between renewable energy and non-renewable energy	EIA	Caetano et al. (2022)
Economic Growth	Gross Domestic Product Growth (annual percentage)	WDI	Appiah et al. (2020)
Urbanization	Growth of urban population (annual percentage)	WDI	Ahmad et al. (2022)

WDI denotes World Development Indicators, and OECD shows the Organization for Economic and Cooperation Development.

Table 2
Descriptive/summary statistics.

Variable	Mean/ Average	Std. deviation	Min Value	Max Value	J-B statistics
CE	5.372	3.781	0.765	11.884	13.022***
ET	0.198	0.231	0.024	0.727	47.763***
NR	5.598	4.805	0.863	21.502	68.237***
FT	0.0089	1.000	−1.007	2.233	15.244***
DIG	0.0063	1.000	−1.256	1.799	10.537***
HC	2.492	0.493	1.6011	3.418	7.475***
RETECH	1447.08	3929.3	1.000	22144.0	988.4***
GDP	4.456	4.034	−7.799	14.230	7.043***
URB	1.881	1.217	−0.466	4.198	3.915***

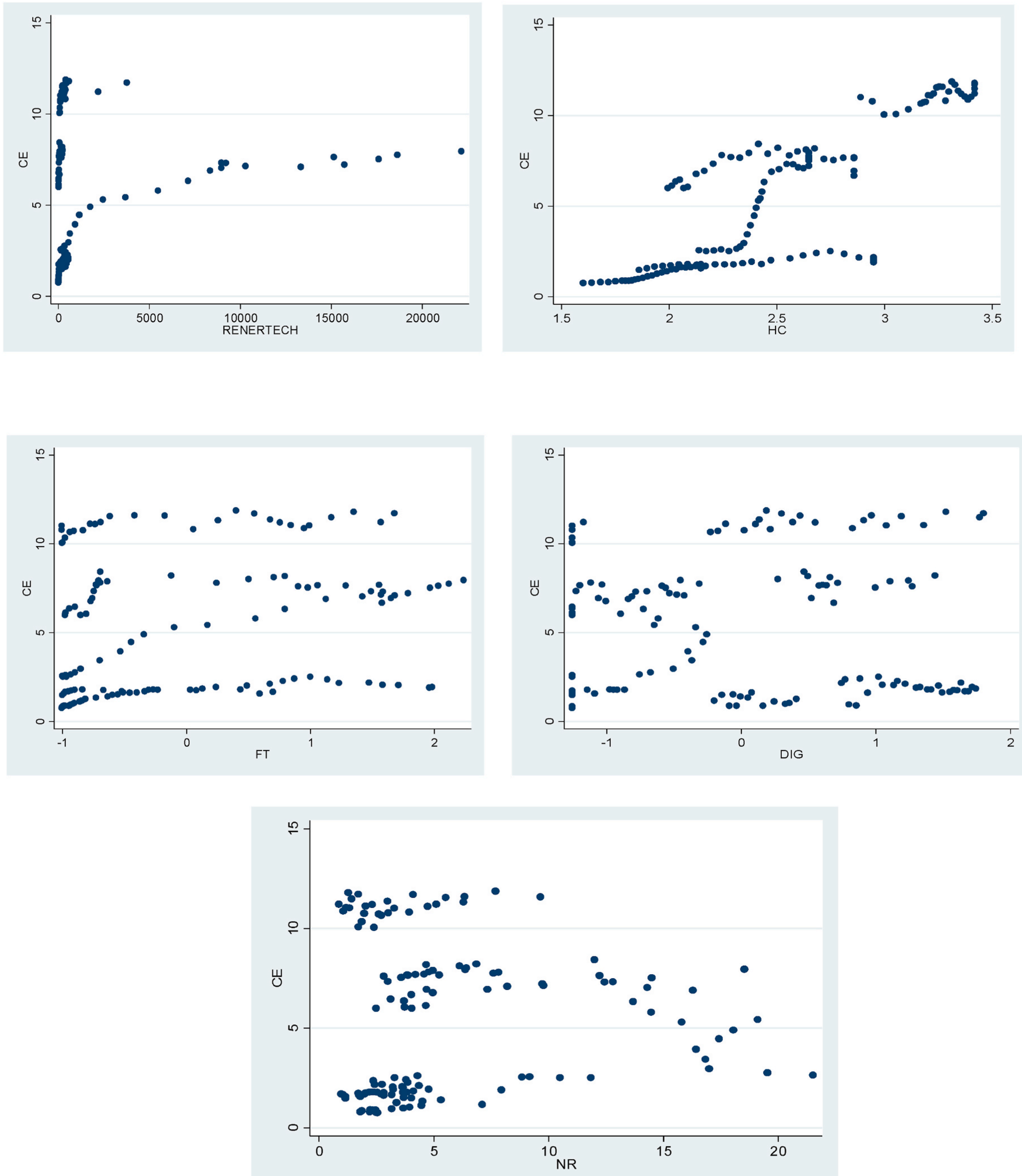

Fig. 6. Visual Representation of the relationship between dependent and independent variables.

Table 3
Correlation matrix.

	CO_2	FT	HC	ET	DIG	ET	NR	URB	GDP
CO_2	1.000								
FT	0.256	1.000							
HC	0.005	0.535	1.000						
ET	−0.421	0.153	−0.028	1.000					
DIG	0.035	0.418	0.363	0.197	1.000				
RETECH	0.180	0.552	0.101	−0.087	−0.155	1.000			
NR	0.052	0.151	−0.103	−0.290	−0.211	0.479	1.000		
URB	−0.610	−0.179	−0.734	−0.201	−0.324	0.174	0.524	1.000	
GDP	−0.207	−0.227	−0.313	−0.259	−0.140	0.213	0.538	0.491	1.000

apply in the present study because of its capability to deal with these issues efficiently.

Table 3 presents a correlation matrix revealing the correlation among study variables. ET, URB, and GDP are negative, whereas FT, DIG, RETECH, and NR correlate positively with CE. Since all values are less than 0.8, multicollinearity is not present among variables.

The second step before proceeding to formal empirical analysis is CSD testing. The Pesaran (2004) test was applied to achieve this, and the corresponding findings are given in Table 4. According to the findings, the variables are cross-sectionally dependent in these countries.

Table 5 gives the findings of the slope homogeneity test. According to these results, the slopes are heterogeneous in BRICS countries.

Due to the presence of CSD and slope heterogeneity in data, the study applies second-generation CIPS and CADF tests. The results of these tests are provided in Table 6. Both test results reveal a mixed order of integration among variables, i.e., some variables are stationary at level, whereas others are stationary at the first difference.

4.1. Baseline regression results (model 1)

The results of long-run estimation using the AMG approach are reported in Table 7 for Model 1. As mentioned previously, that data series has the issues of non-normal distribution, and non-linear relationship is found to exist between dependent and independent variables (evident in graphical analysis); the study selects to apply MMQR estimation also as this technique can efficiently deal with the issues of CSD, non linear relationship between dependent and independent variables and non-normality in the distribution in data series. The corresponding findings for the baseline model are reported in Table 8, capturing the effect of explanatory variables across various quantiles where CE is distributed (conditionally) at all quantiles. The significance and sign of all explanatory variables' coefficients differs across all quantiles. It shows that variables have heterogeneous effects on CE at various quantiles. First, we discuss the findings of both techniques for Model 1 (see Table 9).

First, the FT coefficient is significant and negative in AMG and MMQR estimations.Regarding the magnitude of the effect, a unit increase in FT declines CE by 0.121 units in AMG. Likewise, in MMQR, FT affects CE significantly and negatively over the entire range of quantiles (i.e., 0.1 to 0.9), with the impact gradually increasing as we move from lower to higher quantiles.The finding aligns with the earlier studies of Udeagha and &Muchapondwa (2023a) and Tao et al. (2022). Theoretically, thesustainable effect hypothesis supports the positive effect of FT on CE reduction. FT has a major role in facilitating and promoting the adoption and use of eco-friendly technologies and energy-efficient initiatives thatreduce pollution and improve environmental quality. Furthermore, the FT inclusion in the finance or banking sector significantly reduces the dependence on conventional energy-intensive finance and the banking sector and aids in improving environmental quality. FT optimizes energy use, increases energy efficiency, and facilitates green investment, green finance facilities, and renewable energy consumption (Muhammad et al., 2022).

Second, the coefficient of NR is significant and negative in AMG and MMQR regressions, indicating that NR reduces CE. More specifically, CE is found to decline by 0.0018 units in AMG due to a unit increase in NR. MMQR estimation seconds this finding as the effect of NR on CE is significant and positive at extreme higher quantiles (i.e., 0.7 to 0.9) with increasing magnitude. A possible reason is that the abundance of NR promotes environmental sustainability by promoting the use of a country's own energy resources (e.g., renewable sources and natural gas) because the abundance of NR reduces the need for imports of fossil fuels (e.g. gas or petrol). Lowering the import of fossil fuel-based NR, such as coal, in BRICS countries and their utilization leads to a reduction in emissions. Also, the consumption of renewable NR in production activities enhances environmental quality as it helps in reducing CE. Another reason for the positive contribution of NR in CE reduction is that the sustainable management of NR is combined with production and consumption, which reduces the rate of NR depletion and environmental stress and permits the regeneration of NR. The transition from remote technologies (causing NR exploitation) to advanced technologies that integrate reprocessing, recycling, innovation, artificial resources, and value-addition that substitute NR will lead to economic growth and improve environmental sustainability (Baloch et al., 2019). Previously, the findings of (Baloch et al., 2019)and Tufail et al. (2021) align with our results.

Third, the AMG results indicate that DIG significantly negatively affects CE as we observe a decline of 1.308 units in CE for every unit increase in DIG. Similarly, in MMQR results, the effect of DIG on CE is significantly negative over the entire quantile range (0.1–0.9) but with decreasing magnitude of the impact. This finding indicates the power of DIG to promote environmental sustainability by adopting more sustainable work practices such as online shopping, remote work, digital communications, etc. When communities and individuals have more

Table 4
Results of the CSD test.

Variables	Test Stat/P-value
CO_2	11.302*** (0.000)
FT	15.143*** (0.000)
NR	10.123*** (0.000)
HC	16.038*** (0.000)
DIG	8.388***(0.000)
ET	4.078*** (0.000)
RETECH	6.395*** (0.000)
GDP	14.811*** (0.000)
URB	0.287***(0.037)

Table 5
Slope heterogeneity results.

DV: CO_2 emission	
Test Stat	Statistics/Prob-value
Delta tilde	19.118*** (0.000)
Adjusted Delta tilde	22.109*** (0.000)

Note: DV = dependent variable and *** = $P < 0.05$.

Table 6
Unit root tests.

CIPS CADF				
Variables	Level	1st Difference	I(0)	I (1)
CO_2	−2.433***	–	−2.009	−2.387 ***
FT	−0.241	−3.115***	−1.121	−2.265 ***
NR	−1.679	−4.556 ***	−1.846	−4.310 ***
HC	−4.224	−2.492***	−3.713***	–
DIG	−1.634	−5.146***	−1.614	−2.830***
ET	−0.419	−4.710***	−0.303	−3.131***
RETECH	−0.239	−2.520***	−1.580	−3.536***
GDP	−0.531	−2.605***	−1.049	−3.023***
URB	−1.175	−2.869***	−1.541	−1.813 ***

Table 7
AMG findings for baseline model.

Variables	Coefficient	Prob-Value
FT	−0.1210**	0.0877
NR	−0.0018**	0.095
HC	1.308**	0.052
DIG	−0.0279**	0.069
ET	−5.468***	0.038
RETECH	−0.0021***	0.029
GDP	0.0157	0.363
URB	−0.2602	0.172

*** = $P < 0.05$, ** = $P < 0.10$.

Table 8
MMQR findings for baseline regression (model 1).

Series/Variables											
Location	Scale		Quantile levels								
BRICS Countries			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
FT	−0.733** (0.256) [-2.86]	−0.0727 (0.118) [-0.61]	−0.631** (0.311) [-2.03]	−0.651*** (0.293) [-2.22]	−0.669** (0.281) [-2.38]	−0.6902** (0.268) [-2.57]	−0.741*** (0.256) [-2.90]	−0.762*** (0.258) [-2.95]	−0.799** (0.272) [-2.93]	−0.822*** (0.287) [-2.86]	−0.841*** (0.303) [-2.77]
NR	0.0286 (0.0440) [0.65]	0.203 (0.020) [0.99]	0.0007 (0.053) [0.00]	0.005 (0.0508) [0.12]	0.0107 (0.0486) [0.22]	0.0166 (0.0466) [0.36]	0.031 (0.444) [0.70]	0.036 (0.0448) [0.82]	0.047*** (0.0047) [10.0]	0.053*** (0.0049) [10.8]	0.059*** (0.0052) [11.34]
HC	5.252*** (0.627) [8.37]	−0.229 (0.290) [-0.79]	5.574*** (0.763) [7.30]	5.509*** (0.7199) [7.65]	5.454*** (0.6891) [7.92]	5.388*** (0.6595) [8.17]	5.225*** (0.6287) [8.31]	5.161*** (0.6345) [8.13]	5.044*** (0.6693) [7.54]	4.971*** (0.7060) [7.04]	4.909*** (0.7450) [6.59]
DIG	−0.430 (0.1622) [-2.65]	0.0352 (0.0750) [0.47]	−0.479*** (0.1974) [-2.43]	−0.469*** (0.1860) [-2.52]	−0.461*** (0.1780) [-2.59]	−0.450*** (0.1702) [-2.65]	−0.425*** (0.1622) [-2.63]	−0.416*** (0.1636) [-2.54]	−0.398** (0.1729) [-2.30]	−0.386** (0.1824) [-2.12]	−0.377*** (0.1925) [-1.96]
ET	−6.503*** (0.6412) [-10.14]	0.0603 (0.296) [0.20]	−6.588*** (0.7806) [-8.44]	−6.571*** (0.7357) [-8.93]	−6.556*** (0.703) [-9.32]	−6.539*** (0.6728) [-9.72]	−6.496*** (0.6406) [-10.14]	−6.479*** (0.6464) [-10.02]	−6.44*** (0.6833) [-9.44]	−6.429*** (0.7215) [-8.91]	−6.413*** (0.7614) [-8.42]
RETECH	0.0020*** (0.00004) [4.71]	−0.0016 (0.00002) [-0.82]	−0.0022*** (0.00005) [-4.31]	−0.002*** (0.00005) [-4.48]	−0.002*** (0.00004) [-4.60]	−0.002*** (0.00004) [-4.70]	−0.002*** (0.00004) [-4.66]	−0.001*** (0.00004) [-4.52]	−0.001*** (0.00004) [-4.10]	−0.001*** (0.00004) [-3.78]	−0.001*** (0.00005) [-3.50]
GDP	−0.081** (0.443) [-1.83]	−0.075*** (0.0205) [-3.69]	0.249 (0.0532) [0.47]	0.003 (0.050) [0.07]	−0.0145 (0.0486) [-0.30]	−0.036 (0.0480) [-0.76]	−0.0903** (0.0472) [-1.91]	−0.111** (0.0476) [-2.33]	−0.15*** (0.0478) [-3.13]	−0.174*** (0.0493) [-3.53]	−0.194*** (0.0518) [-3.75]
URB	−0.847*** (0.2514) [-3.37]	0.092 (0.1162) [0.79]	−0.977*** (0.306) [-3.19]	−0.950*** (0.288) [-3.30]	−0.928*** (0.276) [-3.36]	−0.902*** (0.264) [-3.41]	−0.836*** (0.2518) [-3.32]	−0.810*** (0.2541) [-3.19]	−0.763** (0.2681) [-2.85]	−0.734*** (0.2828) [-2.60]	−0.709*** (0.2984) [-2.38]

Note:*** = P < 0.05 and ** = P > 0.05 Standard errors are given in parentheses and z-values in square bracket.

Table 9
AMG findings for Moderation effect regression (model 2).

Variables	Coefficient	Prob-Value
FT	−0.6827**	0.071
NR	−0.246	0.629
HC	3.484**	0.052
DIG	−0.548*	0.093
ET	−29.068	0.690
RETECH	−0.0082	0.892
GDP	0.0164	0.124
URB	0.0138	0.959
HC*NR	0.1818	0.447
HC*FT	0.1858	0.771
HC*DIG	0.0122	0.959
HC*RETECH	0.0050	0.752
HC*ET	2.963	0.937

*** = P < 0.05, ** = P < 0.10.

access to DIG and resources, these practices reduce the need for transportation and, therefore, associated CE declines (Kwilinski et al., 2023). Moreover, DIG adoption promotes production efficiency during production of the output of a country, which promotes environmental sustainability (Ozcan and Apergis, 2018).As DIG advances, more meetings and transactions are being conducted electronically, reducing energy use and environmental degradation (Higón et al., 2017). The findings of Kwilinski et al. (2023), and Ahmed, Nathaniel, and Shahbaz (2021) align with our findings supporting that DIG sector has favorable implications for environmental sustainability.

Fourth, ET is found to have a negative effect on CE in AMG estimation and MMQR estimations. Regarding the size of the coefficient, every unit rise in ET is associated with a decline of 5.468 units in CE and vice versa. The similar finding is observed in MMQR estimation as the ET reduces CE significantly at all quantiles (0.1–0.9) but the magnitude of the effect reducing as we move from lower to higher quantiles. This finding reveals that BRICS countries can achieve sustainable development by including and advancing renewable energy resources for energy generation (Ulucak and Khan, 2020). A reasonable justification of this fact is that renewable resources are free of hydrocarbon, so the combustion of renewable energy resources does not cause CE to rise.ET also; involves the decarbonization of the power sector and by replacing the coal-fired electricity production with wind, hydroelectric or solar power production, CE associated with power generation are significantly declined. Another aspect of the ET is to enhance the energy efficiency measures. The efficient use of energy in transportation, industries, appliances and buildings help in decreasing the overall energy use and ultimately reduces CE(Adebayo et al., 2024). The finding is in line with the earlier estimation of (Q. Wang et al., 2022; Bouyghrissi et al., 2022).

Fifth, RETECH also affects CE negatively in AMG and MMQR estimations. More specifically, the coefficient indicates that for every unit increase in RETECH, CE is observed to be decreased by 0.002 unit in AMG finding. Similarly according to the findings of MMQR analysis, the coefficient of RETECH is statistically significant and negative over all quantiles (0.1–0.9), with the coefficient decreasing as we move from lower to higher quantiles. This also reveals that RETECH reduces CE in BRICS countries. The finding is justified because RETECH increases energy efficiency and promotes socioeconomic development. RETECH helps reduce energy consumption and improves environmental quality (Pata et al., 2023). The degree of RETECH can modify the energy structure and effectively enhance the capacity of renewable energy supply to satisfy energy demand, which ultimately negatively affects CE. Using renewable energy instead of burning fossil fuels in power production significantly reduces or even leads to zero CE.As renewable energy technologies continue to advance, more affordable and efficient solutions are produced, increasing the accessibility and competitiveness of clean energy as compared to fossil fuels (Adebayo et al., 2024). Earlier estimation of Bai et al. (2020) and (Adebayo et al., 2024) support our findings.

Sixth, the findings of AMG analysis reveal that HC has a significant positive impact on CE as a unit increase in HC is associated with 1.30 unit rise in CE in AMG estimation. Similar evidence is provided in MMQR as HC is found to enhance CE over all quantiles (0.1–0.9), with the magnitude of the effect gradually decreasing as we proceed from lower to higher quantiles. Although it is a surprising finding but,it is justifiable by several explanations. First, HC promotes a skilful and knowledgeable workforce that promotes economic activities. Higher economic activities depend on more energy use, which is considered the main factor contributing to promote CE (Nathaniel et al., 2021). Another possible justification for this positive effect can be the use of less skilled labour force to achieve economic development which does not participate in economic production by considering environmental repercussions into account. The adoption of green development would be hampered unless significant investments are made in promoting the health and education of the labour force. There would be short run increase in CE because of the establishment of the educational infrastructure (Aqib and Zaman, 2023). Moreover, the higher unemployment rate of the educated population of a country leads to the depreciation of HC over time being not used and predicts a decline in sustainable development (Sarkodie et al., 2020). Previous studies report similar findings, including Haini (2021) and X. Li and &Ullah (2022), providing empirical support for our results.

Regarding control variables, the study finds that GDP and URB have no significant impact on CE in AMG analysis. However, according to the MMQR analysis, GDP and URB reduce CE. This contradiction in the findings of AMG and MMQR regressions supports the power of MMQR to effectively capture the unobserved heterogeneity that linear estimation techniques fail to consider, making the effect of an independent variable inconsistent not only in means but also over quantile distribution. In this situation, the findings of MMQR are more authentic and reliable as the conditional averages of the variables are weak or inconsistent. Therefore, the association's sign and strength vary as we move from mean to quantile distribution and from one quantile to another (Chikh-Amnache and Mekhzoumi, 2023). The coefficient of GDP is statistically significant and negative from medium to higher quantiles (0.5–0.9) only. Previously, many empirical estimations supported our findings, including Castro and Lopes (2022), as they argued that GDP promote sustainable development by reducing CE. This finding posits that a higher level of economic growth is associated with the transition of production system from higher CE based to lower CE based by creating more demand for environmental sustainability and promoting the use of environmentally friendly technologies (Zubair et al., 2020). Similarly, the findings of MMQR regression indicate that URB negatively impacts CE over the entire quantile range (0.1–0.9) but with a gradually declining magnitude of the impact. This indicates that the process of URB is associated with the flow of knowledge, resources, innovations and information, potentially mitigating the climatic changes and CE level(Chen et al., 2022). This suggests that the scale effect of URB helps to lower the intensity of resource consumption and CE (Wang et al., 2021).The findings of Abubakar and Ejaro (2013) and Chen et al. (2022) support our results from earlier studies.

4.2. Moderation effect regression Results(Model 2)

In contrast to Model 1, as we introduce HC as moderator, the sign and significance of many variables change in AMG and MMQR estimations. This makes the NR, ET, and RETECH effect insignificant in CE in Model 2. Also, we find that all interaction terms are insignificant in AMG analysis. However, according to MMQR findings, the interaction terms (HC*NR) (HC*RETECH) and (HC*FT) are insignificant and negative over all quantiles (0.1–0.9), indicating that HC does not play a moderating role in the effect of NR and FT on CE. However, HC positively moderates the adverse effect of DIG on CE over (0.3–0.8) quantiles and the negative effect of ET on CE over all quantiles as the interaction terms (HC*ET) and (HC*DIG) are statistically significant. In other words, HC enhances the effect of these variables on CE. This shows that although HC alone does not reduce CE, if it is integrated with DIG, the development of green DIG infrastructure can be expected to reduce CE level in BRICS countries. This finding justifies that HC increases the economy's capability to develop new and advanced technologies during development. HC, a combination of skill and knowledge, is a main factor in promoting and adopting advanced technologies during the course of production capable of ensuring environmental sustainability(Zaborovskaia et al., 2020).

HC formation also enhances the capacity of a country to adopt new technological innovations according to the economy's demand (Salam et al., 2019).Investment in HC provides a technologically trained broad HC base well equipped with digital skills(Nkogbu, 2015)to efficiently use DIG infrasture which would help reduce CE (Trkman and Černe, 2022).Likewise, the positive interaction term (HC*ET) implies that more accumulation of human resources improves the understanding of renewable resources, thereby increasing the consumption and environmental benefits of renewable energy resources. Furthermore, HC accumulation enhances efforts and behaviors about awareness of the environment, environmental behavior, and the purchase of environmentally friendly goods, which all aid in the transition to greener energy consumption and enhance its effect on mitigating CE(Wiredu et al., 2023).

However, HC fails to significantly moderate the nexus between FT, NRRETECH and CE in BRICS economies. A possible justification for this finding can be the lack of innovation development in developing or emerging economies, which is insufficient for achieving the institutional and structural modernization of the economies, hindering knowledgeable workforce creation capable of continuing advancement in technology development. Particularly, the labour force in BRICS countries is less skilled and less capable than in advanced economies. This lack of higher and more skilful education increases the countries' dependency on advanced countries for the development and adoption of technologies and innovations (S. Li et al., 2024). This inadequacy in the educational system would present a serious obstacle for the HC to significantly moderate the relationship of RETECH, NR and FT with CE.(see Table 10)

5. Conclusion and recommendations

Extending the traditional STIRPAT framework, this study aims to analyze the effect of NR, FT, DIG, ET, RETECH on environmental degradation under the moderating role of HC considering data of BRICS countries for the 1995 to 2021 period. The study employed AMG to analyze the long-run relationship among the variables. However, because of the issues of non normality in data distribution and non linear relationship between dependent and independent variables, the study selects to apply MMQR which provides more efficient and reliable findings. The outcomes of the AMG analysis reveal that NR, FT, ET, RETECH, and DIG have negative effects, but HC has a positive effect on CE in BRICS countries. These findings are also valid in MMQR regression. Introducing HC as a moderator into the model makes the effect of DIG, ET, NR, ET, and RETECH insignificant on CE in AMG estimation. However, MMQR finds that HC positively moderates the negative relationships of DIG and ET with CE indicating that HC strengthens the negative effect of these factors on CE. However, HC does not moderate the relationship of FT, NR, and RETECH with CE in MMQR regression. The findings of MMQR are more supporting and authentic because of the issues of CSD, non normality and non linear relationship in model.

Based on the results, the study recommends some worthy policies. First, the governments in BRICS countries are recommended to formulate and promote efficient policies for FT promotion, particularly in the finance and banking sector. Secondly, policymakers should strengthen fiscal expenditure to guide capital and financial institutions in transferring funds to promote FT adoption and penetration. Policymakers are also recommended to adopt policies regarding the digital sector to progress in advancing new and environmentally friendly ICT

Table 10
MMQR findings for Moderation Effect Regression (Model 2).

Variables	Location	Scale	Quantile Levels								
BRICS Countries			0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
FT	0.215 (2.147) [0.10]	2.059 (1.664) [1.24]	−2.415 (2.025) [-1.19]	−2.025 (1.890) [-1.07]	−1.394 (1.797) [-0.78]	−0.996 (1.829) [-0.54]	−0.292 (1.979) [-0.15]	−0.7852 (2.447) [-0.32]	−2.031 (3.167) [-0.64]	−3.119 (3.860) [-0.81]	4.376 (4.757) [0.92]
NR	0.0709 (0.3037) [0.23]	0. 334 (0.2354) [1.42]	−0.356 (0.2868) [-1.24]	−0.293 (0.267) [-1.10]	−0.1910 (0.254) [6.91]	−0.1261 (0.259) [-0.49]	−0.0117 (0.280) [-0.04]	−0.1635 (0.347) [-0.47]	−0.366 (0.448) [-0.82]	−0.5432 (0.546) [-0.99]	0.747 (0.672) [1.11]
HC	5.487*** (0.8196) [6.69]	−1.508*** (0.6354) [-2.37]	7.414*** (0.7399) [10.02]	7.128*** (0.681) [10.45]	6.667*** (0.664) [10.03]	6.374*** (0.706) [9.03]	5.859*** (0.776) [7.55]	5.069*** (0.9577) [5.29]	4.157*** (1.198) [3.47]	3.359*** (1.406) [2.39]	2.439 (1.723) [1.42]
DIG	−2.150*** (0.9132) [-2.35]	0.761 (0.7079) [-1.08]	−1.177 (0.863) [-1.36]	−1.321 (0.806) [-1.64]	−1.554** (0.765) [-2.03]	−1.702** (0.777) [-2.19]	−1.962** (0.839) [-2.34]	−2.360** (1.038) [-2.27]	−2.821** (1.346) [-2.09]	−3.224** (1.645) [-1.96]	−3.689* (2.028) [-1.93]
ET	16.135*** (3.0054) [5.37]	−1.862 (2.329) [-0.80]	−18.51*** (2.878) [-6.43]	−18.16*** (2.693) [-6.74]	−17.59*** (2.544) [-6.91]	−17.231** (2.558) [-6.73]	−16.594** (2.754) [-6.02]	−15.620** (3.407) [-4.58]	−14.49** (4.452) [-3.26]	−13.50*** (5.484) [-2.46]	−12.372* (6.767) [-1.83]
RETECH	0.0013 (0.0014) [0.98]	−0.0012 (0.0010) [-1.13]	−0.0029 (0.0013) [-2.21]	−0.002 (0.0012) [-2.18]	−0.002 (0.0011) [-1.98]	0.020 (0.0011) [1.75]	0.00167 (0.0012) [1.30]	0 0.0010 (0.0015) [0.64]	0.0002 (0.0020) [0.14]	−0.0003 (0.0025) [-0.15]	−0.0011 (0.0031) [-0.36]
GDP	−0.0821 (0.0572) [-1.44]	−0.0778** (0.0443) [-1.75]	0.0172 (0.0530) [0.32]	0.0024 (0.0493) [0.05]	−0.0213 (0.0473) [-0.45]	−0.0364 (0.048) [-0.47]	−0.0629 (0.053) [-1.18]	−0.1037 (0.065) [-1.58]	−0.150** (0.084) [-1.79]	−0.191*** (0.101) [-1.90]	−0.239*** (0.124) [-1.93]
URB	−1.277*** (0.315) [-4.05]	−0.383 (0.244) [-1.57]	−0.786*** (0.296) [-2.66]	−0.859*** (0.275) [-3.12]	−0.9770** (0.263) [-3.71]	−1.051*** (0.269) [-3.90]	−1.182*** (0.292) [-4.04]	−1.383*** (0.361) [-3.82]	−1.615** (0.465) [-3.47]	−1.817*** (0.563) [-3.23]	−2.052*** (0.693) [-2.96]
HC*NR	0.0076 (0.108) [0.07]	−0.1059 (0.084) [-1.26]	0.1429 (0.103) [1.39]	0.122 (0.096) [1.28]	0.0905 (0.0913) [0.99]	0.0699 (0.092) [0.76]	0.0337 (0.100) [0.34]	−0.021 (0.123) [-0.17]	−0.0857 (0.160) [-0.53]	−0.141 (0.196) [-0.72]	−0.206 (0.241) [-0.85]
HC*FT	−0.1644 (0.719) [-0.23]	−0.6804 (0.557) [-1.22]	−0.7046 (0.678) [-1.04]	−0.5758 (0.633) [-0.91]	−0.3676 (0.602) [-0.61]	−0.235 (0.612) [-0.38]	−0.0033 (0.662) [-0.01]	−0.352 (0.819) [-0.43]	−0.764 (1.060) [-0.72]	−1.123 (1.293) [-0.87]	−1.539 (1.594) [-0.97]
HC*DIG	0.774*** (0.334) [2.25]	0.317 (0.266) [1.19]	0.3687 (0.324) [1.14]	0.4288 (0.303) [1.41]	0.5259** (0.288) [1.82]	0.587*** (0.293) [2.00]	0.695*** (0.317) [2.19]	0.8618*** (0.392) [2.20]	1.053*** (0.507) [2.08]	1.221*** (0.619) [1.97]	1.415** (0.762) [1.86]
HC*RETECH	−0.0004 (0.0005) [-0.89]	0.0004 (0.0004) [1.11]	−0.0010*** (0.004) [-2.10]	−0.009** (0.0004) [-2.07]	−0.0008** (0.0004) [-1.86]	−0.0007 (0.0004) [-1.64]	−0.00057 (0.0004) [-1.20]	−0.0003 (0.0005) [-0.57]	−0.00006 (0.0007) [-0.09]	0.0001 (0.0009) [0.18]	0.0004 (0.0011) [0.38]
HC*ET	−9.912*** (1.314) [-7.54]	0.1298 (1.018) [0.13]	10.07*** (1.263) [7.97]	10.054** (1.184) [8.49]	10.01*** (1.11) [8.97]	9.989*** (1.11) [8.95]	9.944*** (1.199) [8.29]	9.876*** (1.483) [6.66]	9.798*** (1.947) [5.03]	9.729*** (2.409) [4.04]	9.650*** (2.975) [3.24]

Note:*** = $P < 0.05$ and ** = $P > 0.05$ Standard errors are given in parentheses and z-values in square brackets.

infrastructure that would improve environmental sustainability. DIG infrastructure must be revolutionized to foster sustainable growth. The BRICS government should augment the institutional environment to develop the DIG economy, facilitate the DIG infrastructure development, promote the DIG transformation of the production sector, and allocate the funds for DIG adoption for the green development of the production sector industry.

Based on the positive role of RETECH in reducing CE found in the study, BRICS economies are recommended to strengthen the production of RETECH by enhancing innovation skills which leads to sustainable social and economic development. In this regard, we argue that the government's technology policy should be integrated with environmental policy and technological advancement should be directed towards achieving sustainable development goals. Businesses and firms must be incentivized to invest properly in RETECH to achieve energy efficiency and transition the energy sector in a more environmentally friendly way. As the findings indicate that ET reduces CE, it is recommended that more GDP share should be allocated to the extraction of renewable energy resources. For this, more emphasis should be placed on efficient policies to provide funding facilities to incentivize production firms to use more renewable resources during production processes.

Additionally, collaborations between the public and private sectors can be used in this regard, which will aid in switching the energy sector from nonrenewable to renewable sources. Likewise, HC positively impacts CE in the analyses; the study recommends that governments promote environmental education to improve HC. Particularly in BRICS countries, a policy cycle to develop and enhance environmental education and its deployment is needed to boost HC's contribution towards achieving sustainable development goals. Governments should encourage institutions to promote a green economy, as environmental education is an instrument for a green and clean economy. In this way, BRICS economies could reduce CE through HC without compromising economic growth. Moreover, the companies related to NR extraction should be encouraged to promote efficient resource extraction to avoid over-exploitation of the resources.

The present study has limitations that future research studies must incorporate and fill. The study analyzes the effect of total NR on CE. Future research studies are recommended to analyze the effect of mineral, oil, gas, coal resources, etc., on CE. In addition to RETECH, other green innovations, such as carbon capture and storage, hydrogen technologies, enabling technologies, etc. can be considered for the study. The BRICS countries are considered a panel for empirical analysis in the current study, while future studies can take individual countries for empirical analysis.

Fund information

This work was supported from the project fund (Grant No. KX2024B02) of the Center for Trans-Himalayan Studies, the Sichuan provincial key research base of humanities and social sciences.

CRediT authorship contribution statement

Xiaoli Liao: Writing – original draft, Conceptualization. **Hafizah Mat Nawi:** Formal analysis, Data curation. **Pham Hoang An:** Writing – review & editing, Supervision. **Fatma Mabrouk:** Writing – review & editing, Writing – original draft, Validation. **Rukhsora Kholikova:** Writing – review & editing, Writing – original draft, Methodology. **Gioia Arnone:** Writing – review & editing, Software. **Nizar M.F. Sahawneh:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2023R260), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

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