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Eco-literate societies: the interplay of education, environmental policy stringency, and digital innovation in BRICS nations

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As emerging global economic powers, BRICS nations face a critical challenge in balancing rapid development with environmental sustainability. While industrial expansion, digital transformation, and urbanization have accelerated economic growth, these trends have also intensified ecological pressures, necessitating comprehensive policy solutions. Recognizing this urgency, the present study examines the determinants of environmental sustainability in BRICS nations from 1990 to 2023, focusing on economic growth (E.G.,), urbanization (URB), education (EDU), digital innovation (DI), and environmental policy stringency (EPS). By addressing the complex interactions among these variables, the study aims to provide empirical insights into how socioeconomic and technological advancements shape environmental outcomes. To achieve this, the study employs the Method of Moments Quantile Regression (MMQR) to capture heterogeneous effects across different sustainability levels, Feasible Generalized Least Squares (FGLS) for robustness validation, and Granger causality analysis to establish directional relationships. The findings reveal a nonlinear role of education, where in the linear model, EDU exacerbates environmental degradation due to its early association with industrial expansion. However, in the nonlinear model incorporating EDU^2, education exhibits an inverted U-shaped effect, initially straining the environment but later fostering sustainability as higher attainment levels promote ecological awareness and technological innovation. Urbanization consistently enhances sustainability across models, while digital innovation imposes environmental burdens, highlighting the need for green technological policies. Economic growth presents mixed effects, suggesting that regulatory interventions are required to steer economic expansion toward sustainable pathways. The study's novelty lies in its empirical approach, uncovering threshold effects of education and asymmetries in digital innovation's environmental impact, providing deeper insights into sustainability dynamics within emerging economies. The policy implications are profound—governments must integrate sustainability into education reforms, urban development strategies, and digital regulatory frameworks to ensure long-term ecological resilience. By aligning sustainability policies with SDG commitments and COP climate agreements, BRICS nations can effectively transition toward a green economic model, balancing development with environmental stewardship.

KEYWORDS

sustainable environment, digital innovation, urbanization, education, environment policy stringency

1 Introduction

Environmental sustainability has emerged as a critical challenge for BRICS nations—Brazil, Russia, India, China, and South Africa—as they experience rapid economic growth, urbanization, and digital transformation (Farooq et al., 2023; Zhao et al., 2024). These developmental shifts, while driving industrial progress, have also intensified environmental pressures, particularly in the form of rising carbon emissions and ecological degradation (Caglar et al., 2023; Esmaeil et al., 2020; Kongbuamai et al., 2020; Tariq et al., 2024). Countries like China and India face increasing health and environmental risks linked to air pollution and fossil fuel dependency, highlighting the urgency of aligning economic development with sustainability goals (Dincă et al., 2022; Eyuboglu et al., 2024; Ma et al., 2025; Sajith Kumar et al., 2022).

Ecological sustainability, as used in this study, refers to the capacity of natural systems to maintain their essential functions, diversity, and productivity over time while supporting human development needs (Caglar et al., 2024). To operationalize this concept, we utilize biocapacity as a proxy indicator of environmental sustainability. Biocapacity measures the biological productivity of ecosystems—specifically their ability to regenerate resources and absorb waste, including carbon emissions. It comprises several land-use components: cropland, grazing land, forest land, fishing grounds, and built-up land. These components collectively reflect the ecological pressure exerted by human activities and the regenerative capacity of the environment. Environmental sustainability demands a balance between resource consumption and regeneration, and its attainment requires not just technological innovation but also institutional commitment and societal behavioral change (Buhari et al., 2020; Gao and Fan, 2023). Closely linked is the concept of resilience, which denotes the ability of ecosystems and social systems to absorb disturbances, adapt, and reorganize without compromising long-term functionality or the continued provision of ecosystem services (Gayen et al., 2024; Luo et al., 2024). In the context of BRICS, resilience encompasses the adaptability of environmental policies, urban systems, and human capital to shifting socio-economic and ecological conditions.

The global urgency of these challenges is articulated in the United Nations Sustainable Development Goals (UNSDGs)—a blueprint for achieving a better and more sustainable future by 2030. Several goals are directly pertinent to this study: SDG 4 (Quality Education), SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). These goals underscore the need to integrate environmental objectives into education, technology, governance, and economic development (Akrofi et al., 2022). Moreover, SDGs 14 (Life Below Water) and 15 (Life on Land) are foundational to the entire SDG framework, acting as multipliers of co-benefits across the goals. Conservation of biodiversity under these goals supports the achievement of other SDGs by enhancing ecosystem services, promoting resilience, and sustaining livelihoods. This interdependence highlights the necessity of incorporating biodiversity considerations into strategies aimed at achieving the broader SDG agenda (Obrecht et al., 2021).

In this context, education (EDU), digital innovation (DI), and urbanization (URB) represent three pivotal forces shaping environmental outcomes in emerging economies. EDU is frequently cited as a driver of sustainable behavior and policy innovation (Li et al., 2023). However, its influence is not monolithic. For this study, we adopt the standard classification where primary and secondary education represent lower educational levels, while tertiary education (such as university or vocational degrees) constitutes higher education. Tertiary education is often linked to ecological responsibility and technological advancement, while lower education levels have been historically associated with industrial expansion and increased environmental strain (Haseeb et al., 2023; Kalaycı Alas and Korutürk, 2024; Li et al., 2025), suggesting a nonlinear relationship between educational attainment and environmental outcomes.

Building on this, digital innovation (DI) also plays a complex role. Emerging technologies such as AI and IoT can facilitate sustainability goals through smarter systems and efficiencies but may simultaneously lead to greater emissions and electronic waste if deployed without robust regulatory oversight (Adebayo et al., 2022; Dilanchiev and Taktakishvili, 2021; Hu et al., 2024; Lisha et al., 2023; Ramzan, 2021). Thus, understanding the governance of digital transformation becomes critical, especially in contexts where institutional capacity may be uneven (Li and Jianxing, 2024; Sinha et al., 2020a; 2020b; Waris et al., 2023).

Urbanization (URB), the third focal parameter, continues to reshape socio-environmental systems. While structured urban development can promote sustainability through efficient infrastructure and land use, unregulated expansion frequently contributes to habitat loss and pollution (Mehmood et al., 2023; Yang et al., 2024). The interplay between URB and environmental policy stringency (EPS) is also crucial, as the real-world impact of such policies depends heavily on their design and enforcement, which vary across national contexts (OECD, 2022).

Given these complexities, this study investigates how EDU, DI, URB, EPS, and economic growth (E.G.,) influence the sustainable environment (SE) in BRICS nations from 1990 to 2023. In doing so, it seeks to fill critical gaps in the literature by:

- Examining the nonlinear effects of education on sustainability,
- Evaluating the environmental consequences of digital innovation, and
- Assessing how urbanization and policy stringency interact with sustainability outcomes in different national contexts.

A key methodological contribution of this study lies in its use of a multi-analytical approach to explore the environmental impacts of education, digital innovation, and urbanization across BRICS nations. Specifically, we employ Method of Moments Quantile Regression (MMQR) to capture variations in these relationships across different levels of sustainability performance—an advancement over conventional mean-based models that often overlook such distributional nuances. Additionally, Feasible Generalized Least Squares (FGLS) is applied to enhance robustness against heteroscedasticity, and Granger causality analysis is used to examine potential directional influences among variables. Together, these methods provide a more differentiated and context-sensitive understanding of sustainability dynamics in emerging economies.

By integrating education, technology, urbanization, and policy into a unified analytical framework, this research advances a comprehensive model of sustainability planning tailored to emerging economies. Its alignment with SDG commitments and COP climate agreements ensures relevance for both national policymakers and international development agendas.

This study formulates the following hypotheses to guide empirical investigation:

H1: Higher levels of educational attainment—particularly tertiary education—will have a positive and significant effect on environmental sustainability across BRICS nations, reflecting the role of education in promoting environmental awareness and policy engagement.

H2: Increased digital innovation is expected to exert a positive influence on sustainability outcomes by enhancing efficiency and supporting green technologies, although its benefits may be offset if not managed with appropriate environmental safeguards.

H3: Urbanization, when accompanied by structured infrastructure and planning, will have a positive and significant impact on environmental sustainability through resource optimization and reduced *per capita* emissions.

H4: Both economic growth and environmental policy stringency are hypothesized to have a positive and significant association with sustainability performance, indicating the importance of institutional and economic drivers in shaping environmental outcomes.

These hypotheses are framed to reflect testable, directional expectations based on existing literature and are intended to inform empirical analysis and policy discussions on sustainability in emerging economies.

The subsequent sections are detailed as follows. Section 2 highlights the importance of leveraging digital innovation and education in urban settings to foster environmentally sustainable communities. Section 3 elaborates on the empirical methods used to examine the relationships between environmental policies, urbanization, education, urban population, and environmental health. Section 4 presents the key findings and discussions. Finally, the concluding section offers policy recommendations and final reflections.

2 Literature review

This section presents a review of the literature exploring the connections between education, ecological policies, urbanization, digital innovations, and environmental sustainability.

2.1 Education-environment link

Accurately assessing how environmental awareness influences non-renewable energy use in developing countries remains challenging due to data limitations (Li M. et al., 2021). While education plays a crucial role in promoting sustainable practices, its direct impact on environmental quality remains debated (Wu et al., 2023). Research examining China's low-carbon economy suggests that environmental education enhances public awareness, yet its effect on emissions reduction is conditional on policy enforcement and economic incentives.

Educational attainment has been linked to household energy efficiency and industrial pollution reduction, although these effects vary across sectors and regions Zhang G. et al. (2025) and Zhang et al.'s, (2025b) study focuses on air pollution and green innovation in industrial enterprises, finding that education fosters technological innovation rather than directly reducing household energy use. Similarly, Boujedra and Jebli, (2025) argue that digital transformation, driven by human capital development, improves environmental sustainability, but caution that education alone is insufficient for driving comprehensive emissions reductions.

Cordero et al. (2020) investigate the lifetime impact of education on individual carbon footprints rather than specific pollutants like CO_2, SO_2, and NO_2. Their findings suggest that education influences consumption patterns and long-term environmental behavior, but structural barriers limit its effectiveness in large-scale emissions mitigation. Sahu et al. (2024) examine higher education institutions' role in campus sustainability efforts, highlighting how universities integrate sustainability into research and operations rather than directly affecting national energy conservation trends.

Osuntuyi and Lean, (2023) explore the moderating effect of education on economic growth, energy use, and environmental degradation in African economies. Their results indicate that higher educational attainment supports energy efficiency and sustainable development, reinforcing the necessity of educational reforms in climate policy.

However, linking education directly to pro-environmental behavior (PEB) is complex. Gkargkavouzi et al. (2018) emphasize that educational attainment alone does not consistently predict environmentally responsible actions, as PEB is shaped by environmental identity, cultural norms, and socio-economic context. For instance, individuals with strong environmental identities often engage in sustainable behavior irrespective of their formal education level (Křepelková et al., 2020). Income also mediates access to sustainable lifestyle choices, such as electric vehicle adoption and energy-efficient appliances, suggesting that PEB is highly dependent on structural conditions rather than solely on education (Larson et al., 2015).

PEB spans multiple domains—public, private, and civic engagement—requiring nuanced measurement approaches (Larson et al., 2015; Markle, 2013). Recent studies advocate for multi-dimensional assessments of environmental behavior, incorporating factors such as intent, locality, and collective action (Markowitz et al., 2012). While environmental education may encourage recycling and energy conservation, higher-impact actions like home retrofitting or EV adoption remain contingent on economic affordability.

This understanding underscores that while education plays a vital role in fostering environmental consciousness, its influence is mediated by identity alignment, financial access, and behavioral context. Effective sustainability policies must incorporate these social and economic intersections to maximize education's environmental impact.

2.2 The ecological policies–environmental sustainability nexus

Environmental degradation is widely recognized as a negative externality, where market mechanisms fail to regulate pollution effectively. This necessitates government intervention through stringent environmental policies to mitigate ecological harm (Chen et al., 2020). Environmental economics provides a theoretical foundation for understanding how policy instruments—such as carbon pricing, subsidies for green technology, and regulatory frameworks—can correct market failures and promote sustainability (Baloch and Wang, 2019).

Governments employ various policy tools to enhance environmental sustainability (Li X. et al., 2021; Li et al., 2022; Li M. et al., 2021). Command-and-control regulations, such as emission limits and pollution permits, have been instrumental in reducing industrial emissions (Zhang G. et al., 2025). Additionally, market-based instruments, including carbon taxes and tradable emission allowances, incentivize firms to adopt cleaner technologies. Empirical studies highlight the effectiveness of these policies in reducing ecological footprints across G20 nations (Zhao et al., 2025).

Recent research underscores the role of institutional quality and technological innovation in shaping environmental policy outcomes (Dong and Yu, 2024). Strong governance structures and investment in green innovation significantly enhance policy effectiveness, ensuring long-term sustainability (Jie et al., 2024). Khan (2024) examines provincial environmental laws in Pakistan, demonstrating how constitutional amendments have empowered federal and provincial governments to enact targeted environmental protection measures.

Moreover, government-initiated environmental programs addressing CO_2 emissions and renewable energy adoption have proven effective in mitigating climate change impacts (Ouyang et al., 2020). Studies on low-carbon city transformations reveal that integrated policy approaches—combining regulatory, economic, and technological strategies—yield substantial environmental benefits (Cai et al., 2024; Xu et al., 2023).

2.3 The urbanization–environmental health connection

The relationship between urbanization and environmental health has been widely studied, with researchers emphasizing both its challenges and potential solutions. Jiang et al. (2025) examined the Urban Vulnerability-Adaptation-Settlements (VAS) nexus, demonstrating that rapid urbanization exacerbates environmental stressors, including air pollution and resource depletion. Their study highlights the importance of smart governance and green infrastructure in mitigating these adverse effects. Similarly, James (2024) assessed the environmental consequences of urbanization, identifying key concerns such as habitat loss, excessive resource consumption, and increased greenhouse gas emissions. His findings suggest that equitable development policies and conservation efforts are essential in counteracting urbanization-induced environmental degradation.

Expanding on these perspectives, Qian (2024) conducted an empirical analysis of urban expansion in China, India, and Indonesia, revealing that urbanization significantly accelerates carbon emissions. However, the study also found that institutional quality and renewable energy adoption can moderate these effects, suggesting that policy interventions play a crucial role in shaping sustainable urban growth. These findings align with broader research on urbanization and environmental health, such as Sun et al. (2023), who identified an inverted U-shaped relationship between urbanization and environmental pollution, indicating that while urbanization initially worsens environmental conditions, advanced urban planning and technological innovations can eventually lead to improvements. Additionally, Salgado et al. (2020) conducted a systematic review of environmental determinants in urban settings, concluding that socioeconomic factors, air quality, and access to green spaces significantly influence public health outcomes.

Despite these shared concerns, methodological approaches vary across studies. Jiang et al. (2025) employed a conceptual framework focusing on governance and infrastructure, while James (2024) utilized a policy analysis approach to assess urbanization's environmental consequences. Qian (2024), in contrast, applied econometric modeling to quantify the impact of urban expansion on carbon emissions. Sun et al. (2023) adopted a system GMM method to analyze urbanization's dual effects on environmental pollution and public health, whereas Salgado et al. (2020) conducted a systematic literature review to synthesize findings across multiple urban health studies. These methodological differences highlight the complexity of the urbanization–environmental health nexus, demonstrating that while urbanization presents significant sustainability challenges, targeted policy interventions and technological advancements can mitigate its negative effects.

2.4 Digital innovation-environmental health relationship

The relationship between digital innovation and environmental equitability follows a dynamic trajectory, initially contributing to increased emissions before facilitating sustainability improvements (Luo et al., 2023). Studies examining this link often reference the Environmental Kuznets Curve (EKC) framework, which suggests that technological advancements may first exacerbate environmental degradation before leading to long-term ecological benefits.

Malmodin and Lundén, (2018) highlight that early-stage technological advancements, particularly in the ICT sector, tend

TABLE 1 Data source and variables.

Variables	Acronym	Proxy and measurement	Type of variable	Source of data
Sustainable Environment	SE	Biocapacity (gha per person)	Dependent	GFN (2025)
Economic growth	E.G.,	GDP *per capita* growth (annual %)	Control	WDI (2025)
Urbanization	URB	Urban population	Control	WDI (2025)
Education	EDU	PCA of School enrollment secondary (SES), tertiary (SET), and primary (SEP) (% gross)	Independent	WDI (2025)
Digital innovation	DI	PCA of internet penetration and connectivity proxies (Mobile cellular subscriptions (per 100 people), Fixed broadband subscriptions (per 100 people), and Individuals using the Internet (% of the population))	Independent	WDI (2025)
Environmental Policy Stringency	EPS	Environmental policy stringency index	Independent	OECD (2025)

to increase carbon emissions due to heightened energy consumption and infrastructure expansion. Similarly, Gillingham et al. (2016) emphasize the rebound effect, wherein efficiency gains in digital technologies can lead to increased overall energy use, offsetting initial sustainability benefits. These findings align with Avom et al. (2020), who report that ICT adoption in Sub-Saharan Africa has contributed to higher CO_2 emissions, reinforcing the notion that digital transformation can initially strain environmental resources.

An increasingly relevant concern is the rapidly growing energy demand associated with artificial intelligence (AI) systems. As AI models and data centers expand in scale, so too does the need for energy-intensive computing and cooling infrastructure (Yu et al., 2024). Recent estimates suggest that AI training and deployment could consume as much energy as small nations, particularly if reliant on fossil fuels (Berthelot et al., 2024). The environmental and human health consequences of this trend are closely tied to the type of energy used—renewable sources may mitigate carbon footprints, while nonrenewable energy exacerbates both emissions and localized air quality degradation (Ragazzi et al., 2017).

However, as digital innovation matures, its role in promoting sustainability becomes more evident. Danish (2019) finds that while technology use initially diminishes sustainability in low-income countries, it enhances environmental outcomes in high- and middle-income nations over time. Faisal et al. (2020) further support this trend, demonstrating that technological adoption initially increases carbon emissions in China, Brazil, India, and South Africa but leads to reductions in the long term as efficiency improvements and regulatory frameworks take effect. Godil et al. (2020) confirm this pattern in Pakistan, where digital innovation has contributed to lower environmental pollution through enhanced energy efficiency and smart infrastructure.

This evolving impact of digital innovation cannot be viewed in isolation. Its environmental outcomes are shaped by interconnected factors such as education, which informs responsible tech use, and urbanization, which amplifies energy demand (Singh et al., 2025). Weaving these interdependencies—between human capital, infrastructure growth, and institutional regulation—is essential to understand how digital innovation can either exacerbate or alleviate sustainability challenges (Zeng and Punjwani, 2025).

3 Empirical data and methodology

3.1 Data statistics

The study employs panel data spanning from 1990 to 2023, selected based on the availability and consistency of data across key indicators. The dataset focuses on five BRICS nations—Brazil, Russia, India, China, and South Africa—due to the availability of reliable data on environmental policy stringency; other BRICS-Plus nations were excluded due to data limitations in this variable. Table 1 presents an overview of the variables, their acronyms, proxy measures, classifications, and sources. The dependent variable, Sustainable Environment (SE), is proxied by Biocapacity (global hectares *per capita*) sourced from the Global Footprint Network (GFN, 2025). Control variables include Economic Growth (E.G.,), measured by GDP *per capita* growth, and Urbanization (URB) via urban population figures—both obtained from the World Development Indicators (WDI, 2025). The core independent variables are: Education (EDU), synthesized using Principal Component Analysis (PCA) from gross enrollment rates at primary, secondary, and tertiary levels; Digital Innovation (DI), also PCA-computed from mobile subscriptions, broadband subscriptions, and internet usage rates; and Environmental Policy Stringency (EPS), drawn from the OECD (2025). Any missing values were handled using established statistical imputation techniques to ensure robustness and minimize bias in the analysis.

The descriptive statistics presented in Table 2 offer a preliminary insight into the distribution and variability of the key variables analyzed in this study. The mean value of sustainable environment (SE) stands at 3.889, indicating moderate biocapacity levels across the BRICS nations, with a substantial range (0.326–12.639), reflecting environmental heterogeneity (see Figure 1). Economic growth (E.G.,) displays a notable spread (−14.614 to 13.636), capturing both contractionary and expansionary phases, which is typical for emerging economies. Urbanization (URB) has a relatively high average of 58.33%, suggesting ongoing urban transition, with standard deviation reflecting diverse development stages across countries.

The PCA-transformed variables—education (EDU) and digital innovation (DI)—have standardized means near zero and unit standard deviations, consistent with the

TABLE 2 Results of descriptive statistics.

	SE	EG	URB	EDU	DI	EPS
Mean	3.889	3.021	58.329	−8.09e-10	8.86e-10	0.840
Median	1.394	3.048	61.952	−4.97e-08	−0.531	0.694
Maximum	12.639	13.636	87.788	1.894	2.329	3.139
Minimum	0.326	−14.614	25.547	−2.544	−0.890	0
Std. Dev	3.889	4.673	20.045	1.000	1.000	0.725
J-B stats	50.130***	13.120***	---	8.300**	21.690***	35.810***
Skew	0.001***	0.002***	0.096***	0.003**	0.000***	0.000***
Kurtosis	0.000***	0.019***	0.000***	0.493**	0.001***	0.002***
Observations	170	170	170	170	170	170

Note: The significance at 1% and 5% is denoted by *** and **, respectively.

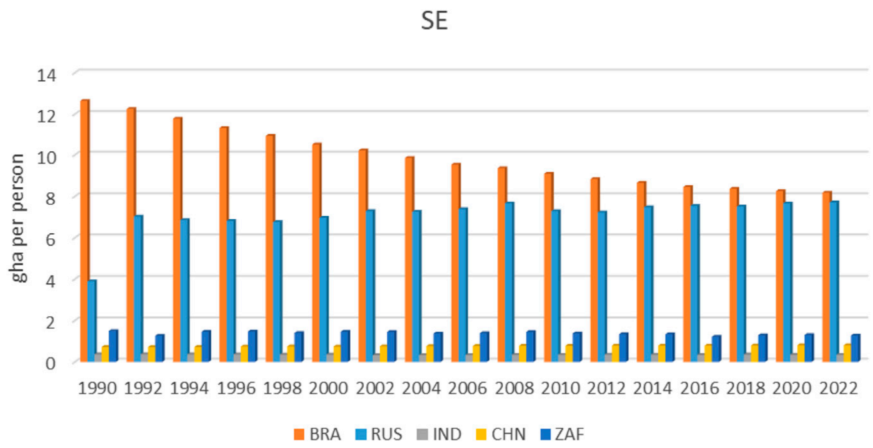

FIGURE 1
Temporal variations in a sustainable environment in BRICS during the study span.

TABLE 3 Correlation analysis.

	SE	EG	URB	EDU	DI	EPS
SE	1.000					
EG	−0.350***	1.000				
URB	0.822***	−0.437***	1.000			
EDU	0.414***	−0.435***	0.735***	1.000		
DI	0.183**	−0.125	0.479***	0.618***	1.000	
EPS	−0.363***	0.176**	−0.245***	0.028	0.361***	1.000

Note: The significance at 1% and 5% is denoted by *** and **, respectively.

dimensionality reduction method used. Environmental policy stringency (EPS) shows a mean of 0.840 but a wide dispersion (0–3.139), highlighting differing regulatory intensities among the countries. The Jarque-Bera (J-B) statistics, along with significant skewness and kurtosis values (mostly at 1% significance), confirm the non-normal distribution of most variables, justifying the use of robust estimation techniques like MMQR and FGLS in the analysis.

The correlation matrix in Table 3 reveals several statistically significant associations among the study variables. Notably, SE is strongly and positively correlated with URB (0.822) and moderately with EDU (0.414), suggesting that higher urbanization and educational levels are associated with improved environmental sustainability across BRICS nations. However, SE shows a significant negative correlation with, E.G., (−0.350) and EPS (−0.363), implying that rapid economic growth and stringent policies might initially strain environmental capacity, possibly due to industrial expansion or short-term compliance costs (Shao et al., 2019; Ullah et al., 2023). The positive but weaker correlation between SE and DI (0.183) suggests a modest role of digital innovation in enhancing environmental outcomes. Additionally, EDU is highly correlated with URB (0.735) and DI (0.618), reflecting interconnected development dynamics where education supports urban digital transformation. Interestingly, EPS is positively linked to DI (0.361) but negatively to URB (−0.245) and, E.G., (0.176), indicating that countries with more stringent policies tend to emphasize digital tools while potentially restraining uncontrolled urban and economic expansion. Overall, while multicollinearity does not appear severe, the significant correlations highlight intricate interdependencies that justify the study's multivariate approach.

3.2 Estimation methodology

The empirical investigation is grounded in two primary models aimed at examining the determinants of environmental sustainability (SE) across BRICS nations. Model (1) specifies a direct linear relationship where SE is a function of economic growth (E.G.,), urbanization (URB), education (EDU), digital innovation (DI), and environmental policy stringency (EPS). This specification is rooted in the Environmental Kuznets Curve (EKC) hypothesis, which posits a nonlinear association between, E.G., and SE, suggesting that after a certain level of income, economic progress leads to environmental improvements (Grossman and Krueger, 1995). Additionally, Human Capital Theory (Becker, 2009) underpins the role of education, asserting that greater investment in education fosters environmentally responsible behavior and supports green innovation.

Model (2) introduces a nonlinear specification for education, by incorporating the square of the education variable (EDU^2) to capture potential diminishing or threshold effects. This transformation allows the model to test for a U-shaped or inverted U-shaped relationship between education and sustainability. This is particularly insightful as it explores whether the effect of education on biocapacity may be initially limited or even negative (due to urban-industrial expansion with basic education), but eventually becomes positive as higher educational attainment promotes environmental awareness and innovation. This dynamic reflects the Threshold Hypothesis in education-environment literature and aligns with the Diffusion of Innovations Theory (Rogers, 2003), which highlights how knowledge diffusion through education accelerates the adoption of environmentally sustainable practices and technologies.

The following empirical models of the study are presented in Equations 1–4:

$$SE = f\,(EG, URB, EDU, DI, EPS) \tag{1}$$

$$SE = f\,(EG, URB, EDU, EDU^2, DI, EPS) \tag{2}$$

The log-linear transformation of the above models appears below:

$$SE_{i,t} = \beta_0 + \beta_1 EG_{i,t} + \beta_2 URB_{i,t} + \beta_3 EDU_{i,t} + \beta_4 DI_{i,t} + \beta_5 EPS_{i,t} + \varepsilon_{i,t} \tag{3}$$

$$SE_{i,t} = \beta_0 + \beta_1 EG_{i,t} + \beta_2 URB_{i,t} + \beta_3 EDU_{i,t} + \beta_4 EDU^2_{i,t} + \beta_5 DI_{i,t} + \beta_6 EPS_{i,t} + \varepsilon_{i,t} \tag{4}$$

In above equations $SE_{i,t}$, $EG_{i,t}$, $EDU_{i,t}$, $URB_{i,t}$, $DI_{i,t}$, and $EPS_{i,t}$ stand for sustainable environment, economic growth, education, urbanization, digital innovation, and environmental policy stringency, respectively. The log-linear transformations in Equations 3, 4 enhance interpretability and address issues of heteroskedasticity, making the coefficients elasticities that reflect percentage changes in sustainable environment outcomes relative to the predictors. Overall, the model structure provides a robust framework to capture both linear and nonlinear dynamics of how educational, economic, technological, and policy factors collectively shape SE in emerging economies. The elasticity coefficients β_1 to β_6 reveal the strength and direction of the relationship, while β_0 identifies the constant's deviation (intercept). In the scenario where t = 1, . . . , T and i = 1, . . . , N represent the time frame and selected country, respectively; $\varepsilon_{i,t}$ denotes the terms utilized in error correction. In the foregoing equation, the letter 'i' represents the cross-section in our case, which encompasses five BRICS nations. The letter 't' represents the operator for the time series, covering the years 1990–2023.

Before establishing the integration order of each element, we must commence our econometric analysis by assessing the degree of cross-sectional dependency (CD) of the highlighted variables. Consequently, the CD test developed by Pesaran (2007) can be employed to estimate the cross-sectional dependence on residuals.

The equation for the CD assessment is shown below in Equations 5–9:

$$\delta_{C-DP} = \frac{((T \times N)(N-1))^{\frac{1}{2}}}{2}\widehat{PR}_N \tag{5}$$

Using the slope homogeneity analysis, the consistency of the slope coefficients in the cointegration equation was determined. Formerly invented by Swamy (1970), Hashem Pesaran and Yamagata (2008) developed and employed the test to generate two statistics. The test was created by, but subsequently utilized to get two statistics:

$$\hat{\Delta}_{S-HT} = \sqrt{N} \times \sqrt{2k} \times \left(\frac{1}{N}\hat{S} - k\right) \tag{6}$$

$$\hat{\hat{\Delta}}_{\text{adj. S-HT}} = \sqrt{N} \times \sqrt{\frac{T+1}{2k\,(T\text{-}k\text{-}1)}} \times \left(\frac{1}{N}\hat{S}\text{-}2k\right) \tag{7}$$

Pesaran's (2007) second-generation panel unit root is the next test, the enhanced cross-sectional IPS (CIPS) evaluation, which is based on the traditional Cross-sectional Augmented Dickey-Fuller (CADF) statistic regression. Westerlund's (2007) cointegration methodologies might then be used to confirm long-term cointegration.

Here, is Pesaran's CADF test:

$$\Delta CS_{i,t} = \varphi_i + \varphi_i CS_{i,t-l} + \varrho\overline{CS}_{t-1} + \sum_{l=0}^{p}\psi_{i,l}\Delta\overline{CS}_{t-1} + \sum_{l=1}^{p}\upsilon_{i,l}\Delta\overline{CS}_{i,t-l} + \mu_{i,t} \tag{8}$$

Equation 9, on the other hand, parades the cross-sectional Parallel to Im, Pesaran, and Shin (Im et al., 2003) scrutiny as follows:

$$\widehat{CIPS}_{UR} = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{9}$$

where N is the number of elucidations.

Westerlund's (2007) cointegration procedure is as follows in Equations 10–12:

$$\Delta y_{i,t} = \Psi_i{}'d_t + \phi_i y_{i,t-l} + \lambda_i{}'x_{i,t-l} + \sum_{j=1}^{pi} w_{i,j}\Delta y_{i,t-j} + \sum_{j=0}^{pi}\gamma_{i,j}\Delta x_{i,t-j} + e_{i,t} \tag{10}$$

The evaluation of Equation 10 will have rendered the subsequent four distinct tests obsolete:

Mean Group Tests:

$$G_t = N^{-1}\sum_{i=1}^{N}\frac{\hat{\varnothing}_i}{SE\left(\hat{\varnothing}_i\right)} \text{ and } G_a = N^{-1}\sum_{i=1}^{N}\frac{T\hat{\varnothing}_i}{\hat{\varnothing}_i(1)} \tag{11}$$

Panel-based tests:

$$P_t = \frac{\hat{\varnothing}_i}{SE\left(\hat{\varnothing}_i\right)} \text{ and } P_a = T\hat{\varnothing}_i \tag{12}$$

$\hat{\varnothing}_i(1)$ and $SE(\hat{\varnothing}_i)$ are the semiparametric kernel and the standard error estimator of $\hat{\varnothing}_i$, respectively.

We model the influence of independent factors on the distribution of SE using the panel MMQR approach developed by Machado et al. (2019) in Equations 13–16.

$$Y_{i,t} = \alpha_i + \acute{X}_{i,t}\psi + \left(\delta_i + \acute{Z}_{i,t}\vartheta\right)U_{i,t} \tag{13}$$

The unidentified factors are indicated by $(\alpha, \psi, \delta, \vartheta)$, (α_i, δ_i), $i = 1, \ldots, n$ denotes the nation-specific, fixed effects and $\acute{Z}$ which portrays the k-vector.

$$Z_l = Z_l\left(X_{i,t}\right), l = 1, 2, \ldots, k \tag{14}$$

$$Q_y\left(\tau|X_{i,t}\right) = \left(\alpha_i + \delta_i(\tau)\right) + \acute{X}_{i,t}\psi + \acute{Z}_{i,t}\vartheta q(\tau) \tag{15}$$

The formula $\acute{X}_{i,t} - \alpha_i(\tau) = \alpha_i + \delta_i q(\tau)$ further describes the numerical expression of each cross-section (i) in a specific time frame (t), the scalar parameters, and the associated fixed effects that result from the estimations of quantiles.

This model's goal is to resolve optimization issues brought on by the observed quantile in Equation 17:

$$\min_q \sum_i \sum_t \rho_\tau\left(R_{i,t}\text{-}\left(\delta_i + \acute{Z}_{i,t}\vartheta\right)q\right) \tag{16}$$

The check function is exemplified by $\rho_\gamma(R) = (\tau - 1)RI\{R \le 0\} + tRI\{R > 0\}$.

As a robustness check following the MMQR estimation, the present study employs the Feasible Generalized Least Squares (FGLS) technique to examine the stability and direction of the associations among education (EDU), economic growth (E.G.,), digital innovation (DI), urbanization (URB), and sustainable environment (SE). FGLS is widely recognized across disciplines for its ability to address issues of heteroskedasticity and autocorrelation, providing efficient and reliable parameter estimates when the error structure is non-spherical, thus reinforcing the credibility of the primary findings.

This study adopts the Granger causality test approach suggested by Dumitrescu and Hurlin (2012) to provide insight into the directional connections between economic variables. This strategy is exemplified as:

$$Z_{i,t} = \alpha_i + \sum_{j=1}^{p}\beta_i^j Z_{i,t-1} + \sum_{j=1}^{p}\gamma_i^j T_{i,t-j} \tag{17}$$

The factors β_i^j and j represent the auto-regressive parameters and lag length in Equation 17, respectively.

TABLE 4 Cross-section dependence (CD).

Variables	Value	P-value
$SE_{i,t}$	−1.090	0.276
$EG_{i,t}$	7.390***	0.000
$URB_{i,t}$	17.140***	0.000
$EDU_{i,t}$	9.840***	0.000
$DI_{i,t}$	17.360***	0.000
$EPS_{i,t}$	11.980***	0.000

Note: The significance at 1% is specified by ***.

TABLE 5 Slope heterogeneity test (S-HT).

Test	Value	P-value
Model: SE = f (E.G., URB, EDU, DI, EPS)		
$\hat{\Delta}_{S-HT}$	3.246***	0.001
$\hat{\tilde{\Delta}}_{adj.\ S-HT}$	3.642***	0.000
Model: SE = f (E.G., URB, EDU, EDU^2, DI, EPS)		
$\hat{\Delta}_{S-HT}$	6.207***	0.000
$\hat{\tilde{\Delta}}_{adj.\ S-HT}$	7.098***	0.000

Note: The significance at 1% is denoted by ***.

4 Results and discussions

The results of the cross-section dependence (CD) test in Table 4 reveal that most variables—EG, URB, EDU, DI, and EPS—exhibit significant cross-sectional dependence, indicating that developments in one BRICS country tend to influence others. This finding aligns with the expectation of strong regional interconnectedness, particularly in areas such as economic growth, technological advancement, and policy responses to global environmental challenges. However, in contrast, SE (proxied by biocapacity) does not exhibit significant cross-sectional dependence (p-value = 0.276), suggesting that biocapacity is shaped largely by country-specific conditions. This apparent isolation may stem from substantial heterogeneity in natural resource endowments, geographic and ecological systems, and the structure of land use and conservation policies across BRICS nations. Unlike policy- or technology-driven variables, biocapacity is deeply rooted in physical and biological characteristics that are not easily transferrable or influenced by external shocks. Moreover, national-level ecological strategies and varying commitments to biodiversity and land preservation may further reinforce this divergence. While this outcome may appear to challenge assumptions of regional environmental interdependence, it underscores the need to differentiate between shared policy challenges and localized ecological capacities. The CD results thus provide important justification for the use of robust estimation techniques like MMQR and FGLS, which can

TABLE 6 Unit root tests.

Variables	Level (I (0))	1st difference (I (1))
Cross-Sectionally Augmented Dickey-Fuller (CADF)		
$SE_{i,t}$	0.037	0.383
$EG_{i,t}$	−3.158**	−4.956***
$URB_{i,t}$	−0.332	−0.884
$EDU_{i,t}$	−2.887*	−3.647***
$DI_{i,t}$	−0.969	−3.199**
$EPS_{i,t}$	−2.635	−4.533***
Cross-Sectionally Augmented IPS (CIPS)		
$SE_{i,t}$	−0.015	−0.484
$EG_{i,t}$	−4.192***	−6.227***
$URB_{i,t}$	0.683	−0.584
$EDU_{i,t}$	−3.303***	−4.739***
$DI_{i,t}$	−0.498	−3.199***
$EPS_{i,t}$	−2.287	−5.160***

Note: ***, **, and * show the significance at 1%, 5%, and 10%, respectively.

TABLE 7 Cointegration test.

Statistic	Value	Z-value	P-value
Model: SE = f (E.G., URB, EDU, DI, EPS)			
Gt	−6.020***	−7.916	0.000
Ga	−7.220	2.104	0.982
Pt	−27.188***	−20.244	0.000
Pa	−5.135	1.658	0.951
Model: SE = f (E.G., URB, EDU, EDU^2, DI, EPS)			
Gt	−7.712***	−11.345	0.000
Ga	−6.396	2.683	0.996
Pt	−37.513***	−29.495	0.000
Pa	−2.000	2.811	0.998

Note: *** Show the significance at 1%.

TABLE 8 Multicollinearity check.

Variable	VIF	1/VIF
$EG_{i,t}$	1.350	0.741
$URB_{i,t}$	2.840	0.352
$EDU_{i,t}$	2.950	0.339
$DI_{i,t}$	2.210	0.452
$EPS_{i,t}$	1.570	0.636
Mean	2.180	-

accommodate both interdependent and independent cross-sectional structures.

The slope heterogeneity test results in Table 5 reveal key differences between the two model specifications. For the linear (SE = f (E.G., URB, EDU, DI, EPS)) and nonlinear (SE = f (E.G., URB, EDU, EDU^2, DI, EPS)) models, both the standard and adjusted test statistics are highly significant at the 1% level, confirming the presence of slope heterogeneity across countries. This suggests that the impact of explanatory variables on SE differs substantially among BRICS nations, reinforcing the need for estimation techniques like MMQR that account for such variation.

To achieve trustworthy and effective estimates, it is essential to eliminate time-dependent elements from the data to assess its stationarity before implementing any robustness or regression analyses (Hu et al., 2022). The unit root diagnostics in Table 6, conducted through CADF and CIPS tests, reveal a mixed integration order among the variables, with critical implications for model specification. E.G., and EDU are found to be stationary at the level under both tests, indicating I (0) behavior, while DI and EPS achieve stationarity only after first differencing, confirming they are I (1). However, SE and URB remain non-stationary even after first differencing in both CADF and CIPS tests, suggesting potential issues with their integration properties. This persistent non-stationarity could reflect structural shifts, measurement inconsistencies, or long-term trends not captured by standard differencing. Therefore, the application of robust estimation methods like MMQR and FGLS is particularly appropriate, as these techniques can accommodate non-stationary panels and provide consistent estimates in the presence of unit root and slope heterogeneity.

The results of Westerlund's (2007) cointegration test in Table 7 provide mixed but insightful evidence regarding the long-run equilibrium relationships among the variables in both model specifications. For the linear model, the Gt and Pt statistics are highly significant at the 1% level, indicating strong evidence of cointegration based on group-mean and panel-based t-statistics. However, the Ga and Pa statistics are not significant, suggesting that when averaging across units, cointegration is not uniformly present—highlighting potential heterogeneity across BRICS nations.

In the nonlinear model, a similar pattern emerges. The Gt (−7.712) and Pt (−37.513) statistics remain highly significant, reinforcing the presence of cointegration based on t-statistics, even when education is modeled nonlinearly. Yet again, the Ga and Pa statistics are not significant, suggesting that cointegration is not consistent across all cross-sectional units when using average-based approaches.

Overall, these results confirm that long-run relationships exist among the variables in both models, particularly when considering individual panel dynamics (Gt and Pt), but also highlight the importance of accounting for cross-sectional heterogeneity, justifying the use of distribution-sensitive techniques such as MMQR.

The Variance Inflation Factor (VIF) results presented in Table 8 indicate that multicollinearity is not a concern in the model. All VIF values fall well below the conventional threshold of 10, with the highest being 2.950 for EDU and a mean VIF of 2.180. The corresponding 1/VIF values, ranging from 0.339 to 0.741, further

TABLE 9 Results of MMQR.

Variables	Location	Scale	Quantiles			
			$Q_{0.25}$	$Q_{0.50}$	$Q_{0.75}$	$Q_{0.90}$
Model: SE = f (E.G., URB, EDU, DI, EPS)						
$EG_{i,t}$	−0.013	−0.046*	0.021	−0.016	−0.049	−0.074
$URB_{i,t}$	0.216***	−0.003	0.219***	0.216***	0.214***	0.212***
$EDU_{i,t}$	−1.250***	0.288*	−1.463***	−1.233***	−1.025***	−0.869***
$DI_{i,t}$	−0.568***	−0.007	−0.562**	−0.568***	−0.573**	−0.577**
$EPS_{i,t}$	−0.132	0.099	−0.205	−0.126	−0.054	−0.001
Constant	−8.580***	1.679***	−9.826***	−8.483***	−7.266***	−6.360***
Model: SE = f (E.G., URB, EDU, EDU^2, DI, EPS)						
$EG_{i,t}$	−0.011	−0.072***	0.056	−0.018	−0.072*	−0.104**
$URB_{i,t}$	0.218***	−0.021***	0.237***	0.216***	0.200***	0.190***
$EDU_{i,t}$	−1.229***	0.002	−1.230***	−1.228***	−1.226***	−1.225***
$EDU^2_{i,t}$	0.031	−0.432***	0.436***	−0.006	−0.338***	−0.528***
$DI_{i,t}$	−0.599**	0.432***	−1.004***	−0.562**	−0.232	−0.042
$EPS_{i,t}$	−0.102	−0.301*	0.179	−0.127	−0.358	−0.491
Constant	−8.715***	3.579***	−12.062***	−8.405***	−5.661***	−4.085***

Note: The significance level is indicated as ***<1%, **<5%, and *<10%.

confirm acceptable levels of correlation among the explanatory variables. These results affirm the independence of predictors—EG, URB, EDU, DI, and EPS—ensuring that the estimated coefficients are not distorted by linear dependencies. This diagnostic supports the validity and reliability of the subsequent regression analyses, particularly the robustness of the Method of Moments Quantile Regression (MMQR) results.

Building on the stable multicollinearity profile, the MMQR estimates reported in Table 9 provide nuanced insights into how the effects of the independent variables on SE differ across its conditional distribution, capturing the heterogeneity among BRICS nations. In the linear model, URB consistently shows a strong positive and significant effect across all quantiles, indicating that urbanization—when accompanied by adequate infrastructure and governance—can support sustainability outcomes. This finding aligns with Bibri et al. (2020), who found that compact urban design and public service access can enhance ecological performance in emerging economies.

In contrast, EDU displays a significant negative effect across all quantiles, a finding that may initially seem counterintuitive. This result, however, echoes the paradox reported by Chen et al. (2024), who observed that educational expansion in the absence of environmental content may not yield eco-conscious behavior. Torroba Diaz et al. (2023) found that environmental literacy positively affects students' sustainability actions, but general education alone does not foster eco-conscious behavior unless specific environmental education programs are implemented. In many BRICS countries, education systems have prioritized economic competitiveness and human capital development, often at the expense of ecological literacy. As a result, increased educational attainment or expanded enrollment—particularly at the secondary and tertiary levels—has not always translated into environmentally conscious behavior or policy engagement. While this interpretation remains partly speculative, it is worth noting the case of India, where expanding access to formal education has occurred alongside rising emissions. This trend is largely attributable to the nation's reliance on coal and other fossil fuels for energy production. Nonetheless, studies have highlighted curriculum gaps in sustainability education that may limit the environmental impact of educational progress (UNESCO, 2025). Such patterns illustrate the complex and potentially nonlinear relationship between education and environmental outcomes proposed in H1.

DI also shows a consistently negative and significant effect on SE, particularly in lower quantiles, suggesting that digital infrastructure expansion may initially strain environmental resources. This is consistent with findings by Alsanie (2025), who reported that digitalization often increases electricity consumption and e-waste before efficiency benefits materialize. These results lend support to H2, highlighting the complex and potentially adverse impact of digital innovation on sustainability in its early stages of adoption. In contrast, E.G., and EPS demonstrate mostly negative or insignificant effects, indicating that economic expansion and environmental policy stringency may have context-specific or delayed impacts. Similar results are found in Efayena and Olele (2024), which emphasizes that policy effectiveness depends on enforcement capacity and institutional quality. These findings offer empirical grounding for H4, which proposes that the effects of economic growth and policy stringency on sustainability are limited and highly contingent on broader policy integration.

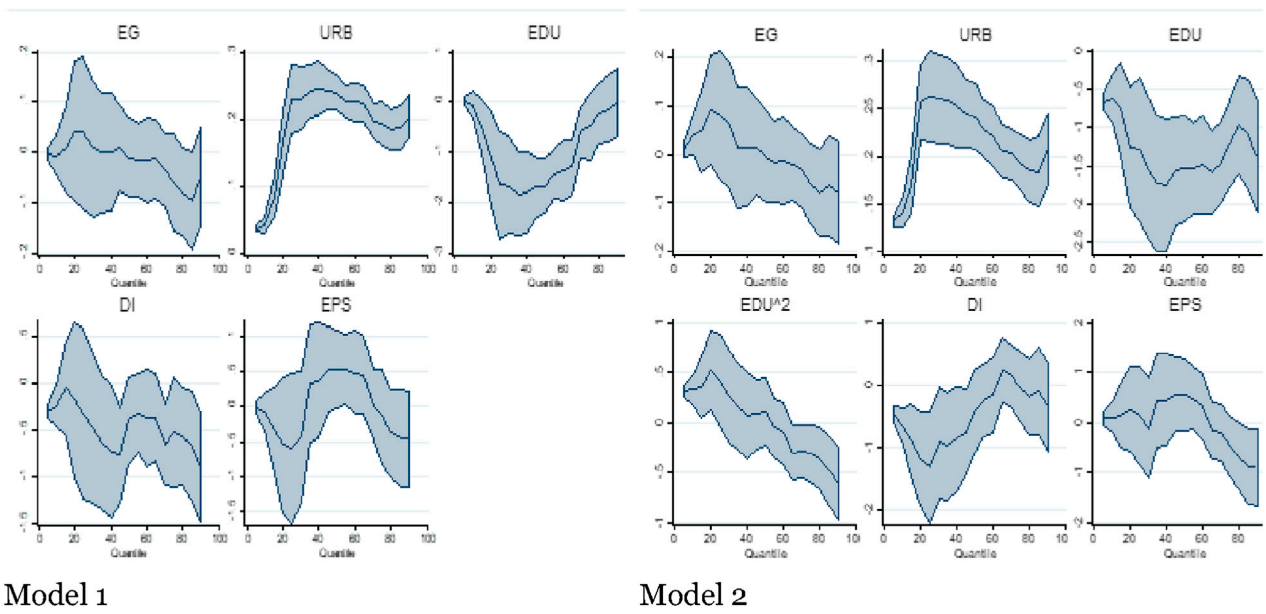

FIGURE 2
Graphical representation of MMQR results.

The nonlinear model deepens these insights by incorporating EDU^2, which reveals a significant U-shaped relationship between education and sustainability. While EDU remains negative, EDU^2 turns positive and significant at the median and upper quantiles. This confirms H1 by demonstrating a threshold effect, where education begins to foster sustainability only after surpassing a certain level of depth and quality. This finding supports the "threshold hypothesis," where education only begins to promote sustainability after reaching a critical level of environmental integration and awareness. This is reinforced by Maneejuk and Yamaka (2021), who found similar nonlinearity in the role of education in East Asian economies. The case of China is illustrative here—where the national curriculum has increasingly integrated green competencies in recent years, resulting in measurable environmental improvements (Yang et al., 2022).

Moreover, DI in the nonlinear model shows diminishing negative effects, becoming insignificant at higher quantiles, suggesting that digital innovation may transition from a source of environmental burden to neutrality or benefit as supporting infrastructure and regulatory frameworks mature. This further supports H2, illustrating that the environmental effects of digital innovation evolve with a country's technological maturity and policy environment. URB retains its strong positive influence across all quantiles in both models, reinforcing H3 and highlighting the importance of guided urban development as a stable contributor to ecological improvement. This echoes the findings of Goel et al. (2024), who argue that the environmental impact of digital tools evolves with a country's digital maturity and policy safeguards. URB retains its strong positive influence across all quantiles in both models, highlighting the crucial role of managed urban development.

Overall, these results justify the use of the MMQR framework by revealing the non-uniform nature of relationships across different sustainability levels (see Figure 2). The nonlinear model, by capturing threshold effects of education and evolving digital impacts, provides a more refined and realistic understanding of the dynamics at play—offering valuable

TABLE 10 An analysis of FGLS panel regression to check robustness.

Variables	Coefficients	Standard error
Model: SE = f (E.G., URB, EDU, DI, EPS)		
$EG_{i,t}$	−0.013	0.035
$URB_{i,t}$	0.216***	0.012
$EDU_{i,t}$	−1.250***	0.245
$DI_{i,t}$	−0.568***	0.212
$EPS_{i,t}$	−0.132	0.247
Constant	−8.580**	0.846
Wald test	572.750***	-
Model: SE = f (E.G., URB, EDU, EDU^2, DI, EPS)		
$EG_{i,t}$	−0.011	0.036
$URB_{i,t}$	0.218***	0.013
$EDU_{i,t}$	−1.228***	0.261
$EDU^2_{i,t}$	0.031	0.128
$DI_{i,t}$	−0.600**	0.249
$EPS_{i,t}$	−0.102	0.273
Constant	−8.715***	1.005
Wald test	573.000***	-

Note: The significance level is indicated as ***<1% and **<5%.

TABLE 11 Granger-causality analysis.

Causality	F-Stat	P-value
$DI_{i,t} \rightarrow SE$	2.634*	0.090
$SE_{i,t} \rightarrow DI_{i,t}$	7.221***	0.003
$EDU_{i,t} \rightarrow SE_{i,t}$	0.759**	0.047
$SE_{i,t} \rightarrow EDU_{i,t}$	0.420	0.661
$EPS_{i,t} \rightarrow SE_{i,t}$	0.235	0.792
$SE_{i,t} \rightarrow EPS_{i,t}$	1.424	0.258
$EG_{i,t} \rightarrow SE_{i,t}$	0.883*	0.083
$SE_{i,t} \rightarrow EG_{i,t}$	0.287	0.753
$URB_{i,t} \rightarrow SE_{i,t}$	1.010*	0.065
$SE_{i,t} \rightarrow URB_{i,t}$	1.547**	0.038

Note: The significance level is indicated as ***<1%, **<5%, and *<10%.

insights for policy design tailored to the specific sustainability profile of each BRICS nation.

The results from the Feasible Generalized Least Squares (FGLS) estimation, presented in Table 10, serve as a robustness check to validate the findings from the MMQR models. Overall, the FGLS outcomes largely corroborate the MMQR results, confirming the direction and significance of key relationships, while providing additional support for the stability of the core findings.

In both the linear and nonlinear specifications, URB maintains a positive and highly significant association with SE, reinforcing the conclusion that urbanization, when well-managed, contributes positively to environmental sustainability across BRICS countries. This consistency across models highlights urban planning and infrastructure development as a pivotal policy lever.

EDU remains strongly negative and significant in both models, consistent with the MMQR findings at lower quantiles. This reinforces the interpretation that mere enrollment—without emphasis on environmental curricula or eco-literacy—may not foster sustainability and could even align with increased consumption or industrial activity. However, in the nonlinear model, while EDU^2 is positive, it is not statistically significant, suggesting that the curvilinear (U-shaped) pattern observed in MMQR is more visible at distributional extremes and not uniform across the panel.

DI also continues to show a significant negative effect, aligning with MMQR findings at lower quantiles. This underlines that digital innovation, in its current form within BRICS, may exacerbate environmental pressures unless paired with green technology initiatives. The influence of, E.G., and EPS remains insignificant, confirming their limited direct impact on SE across the panel, which echoes the MMQR's weaker and less consistent results for these variables.

The significant Wald test values in both models confirm the joint significance of the explanatory variables and the reliability of the estimates.

The Granger causality test results in Table 11 provide important insights into the directional relationships between SE and its predictors, revealing asymmetries in how different variables influence sustainability outcomes across BRICS nations. The bidirectional causality observed between DI and SE suggests a complex interplay between technological advancements and environmental sustainability. The statistically significant result for SE → DI ($F = 7.221$, $p = 0.003$) indicates that environmental conditions strongly dictate the trajectory of digital adoption, possibly through policy interventions aimed at mitigating the ecological impacts of digital expansion. Conversely, the weaker significance of DI → SE ($F = 2.634$, $p = 0.090$) implies that digital innovation exerts a marginal influence on environmental sustainability (Fang et al., 2023; McAleer, 2021; Tiwari et al., 2021; Yıldız et al., 2023), aligning with previous findings that excessive reliance on digitalization without robust green technology frameworks contributes to ecological strain rather than sustainability improvements.

EDU exhibits a unidirectional causality towards SE ($F = 0.759$, $p = 0.047$), suggesting that educational expansion drives environmental outcomes but not *vice versa*. This supports the earlier MMQR and FGLS results, where education was found to degrade the environment at lower quantiles, yet contribute positively when modeled nonlinearly. The absence of causality in the opposite direction (SE → EDU, $F = 0.420$, $p = 0.661$) further reinforces that environmental sustainability does not significantly alter educational structures, implying that any improvements in environmental consciousness through education must be proactively implemented rather than naturally evolving in response to environmental changes.

EPS fails to Granger-cause SE ($F = 0.235$, $p = 0.792$), nor is it influenced by SE ($F = 1.424$, $p = 0.258$), suggesting that regulatory frameworks alone do not substantially dictate sustainability outcomes. This finding resonates with MMQR results, where EPS displayed inconsistent significance across quantiles. The lack of causal directionality implies that without robust enforcement and systemic policy integration, environmental regulation on its own does not lead to measurable improvements in sustainability, reinforcing the need for complementary mechanisms such as technological innovations, educational reforms, and urban infrastructural development.

E.G., demonstrates a weak but significant causality towards SE ($F = 0.883$, $p = 0.083$), supporting the observation that economic expansion plays a role in influencing environmental outcomes, although not strongly. The lack of causality in the reverse direction (SE → E.G., $F = 0.287$, $p = 0.753$) suggests that sustainability conditions do not substantially alter economic growth trajectories, which is consistent with MMQR results indicating mixed effects of, E.G., on SE across quantiles. This highlights that while economic progress can sometimes align with environmental improvements, it is not an inherent driver and proactive policy measures are necessary to balance growth with ecological concerns.

URB presents bidirectional causality with SE, reinforcing the earlier MMQR and FGLS findings that structured urban expansion contributes positively to sustainability. The causality of URB → SE ($F = 1.010$, $p = 0.065$) indicates that increasing urban development fosters environmental improvements, likely through better infrastructure, green urban planning, and technological innovation. Meanwhile, SE → URB ($F = 1.547$, $p = 0.038$)

suggests that sustainability conditions also influence urbanization strategies, possibly encouraging environmentally conscious urban policies in regions experiencing ecological strain. This bidirectional relationship underscores the interdependent nature of urbanization and sustainability, highlighting the importance of sustainable urban policies in shaping long-term environmental outcomes.

Overall, these findings reinforce key conclusions from MMQR and FGLS while providing deeper insight into the directional influences among variables. The unidirectional causality from education to sustainability validates the threshold-dependent impact of education found in nonlinear models, while the bidirectional causality between urbanization and sustainability affirms its role as a stabilizing factor in environmental outcomes. The weak causality from economic growth and the insignificance of environmental policy stringency signal that growth-oriented policies alone do not guarantee sustainability improvements, necessitating a broader focus on regulatory enforcement, infrastructure, and technological integration. Additionally, the asymmetric relationship between digital innovation and sustainability highlights the need for green digital transformation strategies, ensuring that technological advancements complement rather than counteract sustainability efforts. These causality findings offer valuable policy implications, emphasizing the need for targeted interventions that prioritize education, urban infrastructure, and technological sustainability while balancing economic growth with environmental considerations.

5 Conclusion and recommendations

This study investigates the determinants of environmental sustainability (SE) across BRICS nations from 1990 to 2023, focusing on economic growth (EG), urbanization (URB), education (EDU), digital innovation (DI), and environmental policy stringency (EPS). Using a multi-method econometric approach—including Method of Moments Quantile Regression (MMQR), Feasible Generalized Least Squares (FGLS), and Granger causality analysis—we examined how these factors influence SE across varying levels of sustainability performance.

The MMQR results reveal that the influence of these variables is not uniform across the distribution of SE outcomes, indicating the presence of substantial heterogeneity among BRICS nations. Urbanization consistently exhibits a positive and statistically significant effect across most quantiles, suggesting that when managed effectively, it can contribute constructively to environmental outcomes. Education shows a more complex relationship: while associated with negative effects at lower quantiles, a U-shaped pattern emerges, indicating potential benefits at higher educational thresholds—highlighting the importance of both educational quality and curriculum content. Digital innovation also exhibits a generally negative relationship with SE at lower quantiles, suggesting that its benefits are conditional on policy context and technological maturity. Economic growth and environmental policy stringency yield mixed and weaker results, implying that these variables alone may be insufficient drivers of sustainability in this context.

Granger causality analysis further underscores the directional dynamics among variables. Education is found to Granger-cause SE, reinforcing its role as a key input to sustainability transitions. Urbanization and SE show bidirectional causality, suggesting feedback loops between urban development and environmental conditions. Digital innovation and SE exhibit asymmetric causality—where SE influences DI more than the reverse—highlighting that environmental priorities may drive technological change, rather than technology inherently producing sustainable outcomes. The weak or insignificant causality between SE and both economic growth and policy stringency supports the interpretation that deeper structural reforms are needed beyond economic expansion or regulation alone.

Taken together, these findings contribute to a more nuanced understanding of sustainability determinants in emerging economies. The patterns identified offer valuable empirical insights into how education, urbanization, digital innovation, and institutional variables interact within the BRICS context. As these insights are shaped by differences in governance structures, development trajectories, and policy environments, their relevance is most applicable to countries with similar socio-economic and institutional conditions. Broader generalizations may require further investigation in additional regional or global contexts.

5.1 Policy implications

The results offer several policy-relevant insights, aligned with the United Nations Sustainable Development Goals (SDGs), particularly SDGs 4, 9, 11, and 13. Given the nonlinear impact of education, policy efforts should prioritize not just access but the quality and content of curricula, with an emphasis on environmental literacy and sustainability competencies. Investments in environmental education and green academic research are essential for embedding sustainability into long-term human capital development.

Urbanization's consistent association with improved SE outcomes underscores the need for sustainable urban planning. Policymakers should invest in green infrastructure, enforce land-use regulation, and promote smart cities powered by clean energy. These actions can optimize the environmental potential of urban expansion while mitigating ecological risks.

Digital innovation presents both opportunities and risks. Policies must address energy demands—particularly from AI systems and data centers—by mandating efficiency standards and supporting the development of green technologies. Incentives for e-waste management and digital sustainability frameworks are critical, especially in countries at lower sustainability levels.

The limited impact of economic growth and policy stringency suggests that traditional levers may be insufficient. A shift toward green economic models that integrate equity, innovation, and environmental resilience is needed. Tax incentives, circular economy policies, and green procurement can help decouple growth from environmental harm.

Finally, the directional relationships observed suggest that sequencing and integration of policy domains are essential. For example, urban planning should be co-developed with environmental strategy, and digital transformation must include sustainability-by-design principles. Education policy reform is also key to achieving the threshold effects needed to realize sustainability benefits.

5.2 Study limitations and future directions

While the study offers meaningful insights, several limitations merit acknowledgment. The variable selection focused primarily on five drivers, excluding others such as renewable energy, institutional quality, and social equity indicators. Future research should incorporate broader determinants—including green finance, governance metrics, and resilience frameworks—to offer a more holistic perspective.

The proxy indicators used may not fully capture the depth of each construct. For example, enrollment-based measures of education do not reflect environmental content or learning outcomes, while broadband subscriptions may overlook the ecological efficiency of digital infrastructure. Future studies should employ more granular, content-sensitive indicators such as sustainability education indices or green technology adoption rates.

The use of GDP *per capita* as a proxy for economic growth presents limitations in addressing income inequality and access disparities. More inclusive indices like the Human Development Index or Gini-adjusted measures could enhance the socioeconomic realism of sustainability models.

Geographically, the analysis is confined to the five BRICS nations. Expanding the scope to include BRICS-Plus countries or comparable emerging economies would improve external validity and reveal diverse policy dynamics across regions.

Finally, while MMQR, FGLS, and Granger causality offer methodological depth, future studies could benefit from advanced econometric tools such as instrumental variables, spatial models, or machine learning for greater robustness and predictive accuracy.

In sum, this study highlights the complex and context-specific nature of sustainability transitions in emerging economies. It presents policy-relevant insights that contribute to a deeper understanding of how structural, technological, and educational factors shape environmental outcomes. These findings lay the groundwork for future research aimed at developing more integrated and adaptive sustainability models.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org/country.

Author contributions

XZ: Data curation, Methodology, Supervision, Formal Analysis, Validation, Investigation, Funding acquisition, Resources, Writing – original draft, Writing – review and editing. LX: Conceptualization, Validation, Project administration, Supervision, Data curation, Writing – review and editing, Methodology, Investigation, Writing – original draft, Funding acquisition, Resources, Software, Formal Analysis.

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Conflict of interest

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