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# Mineral resource volatility and green growth: The role of technological development, environmental policy stringency, and trade openness

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ABSTRACT

While natural resources significantly contribute to global socio-economic development, the unresolved question of their volatility's role in decoupling economic growth and carbon emissions persists. Previous empirical studies have underscored both positive and negative impacts of natural resource exploration on economic growth and the environment. This study addresses the knowledge gap by employing a linear non-linear panel ARDL framework to investigate the correlation between natural re source volatility and sustainable development in the BRICS economies. Our key findings reveal that natural resource volatility adversely impacts green growth within the linear model in both the short and long run. Conversely, in the non-linear model, an increase in natural resource volatility negatively influences green growth, whereas a decrease encourages green growth, albeit only in the long run. Moreover, we found that technological development, stringent environmental policies, and trade openness are conducive to green growth. These results underscore the necessity for managing natural resource volatility to foster sustainable development, particularly in emerging BRICS economies.

## 1. Introduction

The efficient use and management of natural resources, alongside preserving them for the benefit of current and future generations, is known as sustainable development (Nassani et al., 2021; Zhao et al., 2023). In the recent past, the quality and meaning of the development has altered. The focus of each nation is to preserve the ecosystem by encouraging long-term environmental benefits of sustainable growth and development. As a result, several nations have established objectives for accomplishing sustainable development objectives, including lowering shortages of resources (J. Chen et al., 2023). According to the United Nations, sustainability is supported by three fundamental principles: environmental preservation, social advancement, and economic growth. In other words, they are called a "planet, people, and profits". In order to measure a country's sustainability, it is important to evaluate each of these factors concurrently. Achieving sustainable development and advancement for emerging countries is challenging due to rising energy consumption and ecological issues (Qin et al., 2023; Sharma et al., 2021; Xie et al., 2024). In this regard, past empirical works have estimated the influence of natural resources on economic growth or environmental quality separately. However, there isn't much empirical work on the nexus between natural resource volatility and green sustainable development; therefore, further research is needed, particularly in the context of BRICS economies, as they are not only the exporters of natural resources but also the importers. The study's main goal is to determine the effect of volatility in natural resources on environmentally friendly green growth in BRICS.

Natural resources are substances that have been found and exploited by humans to sustain economic activity or address diverse human needs. In the contemporary period, the availability of resources is a key factor in economic growth and a key sign of a nation's might. Although the resource curse negatively impacts economic growth, the presence of natural resources has consistently served as a reliable factor in output across time (Ahmad et al., 2020). Natural resource volatility describes unpredictable resource costs and supply swings, including minerals, oil, gas, and agricultural products. It enormously affects economies, especially those with a large natural resource industry or those strongly dependent on natural resource exports (Bakhsh and Zhang, 2023). Natural resource volatility makes investors and manufacturers anxious about future revenue. As a result, it might negatively impact the country's economic performance via lower output, decreased investment, and a rise in unemployment. However, natural resource volatility could

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benefit nations exporting such resources (Sun and Wang, 2021). These countries profit greatly from rising prices of natural resources since rising income from these resources boosts their economic performance. Conversely, increasing the prices of natural resources helps nations that import such materials.

In addition to economic impacts, the massive exploitation of natural resources has severe ecological consequences. As a result of the globally significant and devastating climate change, the focus of academia has switched to environmental studies. Global warming has put the sustainable green growth path at risk due to rising carbon dioxide (CO2) and other greenhouse gas emissions (Safi et al., 2023; Shahzad et al., 2023a,b; Zheng et al., 2023; Khaddage-Soboh et al., 2023). Similarly, in reaction to resource exhaustion, which raises CO2 emissions, authorities offer incentives for fuel usage. The present economic structure uses natural and social assets, although natural resources are usually disregarded (Abbasi et al., 2021). Due to the fact that natural resources are provided by nature and are freely accessible, this mindset encourages careless usage and may have disastrous results (Zahoor et al., 2022). Over the last few decades, nations have used more natural resources than ever. Countries have experienced various environmental issues, from the extraction of natural resources to their final use; fossil fuel-based energy has greatly impacted the mining of resources and the environment (Hussain et al., 2020; Umar et al., 2023). In the setting of volatile natural resource prices, any price change may affect the incentives for resource production. Extraction operations may increase during high prices, which might cause environmental damage, deforestation, habitat loss, and higher carbon emissions. Conversely, certain extraction projects can become unprofitable as prices drop, lowering environmental pressures. Various research has cited natural resource volatility as a major motivator for ecological preservation. Gu et al. (2023), Hayat et al. (2023), Safi et al. (2023b,c) and Khaddage-Soboh et al. (2023) stated that utilizing natural resources diminishes reliance on conventional energy sources, reducing emissions. They argued that natural resource rents help reduce carbon emissions and improve environmental quality. Natural resource volatility management policies should also promote environmentally sound resource extraction methods and aid in the shift to a more sustainable and environmentally friendly economic path.

The conflict between the advantages and curses of natural resources has been addressed for a long time (Adams et al., 2019). Within this framework, most empirical research has focused on the relationship between natural resource rents and a country's economic progress, whereas only a small handful of research has examined the impact of natural resources on ecological sustainability. Regarding the correlation between natural resources and economic development, a study conducted by Haseeb et al. (2021) acknowledges that the impact may be random. Specifically, the study highlights that in Russia, the outcome of natural resources on the economy can either be a "resource curse" or a "resource blessing," depending on the specific resources involved. The non-linear link between natural resource rents and growth was also studied by various academics (Ofori and Grechyna, 2021). The effect might change based on the natural resource rents and various types of nations. The bi-directional causative link between natural resource rents and development in resource-rich economies was also examined by Ben-Salha et al. (2018). The empirical results show a substantial positive link between natural resources and affluence. In another study, low ICT nations negatively influence resource rents on ECG, but high ICT nations have favorable effects on economic growth compared to total resources (Erum and Hussain, 2019). Natural resources are blessings for the G7 nations, according to research by Meng et al. (2022) investigated the significant and favorable link between natural resource rents and economic growth. Whether the resource curse exists is evidence that natural resources significantly impact economic success. On the other hand, Danish et al. (2019) observed that environmental contamination is brought on by the excessive utilization of resources brought on by industrialization, deforestation, and mining. Likewise, Ni et al. (2022) suggested that exploiting natural resources leads to serious environmental problems, including global warming and deforestation. Balsalobre-Lorente et al. (2018) contended that manufacturing operations in industrialized nations depend on conventional energy sources, including coal, oil, and natural gas, which exacerbate the climate issues in the economies. The study's main research question is: how does natural resource volatility affect green growth?

The literature we presented above has the following gaps. First, few studies have tested the relationship between natural resources and sustainable development. Secondly, the BRICS, being the exporters and importers of natural resources and also the major players in world decision-making with regard to sustainability, have been overlooked by past studies. Third, hardly any economists in the past have focused on natural resource volatility, green sustainable development, or Thus, further evidence is required to address these shortcomings in the literature, and this analysis is an effort to plug these gaps in the existing body of empirical works. Therefore, this study examines the impact of resource volatility on green growth by controlling technological development, environmental policy stringency, and trade openness.

Against this backdrop, the study makes several novel contributions to the existing empirical work. First, this research offers hitherto uncovered empirical evidence on the relationship between the volatility of natural resources and environmentally friendly sustainable growth. The new study is different and augments the literature by taking a primary position that could inspire decision-makers and future researchers to use it. Second, there is a shortage of research on the connection between natural resource volatility and green growth in the BRICS economies. As a result, this research adds to the body of literature by presenting an empirical analysis of the said variables in the BRICS, which is significant from an economic perspective and has the potential to impact the sustainable future of the world due to the significance of BRICS in the global economic and environmental sphere. In order to analyze this nexus in other established and emerging locations, future scholars might use the information in this work as a starting point. Third, this study overcomes linear model limitations using the non-linear PMG-ARDL framework to capture potential non-linear relationships between natural resource volatility and green sustainable development. The study employs panel PMG-ARDL to estimate short and long-run effects. Lastly, this empirical evidence is important for policymakers and stakeholders in designing effective strategies and policies that promote sustainable economic growth while managing the challenges associated with natural resource volatility.

## 2. Literature review

The primary aim of the analysis is to examine the nexus between sustainable development and natural resource volatility in BRICS economies. Even though a great deal of empirical work has either focused on the impact of natural resource rents on national income or environmental quality, the literature is in its infancy stage on the effects of natural resource volatility on sustainable development, which combines social, economic, and environmental approaches in one term. Below, we will review the literature that is related to our topic. Guan et al. (2021) looked at the effects of natural resource price fluctuations on economic progress and achievement in nations heavily reliant on these resources between 2000 and 2020. According to the study's regression analysis using ARDL and the PMG model, events significantly impact natural resources. The global financial crisis and Covid-19 hit the crude oil market worse than gold. The research found that short-term fluctuations in natural resource prices majorly impact long-term economic growth. Hayat and Tahir (2021) did an analogous analysis, looking at resource-heavy economies in three countries between 1960 and 2016. Even though natural resources greatly assist economic development, according to the study's ARDL methodology. However, the instability of natural resources negatively impacts the UAE's, Saudi Arabia's, and Oman's economic growth. Rahim et al. (2021), compared to the earlier analysis, discovered that between 1990 and 2019, natural resource rents considerably hampered economic development in the Next-11 nations. Nevertheless, fostering the beneficial effects of natural resources on economic growth might be achieved by investing in human capital. Likewise, Perez and Claveria (2020) show that constraints like corruption prevent rental income from natural resources from contributing to economic development in African nations that rely on minerals between 2007 and 2016.

Furthermore, a substantial amount of contemporary work has conducted quantitative analyses on the impact of natural resource prices, particularly crude oil prices, on economic growth and its indicators. Atil et al. (2020) investigated the relationship between oil prices, national income, and financial development in Pakistan from 1972 to 2017. Utilizing the long-run co-variability methodology, the empirical results indicated that natural resources positively contribute to economic growth. Furthermore, the study identified a noteworthy impact of oil prices on financial progress. Chien et al. (2021) looked at the relationship between the price volatility of petroleum and economic development in Pakistan from 1980 to 2018. The analysis concludes that the nation's entire economic sector is adversely impacted by oil prices employing the ARDL technique. On the other hand, only the logistics and telecommunications industries will benefit. Gong et al. (2021) found that economic expansion, inflation, and trade volume had a strong negative impact on mixing frequencies. Nevertheless, the oil price fluctuation considerably impacts these macroeconomic indices in exchange.

Akinsola and Odhiambo (2020) examined the connection between oil prices and economic development in the context of seven poverty-stricken Sub-Saharan African (SSA) nations that import oil. The analysis employs non-linear ARDL and PMG techniques. It concludes that although oil price volatility has little short-term influence on economic expansion, it has a significant long-term impact. The research also shows that a rise in oil prices hurts economic development, while a fall in oil prices boosts it. Baba et al. (2020) looked at the relationship between Nigeria's economic development from 1997 to 2017 with the volatility of oil prices. The research finds that volatility in oil prices considerably lowers economic expansion and the well-being of households and increases the poverty rate in the region. This depends on the vector autoregressive technique. In addition, Maheu et al. (2020) examined the volatility relationship between GDP growth and shocks to the oil market and concluded that there is a strong relationship between the two. Regarding the environmental effects of fluctuations in oil prices, Mohamued et al. (2021) found that the ecological circumstances of fuel-importing and fuel-exporting countries were affected differently.

Natural resources are comprised of not just crude oil and other minerals like gold but also natural gas, which greatly impacts the ecosystem and economic development. In this regard, Etokakpan et al. (2020) used cointegration and the Granger causality test to study Malaysia between 1980 and 2014. The projected findings show that although natural gas supports environmental deterioration, it also supports economic development. Topcu et al. (2020) discovered comparable outcomes for 124 nations across the 1980–2018. According to the authors, these nations' ability to achieve better economic development was significantly influenced by their use of natural resources and energy. Furthermore, Galadima and Aminu (2020) show that using natural gas spurs regional economic development using the non-linear OLS technique. This association, nevertheless, is not proven to be linear. In a study conducted by Magazzino et al. (2021), it was discovered that a reciprocal cause-and-effect connection existed between natural gas and economic progress in Japan and Germany throughout the period from 1970 to 2018. Rafindadi and Ozturk (2016) demonstrate that the use of natural gas has an indirect impact on Malaysia's GDP. But, the nation's economic expansion is unrelated to natural gas consumption.

The literature, with differing views, explores the link between natural resource volatility and environmental quality. One perspective suggests resource volatility enhances sustainability (Balsalobre-Lorente et al., 2018). Kwakwa and Alhassan (2018) found that urbanization and economic success contribute to increased carbon and energy usage in Ghana, emphasizing the role of natural resource exploitation. Contrarily, other research (Bekun et al., 2019) argues that natural resource volatility negatively impacts environmental sustainability, leading to solid waste production and air pollution. This perspective anticipates a positive impact on CO2 emissions. Bekun et al. (2019) studied the long-term relationship between carbon footprint and energy consumption, revealing that both contribute to CO2 release. The research emphasizes that nations' reliance on natural resource rents affects environmental preservation, highlighting the positive impact of renewable energy and the negative effects of fossil fuels on carbon emissions.

## 3. Model and methods

To examine the impact of natural resource volatility on green sustainable development in the BRICS countries, we employ a regression model based on equation (1):

$$GG_{it} = \omega_0 + \omega_1 NRV_{it} + \omega_2 Tech_{it} + \omega_3 EPS_{it} + \omega_4 FD_{it} + \omega_5 Trade_{it} + \varepsilon_{it} \quad (1)$$

Specification (1) is the green growth function that relies on natural resources volatility (NRV), technology (Tech), environmental policy stringency (EPS), financial development (FD), and trade openness (Trade). Long-run coefficient estimates can be derived for equation (1) variables. However, this study intends to assess both short and long-run estimates. Specification (1) is an error-correction structure to capture short-term dynamics. The Pesaran et al. (2001) study uses the bounds-testing technique for conducting cointegration evaluation and error-correction processing, as shown by the framework (2).

$$\begin{aligned}\Delta GG_{it} = {} & \omega_0 + \sum_{k=1}^{n}\beta_{1k}\Delta GG_{it-k} + \sum_{k=0}^{n}\beta_{2k}\Delta NRV_{it-k} + \sum_{k=1}^{n}\beta_{3k}\Delta Tech_{it-k} \\ & + \sum_{k=0}^{n}\beta_{4k}\Delta EPS_{it-k} + \sum_{k=0}^{n}\beta_{5k}\Delta FD_{it-k} + \sum_{k=0}^{n}\beta_{6k}\Delta Trade_{it-k} + \omega_1 GG_{it-1} \\ & + \omega_2 NRV_{it-1} + \omega_3 Tech_{it-1} + \omega_4 EPS_{it-1} + \omega_5 FD_{it-1} + \omega_6 Trade_{it-1} + \varepsilon_{it}\end{aligned} \quad (2)$$

Formally known as the panel ARDL model, specification (2) is widely recognized in econometric literature for its capacity to furnish estimates encompassing both short and long-run effects. In this model, the coefficient estimates of the Δ variables indicate short-run impacts, while the estimates of ω2 and ω6 divided by -ω1 represent long-run effects according to specification (2). Pesaran et al. (2001) propose a cointegration test to assess the significance of these long-run estimates. They emphasize the need for the ECM to be negative and provide new critical values that account for the integrating characteristics of the variables. This technique handles variables with a combination of I(0) and I(1) characteristics, removing the need for a preliminary investigation of unit roots, which is typically redundant for most macro variables. In addition, the technique's robustness is intact even when working with restricted time series data (Zhang et al., 2023). Furthermore, it tackles the concerns of endogeneity and heterogeneity by including a short-term correction process in the framework, successfully managing any difficulties that may occur in time series analysis (Wang et al., 2023). The panel ARDL approach, emphasized by Pesaran et al. (2001), addresses the issues of endogeneity and serial correlation by such a short-term dynamic mechanism.

This research evaluates the non-linear influence of natural resource volatility on advancing environmentally sustainable economic development. The NARDL panel approach enables the examination of non-linear associations between variables, which is crucial for understanding intricate economic processes. The panel NARDL approach is useful for revealing the non-linear characteristics prevalent in many real-world economic interactions. This technique provides a more precise description of the data, taking into account the non-linear behavior. It addresses endogeneity problems often encountered in economic research by including past values of dependent and independent variables within a non-linear structure. This approach enables the analysis of immediate and prolonged changes, including any reciprocal influences between the variables. The panel NARDL approach is resilient to many data characteristics, including non-stationarity and structural breakdowns. To accomplish this goal, we use the partial sum method suggested by Shin et al. (2014) to break down the NRV variable into two distinct variables: one that captures positive movements and another that represents negative movements.

$$NRV^{+}_{it} = \sum_{n=1}^{t} \Delta NRV^{+}_{it} = \sum_{n=1}^{t} \max\left(NRV^{+}_{it}, 0\right) \tag{3a}$$

$$NRV^{-}_{it} = \sum_{n=1}^{t} \Delta NRV^{-}_{it} = \sum_{n=1}^{t} \min\left(\Delta NRV_{it}^{-}, 0\right) \tag{3b}$$

Equations (3a) and (3b) illustrate a couple of variables, where $NRV^{+}$ represents the positive series, and $NRV^{-}$ represents the negative series. In order to include equation (2) into the NARDL structure, the original variable is replaced with the new variables, as illustrated below:

$$\begin{aligned}\Delta GG_{it} = \omega_0 &+ \sum_{k=1}^{n} \beta_{1k}\Delta GG_{it-k} + \sum_{k=0}^{n} \beta_{2k}\Delta NRV^{+}_{it-k} + \sum_{k=0}^{n} \delta_{3k}\Delta NRV^{-}_{it-k} \\ &+ \sum_{k=0}^{n} \beta_{4k} Tech_{it-k} + \sum_{k=0}^{n} \beta_{5k} EPS_{it-k} + \sum_{k=0}^{n} \beta_{6k} FD_{it-k} + \sum_{k=0}^{n} \beta_{7k} Trade_{it-k} \\ &+ \omega_1 GG_{it-1} + \omega_2 NRV^{+}_{it-1} + \omega_3 NRV^{-}_{it-1} + \omega_4 Tech_{it-1} + \omega_5 EPS_{it-1} \\ &+ \omega_6 FD_{it-1} + \omega_7 Trade_{it-1} + \varepsilon_{it}\end{aligned} \tag{4}$$

The model (4) is similar to the panel NARDL framework developed by Shin et al. (2014) as it includes the introduction of partial sum variables. The NARDL model, which expands the ARDL framework, does not necessitate supplementary exceptional handling (Yanzhe and Ullah, 2023). We employ a range of diagnostic procedures to evaluate the accuracy of our estimates. Firstly, the LM test examines the lack of autocorrelation in the error term. Ramsey's RESET test is thereafter implemented to identify any unwanted specification biases in the system. Both tests adhere to a chi-square ($\chi 2$) distribution with a single degree of freedom. Furthermore, the error terms are subjected to CUSUM and CUSUM-sq tests to assess the reliability of the short-term and long-term estimations. The main method utilized in this research is the non-linear ARDL framework. The robustness of the findings is further validated by applying the non-linear panel QARDL model (Dong and Ullah, 2023). The non-linear panel QARDL framework is especially useful when non-normality is detected, as it yields precise estimates under such circumstances.

## 4. Data and descriptive statistics

This study investigates how natural resource volatility affects green, sustainable development in BRICS economies. Data from 1995 to 2021 is collected and analyzed to examine this relationship. Table 1 provides details on definitions and data descriptions. The dependent variable in this study is green sustainable development, which is determined by green growth. Green growth (GG) is measured using environmentally adjusted multifactor productivity. Natural resource volatility (NRV) is quantified by the volatility measure of natural resource rents using GARCH (1, 1). The study has incorporated technology (TECH), environmental policy stringency (EPS), financial development (FD), and trade as control variables. R. Chen et al. (2023) reported that technological advancements significantly impact green growth. The technology variable is measured through total patent applications. Li et al. (2022) revealed that environmental policy stringency (EPS) plays a crucial role in shaping green sustainability practices and outcomes. The environmental policy stringency index is used to measure this variable. Sohail et al. (2022) described that the availability of financial resources and the effectiveness of financial institutions facilitate green growth. Financial development, including access to capital, investment opportunities, and financial markets, influences the ability of economies to finance and implement green growth initiatives. Financial development (FD) is also measured through an index. Ahmed et al. (2023) reported that international trade positively affects sustainable development. It provides access to markets for green products and technologies, facilitates knowledge transfer, and promotes economic growth. However, if not properly regulated, trade activities also lead to environmental degradation and resource depletion. Trade variable is measured by trade as a percent of GDP. Descriptive statistics report the estimates of mean, median, S.D, kurtosis, skewness, and J-B test. The mean scores are reported as 5.264 for GG, 0.054 for NRV, 10.34 for TECH, 0.994 for EPS, 0.542 for FD, and 3.695 for trade. The J-B statistics reveal that none of our model's data series is normally distributed.

## 5. Empirical results and discussion

The results of the panel unit root test, shown in Table 2, provide light on the characteristics of stationarity of the variables used in the investigation. The unit root test aids in determining if the variables are stationary at level (I(0)) or need differencing to attain stationarity (I(1)). All three unit root tests (LLC, IPS, and ADF) highlight that the variables GG, TECH, and FD are I(0), while EPS is I(1). However, the variable NRV is I(1) in the case of LLC and I(0) in the case of IPS and ADF. Lastly, the variable trade is stationary at level (I(0)) in the LLC and stationary at the first difference (I(1)) in the IPS and ADF. In conclusion, the panel unit root test findings show that the analysis's variables exhibit various orders of stationarity. While some variables need differencing (I(1)) to become stationary, others are stationary at level (I(0)).

### *5.1. Panel-wise empirical analysis*

Table 3 presents the short and long-run results of the panel ARDL and NARDL. In the long run, the linear estimates of NRV hurt green growth – a 1% rise in NRV pulls the green growth down by 0.665%. On the other side, the long-run NRV_POS hurts green growth, while the NRV_NEG contributes to the green growth – a 1 % escalation of NRV decreases green growth by 0.718%, while a 1% fall in the NRV contributes to green growth by 1.042%. This finding is supported by Wen et al. (2022), who

**Table 1**
Definitions and data descriptions.

| Variables | Definitions | Mean | Median | Max | Mini | S.D | Skewness | Kurtosis | Jarque-Bera | Prob. |
|---|---|---|---|---|---|---|---|---|---|---|
| GG | Environmentally adjusted multifactor productivity | 5.264 | 4.998 | 13.13 | -4.730 | 3.073 | -0.442 | 3.486 | 5.727 | 0.057 |
| NRV | Volatility measure of total natural resources rents based on GARCH (1, 1) | 0.054 | 0.056 | 0.057 | 0.023 | 0.005 | -3.836 | 9.244 | 114.8 | 0.000 |
| TECH | Patent applications, total | 10.34 | 10.24 | 14.24 | 8.052 | 1.409 | 1.181 | 4.211 | 39.62 | 0.000 |
| EPS | Environmental policy stringency index | 0.994 | 0.806 | 3.341 | 0.056 | 0.801 | 1.241 | 3.708 | 37.49 | 0.000 |
| FD | Financial Development Index | 0.542 | 0.516 | 0.790 | 0.325 | 0.127 | 0.404 | 2.094 | 8.282 | 0.016 |
| Trade | Trade (% of GDP) | 3.695 | 3.821 | 4.240 | 2.750 | 0.344 | -0.774 | 2.722 | 13.92 | 0.001 |

**Table 2**
Unit root test.

| | LLC | | IPS | | ADF | |
|---|---|---|---|---|---|---|
| | I(0) | I(1) | I(0) | I(1) | I(0) | I(1) |
| GG | -5.213*** | | -3.689*** | | -4.255*** | |
| NRV | 4.338 | -2.703*** | -3.348*** | | -3.420*** | |
| TECH | -3.278*** | | -2.665*** | | -2.492** | |
| EPS | 0.923 | -4.679*** | 1.614 | -5.882*** | 1.584 | -5.389*** |
| FD | -2.843*** | | -1.971** | | -1.926** | |
| Trade | -1.522* | | -0.806 | -4.251*** | -0.851 | -4.132*** |

**Table 3**
Panel estimates of green growth (ARDL & NARDL).

| Variable | ARDL | | | | NARDL | | | |
|---|---|---|---|---|---|---|---|---|
| | Coef. | Std. Error | t-Stat | Prob.* | Coef. | Std. Error | t-Stat | Prob.* |
| **Long-run** | | | | | | | | |
| NRV | -0.665** | 0.338 | -1.966 | 0.054 | | | | |
| NRV_POS | | | | | -0.718** | 0.332 | -2.159 | 0.035 |
| NRV_NEG | | | | | -1.042*** | 0.159 | -6.552 | 0.000 |
| TECH | 0.665** | 0.338 | 1.966 | 0.054 | 0.829** | 0.346 | 2.393 | 0.021 |
| EPS | 0.718** | 0.332 | 2.159 | 0.035 | 0.828** | 0.338 | 2.448 | 0.018 |
| FD | 0.227 | 0.272 | 0.834 | 0.419 | 1.327 | 3.024 | 0.439 | 0.663 |
| TRADE | 2.298*** | 0.564 | 4.078 | 0.000 | 1.553 | 0.648 | 2.397 | 0.020 |
| **Short-run** | | | | | | | | |
| D(NRV) | -1.756* | 0.940 | -1.868 | 0.066 | | | | |
| D(NRV(-1)) | -0.431 | 0.422 | -1.021 | 0.311 | | | | |
| D(NRV_POS) | | | | | -0.216* | 0.127 | -1.698 | 0.094 |
| D(NRV_POS(-1)) | | | | | -0.044 | 0.667 | -0.066 | 0.948 |
| D(NRV_NEG) | | | | | -0.255 | 0.204 | -1.248 | 0.215 |
| D(NRV_NEG(-1)) | | | | | -0.132 | 0.085 | -1.549 | 0.125 |
| D(TECH) | 3.149*** | 0.971 | 3.244 | 0.002 | 2.943*** | 1.048 | 2.807 | 0.007 |
| D(TECH(-1)) | -0.377 | 0.493 | -0.766 | 0.446 | -1.232 | 0.964 | -1.277 | 0.208 |
| D(EPS) | 0.376 | 0.866 | 0.434 | 0.666 | 0.761 | 0.949 | 0.802 | 0.426 |
| D(EPS(-1)) | -3.023 | 2.730 | -1.108 | 0.272 | -2.167 | 2.689 | -0.806 | 0.424 |
| D(FD) | 1.175 | 1.329 | 0.884 | 0.380 | 1.614 | 2.115 | 0.763 | 0.449 |
| D(FD(-1)) | -0.021 | 1.334 | -0.016 | 0.988 | -0.051 | 0.212 | -0.240 | 0.811 |
| D(TRADE) | 2.602 | 3.668 | 0.709 | 0.481 | 2.345 | 2.009 | 1.167 | 0.249 |
| D(TRADE(-1)) | -6.098 | 3.925 | -1.554 | 0.125 | -2.903 | 3.796 | -0.765 | 0.448 |
| C | 12.30*** | 4.178 | 2.945 | 0.005 | -5.949*** | 0.950 | -6.262 | 0.000 |
| **Diagnostic tests** | | | | | | | | |
| F-test | 8.065*** | | | | 6.025*** | | | |
| ECM(-1) | -0.801** | 0.311 | -2.578 | 0.012 | -0.868*** | 0.144 | -6.040 | 0.000 |
| LM | 1.023 | | | | 0.658 | | | |

noted that natural resource volatility reduces economic growth. When resource prices are high and stable, governments generate substantial revenue from resource exports, which can be used for investment in infrastructure, social programs, and economic development. However, revenue declined significantly during low prices or price volatility periods, resulting in budget deficits and reduced government spending on critical areas. This hinders economic growth by limiting investment and constraining government initiatives. Uncertainty in natural resource prices discourages investment in resource-dependent sectors. Volatile prices make it difficult for businesses to assess the profitability of long-term projects, such as resource extraction or related industries. This uncertainty leads to a decline in investment, reduced capital inflows, and a slowdown in economic activity (Zhou et al., 2022). Without sufficient investment, economies may struggle to expand production capacities, develop new industries, and create job opportunities, all essential for sustained economic growth. Natural resource volatility contributes to political and social instability, which has detrimental effects on economic growth. Fluctuating resource prices lead to income disparities, social unrest, and political tensions within resource-rich countries. Instability undermines investor confidence, deters foreign direct investment, disrupts production activities, and hinders economic progress (Wu et al., 2022). Weak governance, corruption, and conflict risks further exacerbate these negative effects, impeding long-term economic growth prospects.

In addition, the variables TECH and EPS positively contribute to green growth in linear and non-linear panel ARDL models. Specifically, a 1% TECH (EPS) growth promotes green growth by 0.665% and 0.829% (0.718% and 0.828%) in the linear and non-linear panel ARDL models. The positive impact of EPS has been confirmed by numerous studies (Chien et al., 2022). Technological advancements enable increased productivity in various sectors of the economy. New technology leads to higher output per worker, improved resource allocation, and increased overall productivity. Higher productivity translates into economic growth by enabling more goods and services to be produced with the same or fewer resources. Technological development fosters innovation and entrepreneurship. Advances in technology create new opportunities for businesses to develop innovative products, services, and business models. These innovations often result in new industries and the expansion of existing ones, leading to job creation, higher incomes, and increased economic activity (Mensah et al., 2019). Entrepreneurial activities stimulated by technological progress drive economic growth by introducing new products, improving existing ones, and driving market competition. Meanwhile, environmental policy stringency encourages the development and growth of green industries. Stringent policies create a favorable environment for investment and innovation in these areas, leading to the emergence of new businesses, technologies, and practices. This stimulates economic activity and job creation in the green sector, driving growth (Chen and Tanchangya, 2022). Environmental policy stringency promotes technological innovation aimed at reducing environmental impacts. Environmental policy stringency encourages businesses to adopt resource-efficient practices and technologies. Increased resource efficiency reduces environmental impacts and leads to cost savings for businesses. These savings can be reinvested, stimulating economic growth while minimizing resource consumption and waste generation (Yu et al., 2023).

However, a 1% growth in TRADE only boosts green growth by 2.298% in the long run in the linear model. This finding aligns with the results obtained by Sohail et al. (2022). Trade allows for the transfer of green technologies between countries. Countries that are leaders in developing and implementing environmentally friendly technologies export these technologies to other countries, promoting their adoption and use in different regions. The spread of green technologies is vital in fostering green growth by enhancing resource efficiency and mitigating pollution (Cui et al., 2022). Trade enables countries to access a wider range of green goods and services.

The coefficients of ECM tests exhibit negative significance, and the F-test statistics show significance. This confirms the credibility of our long-run findings. The short-run linear estimates of NRV significantly and negatively impact the green growth – a 1% more volatile natural resource leads to a fall in green growth by 1.756%. The short-run non-linear estimates of NRV, however, only significantly and positively impact the green growth when the NRV series is positive and insignificantly influences the green in the case of negative NRV series – a 1% growth of NRV causes the green growth to fall by 0.216%. In addition, only the variable TECH has significant and positive estimates in both linear and non-linear models in the short run – a 1% upward trend in TECH promotes green growth by 3.149% (linear) and 2.943% (non-linear).

Table 4 presents the results of the non-linear QARDL model. In the long run, the estimates of variables NRV_POS and NRV_NEG are negatively significant from the 20th to 95th quantiles-conferring that a rise in NRV causes the green growth to decrease and the fall in the NRV causes the green to grow at almost all intensities of green growth. The estimated coefficients of EPS and FD are positively significant at all quantiles, i.e., from 0.05 to 0.95 quantiles. In comparison, the estimates of TECH and TRADE are favorably linked to green growth from 0.40 to 0.95 and from 0.60 to 0.95 quantiles. However, the short-run estimated coefficients attached to most variables are insignificant across most quantiles.

### 5.2. *Economy-wise empirical analysis*

Table 5 describes the country-specific outcomes of the non-linear ARDL model. The long-run estimates of the NRV_POS are negatively significant in Brazil, India, and China - a 1% growth in the NRV reduces the green growth in Brazil, India, and China by 1.489%, 1.615%, and 1.945%, respectively. Nevertheless, the long-run estimates for the rest of the variables are insignificant. Brazil heavily relies on mining and is vulnerable to commodity price fluctuations, affecting its green growth initiatives. India's diverse economy, particularly its services sector, may mitigate the impact of natural resource volatility. China's rapid industrialization and dependence on natural resources make it susceptible to production cost fluctuations, impacting its green growth initiatives. These possible factors differ in the impacts of natural resource volatility on green growth in Brazil, India, and China. Similarly, a 1% growth of Tech leads the GG by 1.318% in Russia and 2.058% in China. The estimates of EPS have significantly and favorably influenced GG in Brazil, China, Russia, and South Africa. Similarly, FD encourages the GG in Brazil, Russia, and China, while trade significantly impacts GG in Russia, India, and China.

Similarly, the short-run country-specific estimates for the main variables are insignificant, while the estimates of TECH are significant and

**Table 4**
Panel estimates of green growth (Non-linear QARDL).

| | Long-run | | | | | | Short-run | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NRV_POS | NRV_NEG | TECH | EPS | FD | TRADE | NRV_POS | NRV_NEG | TECH | EPS | FD | TRADE | C | ECM |
| 0.05 | -0.687 | -0.542 | 0.130 | 2.612*** | 1.987** | 0.510 | -0.876 | -0.460 | 0.311 | 0.515 | 0.658 | 0.018 | 1.325*** | -0.654** |
| | -1.534 | -1.045 | 0.787 | 7.424 | 2.120 | 1.188 | -1.015 | -0.366 | 0.555 | 0.201 | 0.325 | 0.221 | 3.255 | -2.055 |
| 0.10 | -0.570 | -0.212 | 0.203 | 1.930*** | 1.871** | 0.375 | -0.676 | -0.265 | 0.339 | 0.558 | 0.698 | 0.123 | 1.452*** | -0.578* |
| | -0.863 | -0.150 | 0.933 | 2.649 | 2.005 | 0.870 | -1.001 | -0.324 | 0.612 | 0.345 | 0.455 | 0.325 | 3.345 | -1.875 |
| 0.20 | -0.680*** | -0.174*** | 0.092 | 0.698** | 1.787*** | 0.282 | -0.576 | -0.190 | 0.412 | 0.654 | 0.789 | 0.213 | 1.715*** | -0.521* |
| | -10.29 | -3.643 | 1.286 | 2.117 | 4.358 | 1.008 | -0.985 | -0.241 | 0.732 | 0.421 | 0.512 | 0.412 | 3.456 | -1.712 |
| 0.30 | -0.955*** | -0.090*** | 0.095 | 0.654*** | 1.572*** | 0.228 | -0.476 | -0.160 | 0.425 | 0.745 | 0.842 | 0.315 | 1.997*** | -0.498* |
| | -19.59 | -3.087 | 1.616 | 3.695 | 11.64 | 1.108 | -0.728 | -0.145 | 0.845 | 0.521 | 0.532 | 0.512 | 3.556 | -1.789 |
| 0.40 | -0.988*** | -0.058** | 0.275*** | 0.621*** | 1.484*** | 0.338 | -0.376 | -0.120 | 0.452 | 0.845 | 0.987 | 0.345 | 2.145*** | -0.458** |
| | -19.04 | -2.368 | 4.632 | 4.513 | 7.670 | 1.344 | -0.406 | -0.101 | 0.897 | 0.625 | 0.632 | 0.623 | 3.785 | -2.121 |
| 0.50 | -1.076*** | -0.161*** | 0.336*** | 0.558*** | 1.332*** | 0.459 | -0.296 | -0.098 | 0.512 | 0.879 | 1.245 | 0.415 | 2.325*** | -0.433** |
| | -16.01 | -3.921 | 4.766 | 4.252 | 5.710 | 1.434 | -0.831 | -0.321 | 0.678 | 0.715 | 0.754 | 0.712 | 3.897 | -2.345 |
| 0.60 | -1.129*** | -0.235*** | 0.428*** | 0.455*** | 1.274*** | 0.673** | -0.176 | -0.041 | 0.545 | 0.989 | 1.456 | 0.512 | 2.456*** | -0.477** |
| | -16.19 | -5.087 | 5.618 | 3.716 | 3.420 | 2.018 | -0.987 | -0.415 | 0.612 | 0.814 | 0.845 | 0.875 | 4.154 | -2.564 |
| 0.70 | -1.213*** | -0.313*** | 0.550*** | 0.177** | 1.013** | 0.870** | -0.147 | -0.128 | 0.498 | 1.023 | 1.654 | 0.654 | 2.785*** | -0.512*** |
| | -16.87 | -5.081 | 6.846 | 2.078 | 1.774 | 2.527 | -1.101 | -1.011 | 0.578 | 0.945 | 0.987 | 0.987 | 3.785 | -3.012 |
| 0.80 | -1.144*** | -0.430*** | 0.730*** | 0.300** | 1.053** | 1.114*** | -0.276 | -0.138 | 0.425 | 1.012 | 1.458 | 0.489 | 2.879*** | -0.532*** |
| | -15.90 | -6.648 | 8.250 | 2.015 | 2.054 | 2.926 | -1.166 | -1.025 | 0.564 | 1.023 | 1.456 | 0.654 | 3.452 | -3.066 |
| 0.90 | -1.052*** | -0.632*** | 1.058*** | 0.858*** | 1.213*** | 1.555*** | -0.376* | -0.240 | 0.378 | 1.232 | 1.325* | 0.345 | 3.211*** | -0.556*** |
| | -15.28 | -8.759 | 10.88 | 5.101 | 2.928 | 3.058 | -1.794 | -1.254 | 0.532 | 1.542 | 1.698 | 0.568 | 3.125 | -3.426 |
| 0.95 | -0.909*** | -0.869*** | 1.297*** | 1.212*** | 1.418*** | 2.009*** | -0.476* | -0.340 | 0.351 | 1.345 | 1.125** | 0.325 | 3.325*** | -0.589*** |
| | -5.996 | -4.020 | 11.59 | 5.531 | 2.792 | 3.015 | -1.845 | -1.345 | 0.498 | 1.445 | 2.125 | 0.488 | 2.598 | -3.766 |

**Table 5**
Country-wise estimates of green growth (ARDL).

| Variable | Brazil | | Russia | | India | | China | | South Africa | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Coef. | t-Stat | Coef. | t-Stat | Coef. | t-Stat | Coef. | t-Stat | Coef. | t-Stat |
| **Long-run** | | | | | | | | | | |
| NRV_POS | -1.489* | -1.793 | -0.793 | -0.231 | -1.615*** | -2.778 | -0.740* | -1.945 | -1.174 | -0.390 |
| NRV_NEG | 0.054 | 1.029 | 0.011 | 0.101 | 0.023 | 1.025 | 0.021 | 0.011 | 0.021 | 1.054 |
| TECH | 1.708 | 0.606 | 1.318* | 1.944 | 1.879 | 1.253 | 2.058** | 2.455 | 0.912 | 0.366 |
| EPS | 1.873* | 1.193 | 1.718*** | 3.148 | 0.285 | 0.208 | 2.002** | 2.397 | 1.202** | 2.388 |
| FD | 1.085* | 1.721 | 0.763* | 1.953 | 1.419 | 1.423 | 1.694** | 2.396 | 0.929 | 1.302 |
| TRADE | 2.015 | 1.556 | 1.898*** | 2.716 | 2.961** | 2.249 | 3.654*** | 3.171 | 1.684 | 0.375 |
| **Short-run** | | | | | | | | | | |
| NRV_POS | -0.621 | -0.789 | -0.948 | -1.438 | -1.040 | 0.224 | 1.058 | 1.505 | -0.177 | 1.064 |
| NRV_POS(-1) | 0.021 | 1.021 | 0.214 | | 0.011 | 0.254 | | | 0.245 | 0.689 |
| NRV_NEG | -0.088 | -1.097 | -0.504 | -0.309 | -0.960 | -0.879 | 0.021 | 1.255 | 0.422 | 0.547 |
| NRV_NEG(-1) | 0.193 | 1.123 | 0.555 | 1.468 | 0.596 | 1.360 | | | | |
| TECH | 1.072 | 1.608 | 1.118* | 1.691 | 1.675 | 1.007 | 1.314** | 2.121 | 3.735*** | 2.699 |
| TECH(-1) | | | | | 1.116 | 1.086 | | | 1.267 | 1.240 |
| EPS | 0.716 | 0.253 | 1.778 | 0.198 | 0.821 | 0.394 | 1.303 | 1.298 | 0.226 | 0.290 |
| EPS(-1) | 0.510 | 1.203 | 0.653 | 0.078 | 1.132 | 0.959 | 1.336 | 1.027 | | |
| EPS(-2) | | | 0.117 | 1.430 | 0.235* | 1.774 | 1.068 | 1.056 | | |
| FD | 1.868* | 1.934 | 1.427* | 1.904 | 0.217* | 1.839 | 2.003** | 1.967 | 0.825 | 1.042 |
| FD(-1) | | | 0.090 | 1.121 | 0.409 | 0.556 | 0.201 | 1.514 | | |
| TRADE | 1.065* | 1.947 | 1.506 | 0.613 | 1.930 | 1.073 | 2.099*** | 2.826 | 1.892*** | 4.074 |
| TRADE(-1) | | | 0.770 | 0.316 | 0.944 | 0.962 | 1.046 | 1.436 | 1.472 | 1.078 |
| C | 14.05*** | 9.482 | 11.42*** | 2.988 | 8.615*** | 12.54 | 9.568*** | 8.868 | 6.461*** | 5.397 |
| **Diagnostics** | | | | | | | | | | |
| F-test | 8.658*** | | 4.689*** | | 5.689*** | | 4.655*** | | 5.650*** | |
| ECM(-1)* | -0.536*** | -10.01 | -0.675*** | -5.350 | -0.689*** | -7.677 | -0.598*** | -6.506 | -0.403*** | -5.858 |
| LM | 1.055 | | 0.542 | | 0.542 | | 0.524 | | 2.011 | |
| Cusum | S | | S | | S | | S | | S | |
| Cusum-sq | S | | S | | S | | S | | S | |

positive in Russ (1.118%), China (1.314%), and South Africa (3.735%); the estimates of FD are positively significant in Brazil (1.868%), Russia (1.427%), India (0.217%), China (2.003%); the estimates of TRADE are significantly positive in Brazil (1.868%), China (2.099%), and South Africa (1.892%). The validity of our findings is confirmed with the help of some diagnostics statistics presented in Table 5. The ECM and F-tests confirm that the long-run relationship between the variables is genuine. Additionally, our models show no first-order serial correlation and demonstrate parametric stability.

## 6. Conclusion and implications

Natural resources are vital for economic growth and development, particularly in emerging economies. However, the volatility of these resources can pose challenges to sustainable development. Because of their abundant natural resources and rapid economic growth, BRICS economies face unique opportunities and risks in achieving green, sustainable development. This study explores the impact of natural resource volatility on sustainable green development in BRICS economies. Green sustainable development, which encompasses economic growth while ensuring environmental protection and social well-being, has become a global priority in the face of climate change and resource depletion. The volatility of natural resources refers to unpredictable fluctuations in availability, prices, and extraction levels. This volatility can arise from various factors, such as geopolitical tensions, market dynamics, technological advancements, and environmental factors. BRICS economies, with their diverse resource endowments ranging from fossil fuels to renewable energy sources and minerals, are susceptible to such volatility. Thus, this study aims to explore how natural resource volatility impacts green development in BRICS. The study utilizes novel panel non-linear estimation methods, specifically non-linear ARDL and QARDL models. This study offers decision-makers and future researchers valuable insights by comprehensively analyzing short- and long-term effects. According to the analysis's key results, the short and long-run natural resource volatility hurt green growth in the linear model. In the non-linear model, the rise in natural resource volatility hurt green growth in the short and long run, and the fall in the natural resources volatility only boosts green growth in the long run. Regarding the country-specific results, the rise in natural resource volatility reduces green growth in Brazil, India, and China in the long run; however, the fall in the natural resource volatility does not significantly influence green growth in any economy. Technological development, environmental policy stringency, and trade openness promote green growth.

The study provides the following policy implications. Firstly, BRICS economies heavily rely on natural resource sectors for economic growth. Policymakers should focus on diversifying their economies to reduce vulnerability to natural resource volatility. Encouraging the development of non-resource sectors, such as technology, manufacturing, services, and renewable energy, can provide alternative sources of income and mitigate the impact of resource price fluctuations. Secondly, stringent environmental policies are crucial for promoting green, sustainable development. Governments should enhance regulatory frameworks to ensure sustainable resource extraction practices, minimize environmental degradation, and promote the transition to renewable energy. Stringent regulations can also help manage the potential negative impacts of natural resource volatility on ecosystems and local communities. Thirdly, technology plays a pivotal role in achieving green development. Technologies like advanced battery storage systems provide a more stable and reliable power supply for green growth initiatives. Governments should allocate resources to research and develop environmentally friendly technologies, encompassing renewable energy, energy-efficient infrastructure, and sustainable agricultural practices. Encouraging innovation and providing incentives for adopting green technologies can help BRICS economies reduce their reliance on resource-intensive industries and foster sustainable growth. Fourthly, access to finance is crucial for implementing green development initiatives. Policymakers should focus on enhancing financial mechanisms, such as green bonds, sustainable investment funds, and specialized lending programs, to attract investment in environmentally friendly projects. Developing robust financial markets and institutions prioritizing sustainable investments can provide the capital necessary to drive green development. Fifthly, natural resource volatility is not limited to national boundaries, and its impacts are often global. BRICS economies should foster international cooperation and partnerships to address shared challenges related to resource management and sustainable development. Collaborative initiatives can include knowledge sharing, technology transfer, joint research projects, and policy coordination to promote sustainable resource use and reduce volatility. Lastly, building human capital is crucial for implementing sustainable development strategies. Governments should invest in education for green sectors and sustainable practices. By fostering a skilled workforce, BRICS economies can adapt to changing market dynamics, capitalize on emerging opportunities, and navigate resource volatility more effectively. Regarding country-wise policies, Brazil's government should encourage economic diversification to reduce dependence on specific natural resources. Also, enhance institutions responsible for resource management and environmental protection to navigate better and mitigate the impacts of natural resource volatility. India should also enhance resource efficiency and minimize the negative impact of resource volatility. China and India should invest in and promote the development and adoption of green technologies to reduce the environmental impact of resource extraction and support sustainable economic growth.

This study has certain research limitations that could be addressed by future research. Firstly, there is a need to expand the sample size and period. Secondly, while this study adheres to the green growth definition of the OECD, upcoming studies could explore definitions provided by UNEP and the World Bank. Thirdly, future research should evaluate the influence of geopolitical risks and conflicts on green growth. Lastly, this study did not consider cross-sectional dependence, whereas future studies should investigate the nexus under the framework of nonlinearity and cross-sectional dependence.

## CRediT authorship contribution statement

**Meihong Feng:** Conceptualization, Funding acquisition, Writing – original draft. **Donghang Zou:** Conceptualization, Methodology, Project administration, Writing – review & editing. **Muhammad Hafeez:** Conceptualization, Formal analysis, Software, Writing – review & editing.

## 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.

## Data availability

Data will be made available on request.

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