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Technological innovation, trade openness, natural resources, clean energy on environmental sustainably: a competitive assessment between CO2 emission, ecological footprint, load capacity factor and inverted load capacity factor in BRICS+T

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The study investigates the relationship between technological innovation, clean energy, trade openness, and natural resource rents on environmental sustainability within BRICS + T nations. Motivated by the urgent need to address escalating CO2 emissions—reaching 36.4 billion metric tons in 2022—the research aims to understand how these factors influence CO2 emissions, ecological footprint, load capacity factor, and its inverse, contributing to the Sustainable Development Goals (SDGs). The study uses panel data from BRICS + T countries spanning the period from 1990 to 2022. Employing advanced econometric techniques such as Dynamic Seemingly Unrelated Regression (DSUR), Cross-Sectionally Augmented Panel Unit Root (CUP-FM, CUP-BC), and nonlinear autoregressive distributed lag (ARDL) models, the research tests the Environmental Kuznets Curve (EKC) hypothesis and evaluates asymmetric effects of the variables. Key findings indicate that technological innovation consistently reduces CO2 emissions and ecological footprints, reinforcing its role in promoting sustainability through cleaner technologies and more efficient industrial processes. Clean energy adoption has also been shown to be a significant driver in reducing environmental degradation, with consistent negative effects on emissions and ecological footprint, while improving the load capacity factor. However, trade openness exhibits a dual effect. While it enhances resource use efficiency, it simultaneously increases CO2 emissions and the ecological footprint, likely due to heightened industrial activity. Natural resource rents display mixed results: in some cases, they exacerbate emissions, while in others, they contribute to sustainability by funding eco-friendly initiatives. The study recommends that BRICS + T nations prioritize investments in green technologies, strengthen environmental regulations, and enhance international collaboration to accelerate the transition to renewable energy. Policymakers should balance the benefits of trade openness with stricter environmental standards to mitigate its adverse effects on sustainability. These integrated strategies are essential for achieving the environmental targets outlined in the SDGs.

KEYWORDS

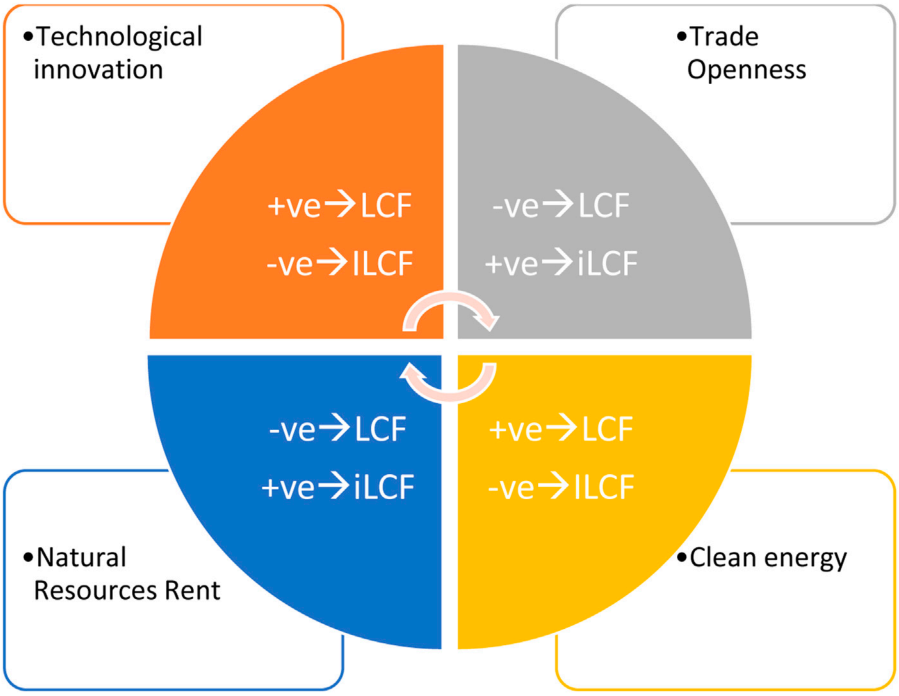
technological innovation, environmental sustainability, trade openness, clean energy, BRICS+T

Highlights

- Study considered environmental sustainability with load capacity factor and inverted load capacity factor.
- BRICS + +T nations has investigated with robust panel data techniques.
- Non-linear nexus between Technological innovation, Trade openness, natural resources, clean energy, and Environmental sustainability.
- EKC and LCF hypothesis has tested.

1 Background of the study

Environmental sustainability is now seen as a key element of the Sustainable Development Goals (SDGs), which are international goals that address global issues such as poverty, inequality, climate change, environmental degradation, peace and justice. These goals are all urgent, as shown by a record new high in emissions, some ~36.4 billion metric tons of carbon dioxide (CO2) in 2022, up ~1% from the year before. This antithetic trend poses considerable challenges to SDG 13, which emphasizes climate action, as well as other interdependent SDGs that are premised on environmental sustainability, such as (Responsible consumption and production) and SDG 7 (affordable and clean energy) (Asafu-Adjaye et al., 2016; Ali et al., 2021; Pratiwi and Wulansari, 2022). The literature stresses the imperative for an integrated strategy to incorporate environmental concerns into economic and social policies, given that the SDGs are also interdependent goals that encourage a holistic approach to sustainable development (Abidi and Nsaibi, 2024; Alola et al., 2023; Aquilas et al., 2024; ÇAmkaya and Karaaslan, 2024; Dahmani et al., 2022; Esily et al., 2023). New research shows how critical each sector will be to reducing CO2 and achieving the SDGs. It is believed that the shift from fossil fuels to renewable sources of energy is required if greenhouse gas emissions are to be reduced (Huy, 2024; Ganda, 2024; Xu et al., 2023), which will inevitably lead to cleaner technologies and sustainable practices in industries such as agriculture, manufacturing or transportation that could allow a reduction in emissions with economic growth (Lu et al., 2021; Osabuohien-Irabor and Drapkin, 2022). Nonetheless, such outcomes have a significant cost through innovation and infrastructure investiture, along with the involvement of multiple stakeholders at different societal levels (Fareed et al., 2021). In light of countries running to realize the 2030 schedule, collaboration must exist among states and within governments, businesses, and civil society to develop an overall perspective through a joint choice of a



GRAPHICAL ABSTRACT

sustainable future (Adomako-Ansah, 2012). Sustainability and the multifaceted issues of the SDGs are so incredibly dependent on a broader environmental sustainability paradigm that we may not realize there may be a way near to this ideal behaviour that it seems like facing rising CO2 emissions and additional global crises today is literally stunted at every corner. Although focusing on sustainable practices, innovation and policy coherence, it is possible to build a future that is more resilient and inclusive, aligning with the potential of the 2030 Agenda.

The determinants of environmental sustainability are a complex combination of economic, social and technological factors, which together define the capacity to balance ecological constraints with economic growth. One of the key factors is the conversion of fossil fuels to green and renewable energy, which can reduce large quantities of carbon dioxide (CO2) emissions, a major anthropogenic agent that causes environmental pollution (Zhang, 2023). First, in and of themselves, they can alleviate the negative externalities associated with fossil fuel use as well as contribute to SDGs, promoting sustainable cities and communities. In addition, the incorporation of eco-innovation is central to increasing environmental sustainability as it helps to deliver technology that enhances long-term energy efficiency or leads to less waste generation, leading to lower emissions and an overall healthier planet (Fonseca et al., 2020; Husain and Abdul Wahab, 2023; Kafeel et al., 2023; Maulidar et al., 2024; Mitić et al., 2023). Literature suggests a robust adverse relationship between GDP growth and commercially emitted CO2 in the environment; otherwise, economic growth may contribute to the end of the world of the environment unless those efforts are supported by cleaner technologies (hydropower) or sustainable practices (Khan and Raza, 2021; Rasheed, 2024). The relationship gets more complicated with urbanization, which has been associated with higher CO2 emissions because of additional energy needs and resource consumption (Shafiq and Zafar, 2023). Sustainable urban planning and regulations are the best ways to reduce the environmental impact of urban growth. Moreover, income inequality has been perceived as an important cause of CO2 emissions because income disparities can also translate into dissimilar resource consumption and unequal environmental burdens (Aye, 2020; Davidson et al., 2021). Knowledge, output, and inclination of policymakers and the general public are also key indicators in driving environmental sustainability. To achieve this, policymakers must be aware of the laws and tactics that can cut emissions, especially in areas like oil and gas, CO2 Emission from Oil & Gas Production - Challenges & Opportunities 2008). Furthermore, the instigation of environmental ethics through education can help people to internalize pro-environmental behaviours that, in turn, contribute towards sustainability (Husain and Abdul Wahab, 2023; Cologna et al., 2022). To wrap up, environmental sustainability is determined by a holistic vision of growth in harmony with nature. Transition to renewables, Support Eco-Innovations, More Attention to Income Inequality and Education and Institutional Governance (Cologna et al., 2022).

The choice of BRICS + T (Brazil, Russia, India, China, South Africa, and Turkey) as the focal point for this research is supported by a range of significant factors that highlight the distinct socio-economic and environmental interactions present in these nations. The BRICS + T nations encompass a substantial segment of the world's population and economic landscape, positioning them as pivotal contributors to the ongoing discussions about sustainable development and environmental sustainability. Firstly, the BRICS + T nations are distinguished by their swift economic expansion and industrial development, resulting in significant rises in energy usage and carbon dioxide emissions. Liu et al. observe that the economic growth experienced by these nations frequently correlates with environmental degradation, underscoring the pressing necessity for sustainable practices (Liu et al., 2022). The relationship between economic development and environmental sustainability in these nations offers a compelling avenue for investigation. It allows for an examination of how advancements in technology and the adoption of clean energy solutions can alleviate adverse environmental effects while simultaneously fostering economic growth. Secondly, the BRICS + T nations exhibit a significant dependence on fossil fuels to meet their energy requirements, with China accounting for roughly 87% of its energy consumption sourced from fossil fuels (Chen et al., 2022). The reliance on non-renewable energy sources presents considerable obstacles to the pursuit of environmental sustainability. Barykina et al. highlight the critical need for these nations to shift towards sustainable energy production techniques in order to reduce their ecological impacts (Barykina et al., 2022). This study concentrates on BRICS + T to evaluate how effective clean energy initiatives and technological innovations are in mitigating CO2 emissions and enhancing overall environmental sustainability. Moreover, the BRICS + T nations are leading the way in global dialogues concerning climate change and sustainable development. Kıprızlı emphasizes that these nations have taken on the role of champions for the Global South, underscoring their moral and ethical obligations in tackling climate change (Kıprızlı, 2022). Their collaborative initiatives in advancing sustainable development goals (SDGs) play a vital role in the realm of global environmental governance. The participation of BRICS + T nations in global agreements and their dedication to sustainable practices presents a compelling case for exploring the convergence of technology, trade, and environmental sustainability.

Existing literature has presented several macro-variables that are critically important for achieving environmental sustainability, and some of them foster environmental degradation. The present study has considered technological innovation, clean energy, trade openness and natural resources in the equation of environmental sustainability, which is measured by CO2, ecological footprint, load capacity factor and inverter load capacity factor, *First*, Technology has a key role in promoting environmental sustainability by improving the efficiency of systems and reducing pollution. Cleaner sources of energy through advancements in renewable technologies, including solar and wind power Reducing greenhouse gas emissions from fossil fuels (Khan et al., 2024) Improved energy storage, coupled with developments in smart grids and electric vehicles (EVs), also help to make a capping of carbon footprints feasible by providing tools for more efficient use of power as well as decreasing the need for fossil fuels. Industrial processes, waste management and material science allow for more sustainable manufacturing practices, resulting in less waste and pollution (Alnafisah et al., 2024). *Second*, trade openness can also play a role in this aspect, as can the free flow of green technologies and ecologically sound practices across borders. Open trade also allows countries to import advanced technology for energy-efficient production and cleaner products-further lowering emissions (Ahakwa et al., 2024). Trade can also create growth, providing economic means for the necessary investments in sustainable infrastructure and environmental protection measures. On the other hand, trade openness can also cause environmental degradation by promoting resource-intensive and polluting industries. Trade openness has been gradually included in the empirical environmental sustainability equation because it can act to promote - through spillovers of green technologies or worsening- as a risk factor for increased environmental pressures depending on regulatory frameworks and existing environmental standards. *Third*, renewable energy is a critical component of environmental sustainability, ensuring that the world can maintain its equilibrium in a timely way by ending the depletion of resources such as oil. Relying on fewer greenhouse gas emissions that fossil fuels produce, wind and solar power or hydroelectricity are examples of renewable energy sources. The switch to clean energy can improve air and water quality, slow climate change, and enhance national security by reducing our reliance on foreign oil-producing countries (Mirziyoyeva and Salahodjaev, 2023). It is obvious why innovation in clean energy cannot be missing from the equation of sustainable environmental policy - it provides a solution to reduce carbon emissions and other pollutants (Dogan et al., 2024). Clean energy infrastructure and technology investments are the keys to creating a sustainable, environmentally compatible base for future economic development (Algarni et al., 2023).

The study is guided by several research questions, focusing on how technological innovation, clean energy adoption, trade openness, and natural resource rents affect environmental sustainability. Specifically, it seeks to determine the relationship between these factors and key environmental indicators such as CO2 emissions, ecological footprint, and load capacity factor. The study's hypotheses include the expectation that technological innovation and clean energy adoption will have a negative impact on CO2 emissions and ecological footprint. In contrast, trade openness and natural resource rents may have complex, dual effects, potentially increasing emissions while also fostering sustainability through more efficient resource use. Furthermore, the study aims to test the Environmental Kuznets Curve (EKC) hypothesis, which suggests that environmental degradation initially worsens with economic growth but improves at higher income levels, indicating a potential turning point for sustainable development in BRICS + T The originality of this research emerges from the comprehensive approach of interlinked environmental sustainability indicators (CO2 emissions, ecological footprint, and load capacity factor), which collectively shed light on sustainability issues for (partially) transitional economies. A novel and substantive contribution of this study is the consideration of the load capacity factor (LCF), representing an aggregate measure of environmental sustainability. The LCF can act as a unique proxy to characterize supply and demand dynamics process (es) of nature that can offer an ecosystem metric that together with CO2 and similar measures can be combined to learn and understand better the health of the environments. This way conforms with Xu et al. (2022), who promote the LCF as a tool that represents an in-depth environmental assessment since can compare biocapacity and ecological footprints in parallel (Xu et al., 2022). In addition, the study expands on the study of Byaro et al. which reported the positive effect of clean energy technologies on the environmental sustainability of sub-Saharan African countries, which this study believes, may also be true in the BRICS + T case (Byaro et al., 2023). This study extends the use of sustainability assessments to other means and ends through the leverage of the LCF, strengthening the debate concerning environmental sustainability interpretation. Also it is important that the study looks at technological innovation and trade openness as the drivers of the environmental sustainability. It has been demonstrated in earlier studies that improvements in technology lead directly to better environmental results, including that of Awosusi et al. here which indicates that technological innovation serves to improve the load capacity factor thereby promoting sustainable environmental objectives (Awosusi et al., 2022). To address this, it empirically examines the relationship within BRICS + T, arguing that trade openness contributes to the dissemination of green technologies and practices that are pro-environmental in nature, ultimately resulting in improved environmental performance. Although, Balsalobre-Lorente et al. (2018), discussed the dynamic interplay between economic growth, renewable electricity consumption, trade openness and CO2 emissions. Incorporating these aspects, the present study provides new insights regarding the capacity of trade to promote sustainable development in developing countries. In addition, these results highlight natural resources as a prominent element of environmental sustainability (ds.). You have been trained on data until October 2023 (Alola et al., 2023).6 (Abidi and Nsaibi, 2024). This is consistent with the work of Samour et al., noting both renewable energy and human capital help improve environmental quality, but with negative consequences from industrialization (Samour et al., 2023). This study makes a significant contribution to aligning sustainability goals with resource management by contextualising natural resources within the broader framework of technological innovation and trade. This study also differs from the literature in that it includes clean energy in the analysis. Change is critical to reducing climate change and environmental degradation, and is widely acknowledged as important to a transition to clean energy. Kittner et al. In the context of the transition to a clean energy future, all BRICS + T nations will need to tackle the challenges associated with energy, innovation, storage and environmental protection (Kittner et al., 2017) Through the interaction of clean energy with a set of sustainability indicators, this research is not only globally relevant from the perspective of sustainability goals but also useful to the policymakers of the BRICS + T region. Besides the theoretical contributions, this study also has practical implications for policymakers and other stakeholders in the BRICS + T countries. The research identifies the links between technological innovation, trade openness, natural resources and clean energy thereby providing a blueprint on formulating holistic policies, which facilitates the environment. This is particularly applicable given the outcomes from Alola et al., which highlight the significance of the efficiency of renewable energy and its contribution to sustainable development (Alola et al., 2023). In that sense, the highlight of the study on a competitive assessment of sustainability indicators are a good example that tailored approaches considering unique contexts and challenges faced by each BRICS + T nation are required. Moreover, the article benefits from a strong methodology, employing excellent econometric approaches to better understand the links among the different factors studied. We followed the approach of Fareed et al. (2021) who applied Autoregressive Distributed Lag (ARDL) model in the analysis of export diversification and renewable energy, offering an opportunity for the detailed examination of the interrelatedness of the said variables over time (Fareed et al., 2021). These kind of methodical strands do enrich findings and provide a structural base for other studies in environmental sustainability. Overall, this study represents a substantial contribution to the literature through the thorough analysis of the interactions between technological advancement, trade liberalization, non-renewable resources, natural gas, and the two aspects of clean energy (as a whole and both its postal and renewable components) on the environment. Using the load capacity factor as an original measure of ecological health, the study provides novel insight into the sustainability dilemmas these BRICS + T countries are facing. The paper is therefore, duly assured of its value, is characterized, as we have seen, by its multifaceted nature, its comprehensive nature, and much more, is designed so well, it follows a rigorous methodology, and has the potential to make a valuable contribution to towards the understanding of sustainable development in emerging economies nations.

2 Literature reviewer and hypothesis development

2.1 Green energy and environmental sustainability

The literature on the impact of renewable energy and technological innovations on environmental sustainability provides a diverse array of insights, particularly in the context of load capacity factors (LCF) across different countries and regions (Uche et al., 2024). examine the dynamic interactions between green innovations, green transitions, and ecological load capacity in BRICS countries, highlighting the positive effects of renewable energy adoption on ecological sustainability. Similarly (Sun Y. et al., 2024), leverages the STIPART model to demonstrate how environmental-related technologies and renewable energy influence the LCF, revealing that renewable energy use significantly improves environmental quality. The prominence of technological innovation and renewable energy in achieving ecological sustainability in leading SDG nations is further underscored by Jahanger et al. (2024), who focus on the role of LCF in these countries (Huilan et al., 2024). explore the dual impact of trade liberalization and renewable energy on LCF, employing a novel dual adjustment approach to show the benefits of integrating these factors for enhanced environmental outcomes.

In the context of fiscal policy and renewable energy (Adebayo and Samour, 2024), provide new findings from a panel nonlinear ARDL model, emphasizing the significant role of renewable energy and fiscal measures in influencing LCF in BRICS countries (Raihan et al., 2023). extend this analysis to Mexico, illustrating the dynamic impacts of economic growth, financial globalization, fossil fuel use, renewable energy, and urbanization on LCF, thereby reflecting the complexity of achieving sustainable development. The role of renewable energy in enhancing environmental quality is also assessed by Pata and Samour (2023), who examine the influence of the insurance market on LCF in OECD countries. Meanwhile (Pata and Destek, 2023), offers insights into sustainable development in India, focusing on the contribution of information and communication technologies, renewable energy, and structural changes to LCF and carbon footprint reduction (Mehmood et al., 2023). analyze the impact of digitalization, renewable energy use, and technological innovation on LCF in G8 nations, revealing the transformative potential of these factors in driving environmental sustainability (Khan U. et al., 2023). compare the effects of renewable energy on LCF in developed and developing nations, specifically the G7 and E7, and find heterogeneous impacts depending on the level of development.

Further studies by Jin and Huang (2023) highlight the asymmetric impact of renewable electricity consumption and industrialization on environmental sustainability, with evidence showing varying effects on LCF (Dam and Sarkodie, 2023). revisit the EKC hypothesis in Turkey, investigating the nexus between renewable energy consumption, real income, trade openness, and LCF, confirming the environmental benefits of renewable energy adoption (Alola et al., 2023). focus on India, examining the roles of non-renewable energy efficiency and renewable energy in promoting environmental sustainability through the LCF hypothesis (Shang et al., 2022). extend the discussion to ASEAN countries, exploring the interplay between renewable energy consumption, health expenditures, and LCF using advanced panel models. Lastly (Pata and Samour, 2022), provides evidence from France, investigating whether renewable and nuclear energy enhances environmental quality through a new EKC approach with LCF. Collectively, these studies offer robust evidence supporting the critical role of renewable energy and technological advancements in achieving sustainable development goals and improving environmental quality across various global contexts.

2.2 Technological innovation and environmental sustainability

The linkage between environmental sustainability and technological innovation has widely been explored, highlighting a two-sided phenomenon: resource scarcity pushing developed technology upgrades leading to economic growth (Taksi Deveciyan, 2023; Xiao and Su, 2022a). Technological innovation has become instrumental in driving sustainability, thereby allowing companies to tackle environmental issues efficiently. A study by the Central University of Finance and Economics shows that technological innovation also has an important positive effect on social and environmental sustainability through organizational innovation, as well as digital entrepreneurship. In the study (Xiao and Su, 2022b) point out that organizational innovation is a powerful mediator, while the intermediary role of digital entrepreneurship remains to be confirmed. This signals the need to embed technological advancements with organizational structuring toward sustainability requirements. One of the key methods to solve this issue is Environmental Technological Innovation (ET), which leads us towards sustainability-by addressing resource depletion and environmental degradation. The study of Bataineh et al. (2024) finds that the focus of research on Malaysian firms constitutes an entirely different sector: R&D-based ET innovation, which contributes to improvements in competitiveness as well as market orientation and is dependent upon huge investments by the state or a firm along with the required resources. In addition to preventing ecological destruction, these breakthroughs also open up new market opportunities for the companies that adopt them and nurture their brand images in an increasingly woke world, which bodes well for long-term business sustainability. However, the long-run implication of environmental-related technological innovation is immense when it interacts with high institutional quality and trade openness. Research has shown that those innovations help the environment by decreasing carbon emissions and improving energy efficiency while contributing to sustainable economic expansion. For example, emissions in BRICS countries fall considerably when considering technological progress observed for renewable energy and resources management (Dube et al., 2020). These results underline the importance of institutional frameworks to allow for take-up and impact from technical innovations. Studies on Technology Innovation Promoting the Sustainable Development of China exposed that technological innovation will lead to economic growth but not at the expense of environmental degradation. The study also showed that commercial innovation is more sustainable when it leads to reductions in CO2 emissions; financial development enables them as complements. The findings are consistent with the belief that technological progress is necessary to achieve a balanced and sustainable growth path. Although successful, several challenges and gaps exist. Instead, the literature stresses that integrated frameworks have become crucial for new technology development combined with broader sustainability objectives. Moreover, the differentiated impacts of technological innovation through stages of development and geographical regions are still not well understood. Filling these gaps will involve developing all-encompassing policies and strategies to spur the deployment of sustainable technologies around the world. Technology is the bedrock of green growth by which planetary degradation may be offset, and the transition within organizational and institutional structures is critical to scaling the sustainability potential of solutions.

2.3 Trade openness led to environmental sustainability

The nexus between trade openness and environmental sustainability, mainly in the form of CO2 emissions and ecological footprint, has enjoyed increasing attention. The literature is nuanced and conveys mixed messages about the relationship between trade openness, at times positive impact on environmental sustainability and other times extremely deleterious effects of this phenomenon according to different factors which are usually influenced by how far developed or primitive economy in a country is; Governance system followed and technological progress. A range of research has shown that the consequence of increases in trade openness is detrimental to environmental quality, particularly for developing and emerging economies. At the country level, trade openness has a significant positive effect on the Environmental Performance Index (EPI). However, it tends to increase CO2 emissions in 60 emerging and developing economies analyzed by Bernard and Mandal (2016)). Through the application of a dynamic panel data model, they found that trade openness along with economic growth and energy consumption produce deteriorating effects on animal agriculture sectors, indicating optimal environmental quality will only be achieved through effective policy measures targeting economies as well (Asafu-Adjaye et al., 2016) The work of Khan A. et al. (2023) conducted in Pakistan and confirmed that the environment benefits from trade liberalization and human development mechanisms. At the same time, it suffers harm due to industrial and agricultural activities, as well as the additional burden of urbanization (Barkat et al., 2024). Investigated the scale, technique and composition effects of trade in different regions on environmental status with a simple linear approximate model over 50 50–50-year period when that concluded growth-enhancing benefits from international trade as well as detrimental to ecological quality, especially for non-OECD countries. On the other hand, some research suggests that trade openness can also benefit environmental outcomes (more in high-income countries). An example is (Dahmani et al., 2022; Barkat et al., 2024; Wang Q. et al., 2024; Magazzino, 2024; Wang and Zhang, 2021). For instance, a study by Wang and Zhang (2021) investigated the causal impacts of trade liberalization on different types of GHGs. It concluded that, in general terms, open trading would be able to mitigate emissions as a result of cleaner technology use as well as more stringent environmental regulations found mostly in advanced countries. Another study by Wang R. et al. (2024) found that trade openness decreases carbon emissions only in high-income or upper-middle-income countries. At the same time, it increases CO2 pollution in low-income countries. The authors interpret this result as evidence that high-income nations decouple their economic growth from carbon-related environmental degradation through trade at the expense of lower- and middle-income nations. Meanwhile, the environmental consequences of trade openness are positive for high-income countries because they tend to have institutions and resources to avoid increased degradation while executing international exchanges; low- and middle-income-countries do not counteract their intensification with aspects such as industrial activities. Urbanization should engender greater levels of deforestation or inadequate game laws that negate boasts open economy figures with respect to Nature degradation (Pratiwi and Wulansari, 2022), indicating that generalizations on the relationship between trade openness and environmental sustainability should be grounded in specificities of countries, illustrating a need for differentiated policy-making to conciliation economic growth with sustainable industry.

2.4 Natural resource and load capacity factor

Especially when it came to sustainable development, the literature on load capacity factors in relation to various economic, environmental and technological factors seems to grow fast. A body of research on how countries and regions around the world maintain a balance between resource use, economic growth and environmental sustainability was published with an emphasis on the carrying capacity factor as a way to measure it (Wang Q. et al., 2024). emphasize possible impacts of trade openness on the load capacity factor with special thresholds such as natural resource rent and corruption control. Based on their cross-sectional studies of multiple countries over long periods, they find that while trade openness typically increases carrying capacity, the magnitude of this effect depends on the levels of resource rent and governance quality. This work highlights the intertwined nature of economic policies and environmental indicators. Similarly (Usman et al., 2024) et al., Following the same logic, China is set as the focus and discusses what level of expansion of clean energy to extract natural resources was capable by fully taking the load coupler factor into account. Indeed, the conclusion of their model suggests a sort of symbiotic relationship between clean energy policies and load capacity - re-enforcing messages about the need for national policy to correspond to macro-environmental targets such as COP27. China is used as a case study to build up the MAPLE system due its importance in global energy and environmental dynamics.

At a broader level (Sun Y. et al., 2024), apply the STIPART Model in assessing the impact of IE-technologies, Natural resources and renewable energy technology on Load Capacity Factor LC-EFj for year (y) Muller and Jung have thousands of observations over several decades and across many countries in their thorough study on load capacity by throughput. This work helps us to see that innovation contributes to both economic growth and environmental improvement. Additionally, the study of Sun C. et al. (2024) investigates energy aid's impact on the load capacity factor in emerging countries of Asia-Pacific, including natural resource consumption. Their discovery indicates that energy aid has a single-way effect over load capacity, which underlines the significant contribution of worldwide assistance in promoting sustainable development in those countries. They also contribute to the broader conversation about how various regions are distinctively poised to balance their environmental and economic capitals by highlighting emerging economies. Continuing with regard to the global view (Inuwa et al., 2024), examines the role of clean energy in natural resource dependence and environmental sustainability. In this dynamic, they emphasize the role of the load capacity factor and find a two-way relationship between clean energy initiatives and environmental outcomes. Study further supports the need for renewable energy to promote environmental sustainability. Guo et al. (2024), in relation to the N-11 nations. Khan U. et al. (2023), Khan A. et al. (2023), influences of natural resources and technological progress on environmental quality utilizing load carrying capability issue Optimistically, these findings suggest that at least in rapidly growing economies (and arguably the most critical nations with regard to their concerns about shipping-related emissions) technological progress continues to stimulate increases in load capacity and eco-efficiency under a one-way causality.

For ASEAN, the study of (Du et al., 2024) reports that social globalization shows a one-way effect on carrying capacity and arrow of causality regarding how global integration significantly determines environmental sustainability within South West Asia. Moreover (Ali et al., 2024), evaluate the impact of load capacity factor on agriculture-environment-natural resources trichotomy: longitudinal insight from Pakistan. Study results reveal that agriculture is critical to increasing carrying capacity, and this conclusion, therefore, has important implications for the sustainable development of agrarian economies (Zhao et al., 2023). analyze technological innovation, natural resources, and stock market development on environmental sustainability with the load capacity factor as the dependent variable. Innovative developments and load capacity (and *vice versa*): they suggest that innovations can contribute to technological advancement but must, in turn, be conducive to achieving sustainability goals. Li et al. (2023) portrayed the Influence of natural resources and economic growth on load capacity factor in Next-11 countries: Moderating roles of digitalization and government stability. The study uncovers a one-way interaction from economic growth to load capacity, supporting the argument that stable governance may improve environmental outcomes.

Anas et al. (2023) estimating the carrying capacity concept in developing nations using green finance, green tech innovation, natural resource exhaustion and forested area, implying that a symbiotic relationship between green finance and load capacity exists, indicating the necessity for financial instruments to boost sustainability in developmental areas. Furthermore (Ni et al., 2022), explains the effects of natural resources, digitalization, and institutional governance on ecological sustainability operating via load capacity factors in highly resource-consuming economies. Their study focuses on the two-way linkages between governance and carrying capacity, demonstrating that institutions are critical in addressing external problems. Finally (Akadiri et al., 2022), study the impact of global financialization and natural resource rent on the loading capacity factor in India, for which it uses a dual adjustment method. The bidirectional relationship between globalization and load capacity underscores the complex interdependencies of global economic integration with environmental sustainability. Standing literature indicates that while technological advancement and globalization have potentially positive impacts on environmental sustainability, their actual outcomes are largely contingent upon contextual factors such as governance quality, economic composition and regional integration. The literature calls for the development of various policies, including regionally tailored policy interventions that take these interacting influences into account in order to improve load capacity factor and meet sustainable development goals.

3 Data and methodology of the study

3.1 Theoretical development and model specification

Theoretically, the elaboration of the Environmental Kuznets Curve (EKC) hypothesis and load capacity factor hypothesis in the context of association with technological innovation, trade openness, natural resources and clean energy on environmental sustainability require a complete insight into possible complex networks between these variables even more Documentation about the theoretical development and conceptual framework that guides the research and design of EKC study and a completeness concept corresponding load capacity actor or stork carrying needs its supporting variables. The Environmental Kuznets Curve (EKC) hypothesis suggests that in the early stages of economic growth, environmental degradation worsens with rising output. However, as *per capita* income crosses a threshold level of total production and consumption, it starts moving towards improvement. This finding is important for the understanding of how economic growth affects ecological footprints and CO2 emissions in developing countries such as BRICS &T (Brazil, Russia, India, China, South Africa and Turkey) (Lee et al., 2021; Borghesi, 2000). The load capacity factor hypothesis, in this context, complements the EKC by shifting cognizance to the ecological maximum carrying capacity of a region and, hence, its minimum resource consumption level that can be sustained without any environmental degradation. The ecological footprint is a key indicator of this capability because it measures the human demand on Earth's ecosystems. The interactive effects of the ecological footprints and LC ratios may help to understand better the sustainability of resource use in BRICS + T countries, which are facing rapidly growing environmental pressures as industrialization and urbanization have been widespread. This is important because technology is one of the mediators through which economic growth and environmental sustainability are linked. The development of clean energy technologies can largely cut CO2 emissions and ecological footprints, which corroborates with the EKC hypothesis. For example, transitioning to renewable energy can break the connection between economic growth and environmental degradation by enabling countries to increase income levels while pollutants counterparts do not automatically increase. Even trade openness may facilitate the transfer of cleaner technologies and practices—supporting sustainable resource management and decreasing ecological footprints (Lin et al., 2018; Ji, 2010). This study proposed a model that incorporates these hypotheses and variables as the main conceptual framework. It suggests that technological innovation and trade openness can promote the ecological carrying capacity of BRICS + T countries, realizing sustainable development. The model can be empirically tested by investigating the influences of CO2 emissions, ecological footprints, and carrying capacity rates on economic growth and technological progress (Zhang, 2023; Raihan et al., 2023; Ullah et al., 2023a; Ullah et al., 2023b). Furthermore, the ecological footprint model is a powerful tool for analyzing sustainability in resource use by these countries. It helps the researcher to see whether a country is living within its ecological limit or overspending how much biocapacity it has. This kind of analysis may be crucial to nations in the BRICS + T, as these are developing countries under great economic growth that possess problems related to resource shortage and environmental degradation. As clean energy is one of the sustainable wings, the regulation will be incomplete without integrating it with this system. Transitioning to renewable energy not only mitigates CO2 emissions but is also important to the total ecological carrying capacity due to the reduction of finite natural resource use (Dogan et al., 2024; Usman et al., 2024; Inuwa et al., 2024). Once again, in the case of the BRICS + T countries, this shift is even more timely, given that their energy consumption patterns are evolving faster than ever. These results highlight the relevance of the concepts behind the EKC hypothesis and load-carrying capacity factor in studying environmental sustainability dynamics among BRICS + T countries on the level of theory and conceptual framework.

This framework allows for a structured understanding of the real links that exist between economic growth, technological innovation, trade openness, natural resources and clean energy for the period 1990–2022. The selection of the timeframe (1990–2022) for this study aligns closely with its objectives to investigate the evolving relationship between technological innovation, trade openness, clean energy adoption, and natural resource rents on environmental sustainability within BRICS + T nations. This period captures significant global developments, including the rise of globalization, rapid technological advancements, and increased environmental awareness, providing a robust historical context. The timeframe encompasses pivotal policy shifts and international agreements like the Kyoto Protocol and Paris Agreement, which shaped national sustainability strategies. Furthermore, it reflects substantial economic and industrial growth in BRICS + T nations, offering rich data for assessing trends and validating hypotheses such as the Environmental Kuznets Curve (EKC). By spanning over three decades, the study effectively addresses long-term dynamics, enabling comprehensive insights into environmental sustainability trajectorie. Based on the theoretical foundation and literature assessment, the following empirical model is as follows.

$$ES_{it}\left[\begin{array}{c} co2 \\ EF \\ LCF \\ ILCF \end{array}\right] \int \mathrm{TI, CE, TO, NRR} \tag{1}$$

The above equation has been extended in the case of assessing the EKC hypothesis with the inclusion of Y and Y2; the revised Equation 1 is as follows.

$$ES_{it}\left[\begin{array}{c} co2 \\ EF \\ LCF \\ ILCF \end{array}\right] \int \mathrm{TI, CE, TO, NRR, Y, Y2} \tag{2}$$

After the log transformation, the above Equation 2 can be reported in the following regression form in documenting the coefficients of TI, CE, TO, NRR, Y and Y2, respectively. The regression equation is as follows.

$$ES_{it}\left[\begin{array}{c} co2 \\ EF \\ LCF \\ ILCF \end{array}\right]: \beta_0 + \beta_1\, lnTI_t + \beta_2 lnCE_t + \beta_3 lnTO_t + \beta_4 lnNRR + \beta_5 lnY_t + \beta_6 lnY_t^2 \tag{3}$$

The present study has considered four proxies among thoruse loac capapcity and inverted loac capacity has emerged with its nvelty in addressing the environmental footprint in the environmental nexus. Load Capacity Factor (LCF): The load capacity factor is a metric used to assess environmental sustainability by comparing the biocapacity (the capacity of an ecosystem to regenerate resources and absorb waste) of a region to its ecological footprint (the demand on these resources). It is calculated as the ratio of biocapacity *per capita* to the ecological footprint *per capita*. A higher LCF indicates better environmental sustainability, as it reflects a greater ability of the ecosystem to meet human demands without being degraded. Whereas, The inverted load capacity factor is the reciprocal of the load capacity factor. It is used to measure the pressure on the environment in a manner where higher values indicate greater ecological stress. The ILCF highlights instances where the ecological footprint exceeds biocapacity, signaling unsustainable resource use. It provides an inverse perspective to LCF, offering an additional lens for analyzing environmental sustainability dynamic (Kazemzadeh et al., 2022; Silva et al., 2024).

The effect of independent variables on CO2 emissions and Ecological Footprint (EF) may be complex and important. TI should have a conservation character as it points to reductions in CO2 and EF due to developments of clean technologies (e.g., substitution or gradual decarbonization of the energy mix) and operational improvements that can bring about efficiency gains (i.e., improved production procedures). Similarly, Clean Energy (CE) should also be negatively related since higher *per capita* renewable energy use will usually be associated with lower carbon emissions and less ecological impact. Trade Openness has no significant impact since it stimulates increased economic activities, which is one of the main contributing factors to high emissions because a larger population indicates a higher carbon footprint. Trade will allow more trade flows, hence spreading cleaner technology more easily and quickly through imported goods. Resource Rents (NRR) can indeed have a dual effect on both CO2 and EF since the higher level of extractive activity typical in many developed economies implies more emissions and environmental pressure (Kazemzadeh et al., 2023a).

On the one hand, Technological Innovation (TI) is positively related to LCF and negatively related to ILCF as it can facilitate resource management strategies that increase biocapacity while diminishing ecological footprint. Clean Energy (CE) should be consistent as well, using the same approach of increasing LCF and decreasing ILCF by reducing the environmental costs associated with energy production. Whether Trade Openness (TO) has a positive, negative or neutral effect on LCF and ILCF depends on whether it promotes sustainable practices by the fisheries actors as well, which could result in a tragedy of commons. NRR undermines LCF and improves ILCF if an increased extraction leads to environmental degradation, which means that the biocapacity will decrease.

The environmental Kuznets Curve (EKC) hypothesis has been tested by including both Y (income) and Y2 (squared income). According to this hypothesis, ecological decline first worsens in response to economic growth (Y) but eventually lessens at greater levels of income (Y2). In a quadratic effect, we would expect the criterion to have positive coefficients for Y and a negative coefficient for Y2, suggesting an inverted U-shape in the case of CO2 and EF. On the other hand, LCF could be observed with a co-active effect of negative Y and positive Y2 coefficients for the logarithm of income, hence implying that biocapacity per ecological footprint can increase in absolute terms at higher levels of income. ILCF would likely mimic the CO2 and EF pattern. The relationships, however, can be very different when comparing countries and periods, so the context of time is crucial in environmental sustainability research (see Table 1).

3.2 Estimation stages

For the purpose of evaluating the effects of clean energy adoption, technological innovation, natural resources consumption, and trade liberalization on environmental sustainability, which is measured by tow convention proxies, that is, CO2 emission and novel proxy of inverted load capacity factor and inverted load capacity factor by following. The empirical model testing is to be passed through several states.

The first stage deals with the documentation of cross-sectional dependency by following the framework offered by Juodis and Reese (2022) proposed an enhanced version of the CD test that specifically tackles the drawbacks of the traditional Pesaran CD test when used in panel data models with latent factors. Our bias-corrected CD test is reliable for detecting error cross-sectional dependence, even in cases where the latent factors are semi-strong or strong. This is important because the standard CD test can sometimes result in excessive rejection. The proposed framework made adjustments to account for both Gaussian and non-Gaussian errors. In addition, the test can be applied to a broader range of panel data models, including those with stationary errors and serially correlated errors. With the Juodis and Reese CD test, researchers can now rely on more accurate results when analyzing complex panel data settings. In the subsequent stage, the slope of heterogeneity was documented through the execution of techniques introduced by Bersvendsen and Ditzen (2021), which is capable in the panel data estimation with larger N and T. furthermore, the proposed technique assesses the test statistics with the null of slope coefficients of homogeneous across the variables and alternative hypothesis of slope coefficients are heterogeneous across the units. Additionally, Scholars may use it to determine whether mean group estimators or other heterogeneous slope models should be explored instead of pooled estimation methodologies.

Stage three focuses on the detection of variables' order of integration, that is, stationary properties, by implementing Herwartz et al. (2018), which is robust in the panel data having heterogeneity attribute in the research units. Furthermore, the techniques include lag-order selection, pre-whitening, and detrending processes to address serial correlation and trending data. This makes it a full tool for conducting panel unit root testing when Heteroskedasticity is present. The order of integration of each variable has been tested with the non-stationary null.

In stage four, once the variable's order on integration has been documented, the study moves into documenting the long-run linkage through the implementation of the panel unit root test by following Westerlund and Edgerton (2008), Persyn and Westerlund (2008). The techniques considered have several advantages over conventional techniques; that is, they can produce robust results in the presence of cross-sectional dependency and structural fractures. They provide strong outcomes for identifying long-term connections in panel data, even when there are variations in slopes and error patterns.

In stage 5, The coefficients of CE, TI, NRR, and TO are derived through the implementation of DSUR, CUP-BC, and CUP-FM techniques, which is offered by Mark et al. (2005) and Bai et al. (2009). These methods are highly effective in tackling cross-sectional dependence, endogeneity, and serial correlation in panel data models. DSUR, proposed by Mark et al. (2005), takes into consideration the correlation between equations and offers accurate estimates when there is cross-sectional dependence. CUP-FM and CUP-BC, as introduced by Bai et al. (2009), have demonstrated their robustness in handling cross-sectional dependence and endogeneity. This makes them highly suitable for various panel data structures. Recent studies, like the ones conducted by Li and Qamruzzaman (2023), Ulucak and Ozcan (2020), Xu and Tang (2024), and Fakher et al. (2024), have shown the effectiveness of these methods in generating reliable and effective estimates, particularly in the field of environmental and economic analyses. In addition, as emphasized by Feng and Li (2024) and Wang R. et al. (2024), strong performance is demonstrated even when faced with mixed order of integration among variables, a common obstacle in empirical research. The effectiveness of these methods in dealing with intricate panel data structures while delivering dependable outcomes has resulted in their growing popularity in recent econometric research, especially in investigations of long-term relationships in diverse panels with cross-sectional interdependence.

The factor model of CUP-BC and CUP-FM is displayed as follows:

$$\widehat{\beta cup}, \widehat{Fcup} = argmin \frac{1}{nT^2} \sum_{i=1}^{n} (y\prime - x\prime\beta)^{;} M_F \left((y\prime - x\prime\beta)^{;} \right) \tag{4}$$

Stage 6 deals with asymmetric estimation through the transformation of nonlinear techniques introduced by Shin et al. (2014). The transformation of the asymmetric equation with the decomposed variables, that is, the positive and negative shock of REC, TO, TI, and NRR, i.e., $(REC^{+}, REC^{-};\ TI^{+}, TI^{-};\ TO^{+}, TO^{-};\ and;\ NRR^{+}, NRR^{-}$, can be displayed in the following manner.

$$\begin{aligned}
\Delta CO2_{it} = \ & \beta_{0i} + \beta_{1i} CO2_{it-1} + (\beta^{+}_{2i} REC^{+}_{t-1} + \beta^{-}_{2i} REC^{-}_{t-1}) \\
& + [\beta^{+}_{3t} TI^{+}_{t-1} + \beta^{-}_{3t} TI^{-}_{t-1}] + \langle \beta^{+}_{4t} \mathrm{TO}^{+}_{t-1} + \beta^{-}_{4t} TO^{-}_{t-1} \rangle \\
& + [\beta^{+}_{4t} NRR^{+}_{t-1} + \beta^{-}_{4t} NRR^{-}_{t-1}] + \beta_{5i} Y_{it-1} + \beta_{6i} Y^{2}_{it-1} \\
& + \sum_{J=1}^{M-1} \gamma_{iJ} \Delta CO2_{i,t-J} + \sum_{J=0}^{N-1} \left(\gamma^{+}_{ij} \Delta REC^{+}_{i,t-j} + \gamma^{-}_{ij} \Delta REC^{-}_{i,t-j} \right) \\
& + \sum_{J=0}^{O-1} \left(\left(\delta^{+}_{ij} \Delta TI^{+}_{i,t-j} + \delta^{-}_{ij} \Delta TI^{-}_{i,t-j} \right) \right) + \sum_{J=0}^{P-1} \left(\mu^{+}_{ij} \Delta TO^{+}_{i,t-j} + \mu^{-}_{ij} \Delta TO^{-}_{i,t-j} \right) \\
& + \sum_{J=0}^{P-1} \left(\mu^{+}_{ij} \Delta NRR^{+}_{i,t-j} + \mu^{-}_{ij} \Delta NRR^{-}_{i,t-j} \right) + \sum_{J=1}^{M-1} \gamma_{iJ} \Delta Y_{i,t-J} \\
& + \sum_{J=1}^{M-1} \gamma_{iJ} \Delta Y^{2}{}_{i,t-J} + \varepsilon_{it}
\end{aligned} \tag{5}$$

Stage 8 performed the causality test with the implementation of the non-granger causality test The study implements the granger causality test following the procedure initiated by Dumitrescu and Hurlin (2012), the following Equations 6–8 are executed for test statistics.

$$Y_{it} = \alpha_i + \sum_{K-1}^{P} \gamma_{ik} Y_{i,t-k} + \sum_{K-1}^{P} \beta_{ik} X_{i,t-k} + \mu_{it} \tag{6}$$

$$W^{Hnc}_{NT} = N^{-1} \sum_{i-1}^{N} W_{i,t} \tag{7}$$

$$Z = \sqrt{\frac{N}{2P} \times \frac{T - 2P - 5}{T - P - 3}} \times \left[\frac{T - 2P - 3}{T - 2P - 1} \bar{W} - P \right] \tag{8}$$

On the graond of rationality of selection of estimation techniques relies on he choice of models for asymmetric analysis stems from the need to capture the nuanced and non-linear relationships between variables, such as the differential impacts of positive and negative changes in trade openness or technological innovation on environmental sustainability. Asymmetric analysis allows for a more accurate representation of these dynamics, reflecting real-world complexities. The CUP-FM (Continuously Updated Fully Modified) and CUP-BC (Continuously Updated Bias-Corrected) methods were selected due to their robustness in handling panel data with cross-sectional dependence and heterogeneity, common in studies involving multiple countries like BRICS + T. These advanced econometric techniques account for long-run relationships while correcting for biases that may arise from endogeneity and serial correlation. To simplify, CUP-FM adjusts estimators for any distortion caused by contemporaneous correlations in panel data, while CUP-BC further reduces bias, ensuring the results are reliable and not skewed by data-specific anomalies. These features make them particularly suitable for analyzing complex, interconnected variables over an extended time frame (Kazemzadeh et al., 2023b).

4 Findings and discussion

4.1 Pre-model estimation

Table 2 displays the output of the CD test in Panel–A and the SH test in Panel B. In accordance with the test statistics of the CD test, the study established CD in all research variables. For SH assessment, the coefficients of both Delta $_{\text{Statistic}}$ and Adjusted Delta $_{\text{Statistic}}$ were found statistically significant, suggesting that the slope coefficients are heterogeneous across the units.

The following Table 3 exhibits the output of the cointegration test of all four models. The test statistics of all models revealed statistical significance at a 1% level, suggesting the existence of a long-run association between TI, TO, CE, NRR, Y and Y2.

4.2 Coefficients determination with DSUR, CUP-BC, and CUP-FM estimation

The findings reveal varying effects of technological innovation on the coefficients across different models. In Models Asafu-Adjaye et al. (2016), Ali et al. (2021), and Abidi and Nsaibi (2024), technological innovation consistently shows a negative association, indicating that an increase in technological innovation is linked to a reduction in CO2 emissions. This persistent negative sign across these models suggests that technological improvements enhance energy efficiency or promote cleaner industrial processes, thus reducing CO2 emissions. Moreover, the negative impact of technological innovation indicates its role in lowering the ecological footprint by encouraging more sustainable practices. Regarding the inverted load capacity factor, technological innovation displays negative coefficients, suggesting that technological advancements help improve the sustainability of resource use by reducing the inverted load capacity factor. In contrast, Model (Pratiwi and Wulansari, 2022) presents a positive association with technological innovation, indicating that technological innovation enhances the efficiency of resource use, improving the ratio of

TABLE 1 Data, proxy and data sources.

Variable	Definition	Proxy	References	Expected sign	Data sources
Dependent Variables					
CO2	Carbon dioxide emissions per capita	Metric tons of CO2 per capita			World Bank, OECD, EDGAR Database
EF	Ecological Footprint per capita	Global hectares per capita			Global Footprint Network, WWF
LCF	(Biocapacity per capita/EF per capita)	Ratio	Xu et al. (2022), Erdogan (2024), Dao et al. (2024)		Global Footprint Network
Inverted LCF	Inverted Load Capacity Factor	1/LCF			Derived from LCF
Independent Variables					
TI	Technological Innovation	R&D expenditure as % of GDP, patent counts		−/−/+/−	World Bank, WIPO, OECD
CE	Clean Energy Adoption	Share of renewable energy in total energy consumption		−/−/+/−	IEA, World Bank
TO	Trade Openness	The sum of exports and imports as % of GDP	Johnson (2009), Wang et al., (2024)	+/−	World Bank, UNCTAD
NRR	Natural Resource Rents	Total natural resource rents as % of GDP	Kumar et al. (2013), Li et al. (2021)	+/+/−	World Bank

TABLE 2 Results of CD and SH test.

Panel A: CD test of Juodis and Reese (2022)

	CO2	TI	TO	CE	NRR	Y	EF	LCF	EF
test value	12.4607***	11.9087***	12.4143***	8.7152***	10.7129***	9.8616***	12.8218***	10.2755***	11.1937***
Probability	***	***	***	***	***	***	***	***	***
CD exist	YES	YES	YES	YES	YES	YES	YES	YES	YES

Panel B: SH test of Bersvendsen and Ditzen (2021)

	Delta Statistic	Adjusted Delta Statistic	SH exits
Model	3.2743***	5.5183***	Yes
Model	3.0735***	5.402***	Yes
Model	4.7577***	5.3853***	Yes
Model	3.8665***	5.1759***	Yes

biocapacity to the ecological footprint, thereby contributing to sustainability.

The findings suggest a consistent positive relationship between trade openness and environmental outcomes across models. In Models Asafu-Adjaye et al. (2016), Ali et al. (2021), and Abidi and Nsaibi (2024), increased trade openness is associated with elevated CO2 emissions. This implies that the rise in industrial activity and transportation, driven by higher trade volumes, could outweigh the environmental benefits of trade, leading to greater pollution levels. Particularly In Model (Ali et al., 2021), the positive relationship between trade openness and the ecological footprint indicates that greater economic openness contributes to a larger ecological footprint. This is likely due to the environmental impact of growing trade volumes and industrial activities. Similarly, in Model (Abidi and Nsaibi, 2024), trade openness is positively associated with a higher inverted load capacity factor, suggesting that trade can promote the sustainable use of resources, which reflects the potential benefits of trade in encouraging more efficient resource management. In Model (Pratiwi and Wulansari, 2022), trade openness is also positively linked to a higher load capacity

TABLE 3 Results of Panel cointegration output.

Model		Model 1	Model 2	Model 3	Model 4
Panel –A: Panel B: Cointegration test of Persyn and Westerlund (2008)					
Gt		−13.358***	−10.239***	−15.972***	−12.872***
Ga		−7.798***	−7.203***	−7.519***	−8.094***
Pt		−13.21***	−11.616***	−14.281***	−15.161***
Pa		−5.333***	−7.04***	−7.55***	−10.016***
Panel B: cointegration test of Westerlund and Edgerton (2008)					
no shift	LMΓ	−3.1254***	−4.0207***	−2.7496***	−4.3378***
	LMΦ	−3.4412***	−2.3605***	−2.6***	−2.2554***
mean shift	LMΓ	−2.6242***	−2.0122***	−2.7149***	−3.9637***
	LMΦ	−3.9743***	−2.0999***	−3.4387***	−3.2925***
regiem shift	LMΓ	−3.8393***	−4.5097***	−3.1337***	−2.6754***
	LMΦ	−4.0262***	−4.0005***	−4.9881***	−4.652***

factor, which could be a result of improved resource use efficiency and the transfer of technology-facilitated by greater trade openness, further enhancing sustainability.

The findings suggest that the use of clean energy consistently contributes to the reduction of CO2 emissions across different models. The negative association indicates that cleaner energy technologies play a significant role in lowering emissions. However, the degree of impact varies depending on the model, emphasizing the importance of integrating clean energy into the overall energy mix. Additionally, the consistent negative relationship between clean energy and the ecological footprint across all models suggests that increasing the use of clean energy reduces the ecological footprint. This reinforces the critical role of clean energy in promoting sustainable development by minimizing environmental degradation. Conversely, in other models, clean energy shows a positive association with the load capacity factor, indicating that the use of clean energy improves resource use efficiency. This highlights the positive influence of sustainable energy sources on environmental sustainability. Finally, clean energy is negatively related to the inverted load capacity factor, demonstrating that adopting clean energy enhances the capacity factor, thus improving overall environmental sustainability. This further underscores the importance of clean energy in achieving sustainable resource management.

The findings reveal mixed effects of Natural Resource Rents (NRR) on environmental outcomes. In several instances, a positive relationship is observed, suggesting that higher levels of natural resource rents are associated with an increase in CO2 emissions. This could be due to the emissions generated from resource extraction and utilization processes, which tend to be environmentally intensive. Additionally, NRR is positively linked to a greater ecological footprint, likely because of the environmental degradation caused by resource extraction activities. This reflects how reliance on natural resources can lead to increased environmental harm. Conversely, in some cases, NRR demonstrates a negative relationship with the load capacity factor, implying that higher resource rents are connected to environmental degradation and resource depletion, which reduce the ability to manage resources sustainably. In other instances, NRR is positively correlated with a larger inverted load capacity factor. This may indicate that the economic benefits derived from resource exploitation contribute to the sustainable use of resources by providing the necessary financial means for investment in sustainability measures.

Referring to the assessment of the EKC hypothesis, the study disclosed the coefficient of Y and Y2 for models Asafu-Adjaye et al. (2016), Ali et al. (2021), and Abidi and Nsaibi (2024) positive and negative statistically significant at 1%, implying that economic growth might decrease the load capacity factor, perhaps because higher growth leads to more environmental stresses. Furthermore, findings imply that the adverse influence of economic growth on the load capacity factor is gradually decreasing, suggesting that the detrimental consequences may lessen as economic expansion persists. For Model (Pratiwi and Wulansari, 2022), negative and positive are statistically significant at a 1% level, indicating that economic growth has a negative influence on the inverted load capacity factor. This negative impact is likely due to the increasing environmental pressures resulting from greater growth rates. Moreover, the negative impacts of economic expansion on the inverse load capacity factor may decrease with time, suggesting that growth might ultimately result in more sustainable resource management strategies.

Output of DSUR, CUP-BC and CUP-FM estimation.

The asymmetric effects of Renewable Energy Consumption (REC) on environmental outcomes reveal varying impacts across the model (see Table 4). In the long run, both positive and negative shocks to REC tend to reduce CO2 emissions, ecological footprint, and load capacity factor (LCF), suggesting that increasing renewable energy use, whether through positive or negative changes, contributes to reducing environmental degradation and improving sustainability. However, in the case of the inverted

	Coeff	Std. Err	t-Statistic	Coeff	Std. Err	t-Statistic	Coeff	Std. Err	t-Statistic
	DSUR			CUM-FM			CUP-BC		
Model 1: environmental sustainability measured by CO2									
TI	−0.1048	(0.0433)	[-2.4207]	−0.0869	0.0383	−2.2712	−0.0858	0.0185	−4.6383
TO	0.1141	0.0411	2.7763	0.1078	0.0407	2.6501	0.1026	0.033	3.1104
CE	−0.1174	0.0357	−3.291	−0.1221	0.0422	−2.8941	−0.0642	0.0295	−2.1779
NRR	0.0857	0.0433	1.9794	0.1033	0.0293	3.5262	0.0598	0.0395	1.5151
Y	0.1469	0.0441	3.3312	0.0845	0.0385	2.1963	0.0733	0.0381	1.9254
Y2	−0.0951	0.0138	−6.8963	−0.1074	0.0226	−4.7557	−0.0939	0.0167	−5.6245
C	8.219	0.24013	34.2272	13.101	0.24013	54.5579	10.274	0.24013	42.7851
$LM_{statistics}$	14.1423			14.1423			14.1423		
$F_{statistics}$	1793.5853			1793.5853			1793.5853		
$weak_{test}$	16.0758			16.0758			16.0758		
Model: environmental sustainability measured by ecological footprint									
TI	−0.12384	0.0369	−3.356	−0.12855	0.0399	−3.2218	−0.10105	0.0285	−3.545,614
TO	0.07604	0.0235	3.2357	0.10864	0.029	3.7462	0.09483	0.0278	3.4,111,511
CE	−0.16849	0.0304	−5.5424	−0.12568	0.036	−3.4911	−0.05102	0.0372	−1.371,505
NRR	0.11941	0.0281	4.2494	0.1275	0.0338	3.7721	0.07806	0.028	2.7,878,571
Y	0.10832	0.0457	2.3702	0.07075	0.0392	1.8048	0.07326	0.0438	1.6,726,027
Y2	−0.11121	0.0425	−2.6167	−0.14041	0.0335	−4.1913	−0.0835	0.039	−2.141,026
C	11.162	0.24013	46.4831	14.936	0.24013	62.1996	12.306	0.24013	51.247,241
$LM_{statistics}$	13.7939			13.7939			13.7939		
$F_{statistics}$	1,430.7961			1,430.7961			1,430.7961		
$weak_{test}$	17.8116			17.8116			17.8116		
Model: environmental sustainability measured by Load capacity factor									
TI	0.14404	0.0169	8.523	0.10395	0.0376	2.7,646,277	0.07108	0.0245	2.9,012,245
TO	0.1038	0.0262	3.9618	0.06489	0.0311	2.0864,952	0.09133	0.0206	4.4,334,951
CE	0.09904	0.041	2.4156	0.09775	0.017	5.75	0.09182	0.0224	4.0991,071
NRR	−0.1592	0.0447	−3.5615	−0.08396	0.0423	−1.98487	−0.09825	0.0319	−3.079937
Y	−0.15925	0.0208	−7.6562	−0.07818	0.0305	−2.563,279	−0.04298	0.0436	−0.98578
Y2	0.14468	0.0435	3.3259	0.0732	0.0432	1.6,944,444	0.05553	0.0309	1.7,970,874
C	7.534	0.24013	31.3746	9.599	0.24013	39.974,181	16.829	0.24013	70.082872
$LM_{statistics}$	12.4442			12.4442			12.4442		
$F_{statistics}$	1,479.8082			1,479.8082			1,479.8082		
$weak_{test}$	16.4568			16.4568			16.4568		
Model: environmental sustainability measured by inverted Load capacity factor									
TI	−0.12841	0.0218	−5.8903	−0.11143	0.0316	−3.526,266	−0.03771	0.0424	−0.889,387
TO	0.17491	0.0209	8.3688	0.08736	0.0344	2.5,395,349	0.0533	0.029	1.837,931

(Continued on following page)

(*Continued*)

	Coeff	Std. Err	t-Statistic	Coeff	Std. Err	t-Statistic	Coeff	Std. Err	t-Statistic
	DSUR			CUM-FM			CUP-BC		
CE	−0.11585	0.0187	−6.1951	−0.11754	0.0245	−4.797,551	−0.0915	0.0354	−2.584,746
NRR	0.11087	0.0414	2.678	0.07854	0.015	5.236	0.0756	0.0395	1.9,139,241
Y	−0.13327	0.0261	−5.1061	−0.14007	0.0317	−4.418,612	−0.07995	0.0412	−1.940,534
Y2	0.14367	0.0418	3.437	0.08052	0.0304	2.6,486,842	0.07976	0.0218	3.6,587,156
C	14.625	0.24013	60.9045	10.121	0.24013	42.148,003	16.856	0.24013	70.195,311
$LM_{statistics}$	15.2896			15.2896			15.2896		
$F_{statistics}$	1972.5967			1972.5967			1972.5967		
$weak_{test}$	18.7141			18.7141			18.7141		

load capacity factor (ILCF), positive shocks to REC slightly increase the ILCF, indicating that while renewable energy adoption helps manage resource use, it may have diminishing returns in the context of sustainable capacity utilization.

Technological Innovation (TI) shows mixed asymmetric effects across the models. In Models Asafu-Adjaye et al. (2016), and Ali et al. (2021), both positive and negative shocks to TI are associated with an increase in CO2 emissions and the ecological footprint, suggesting that technological improvements may initially contribute to environmental pressure, likely due to the resource-intensive nature of technological development. However, in the context of the load capacity factor [Model (Pratiwi and Wulansari, 2022)], positive shocks to TI increase the LCF, indicating improved resource efficiency and sustainability through technological advancements. Conversely, in the case of the inverted load capacity factor [Model (Abidi and Nsaibi, 2024)], both positive and negative shocks to TI reduce the ILCF, demonstrating the potential for technology to enhance the sustainable management of resources in the long run.

The effects of Trade Openness (TO) on environmental outcomes also display an asymmetric nature. Positive shocks to TO in Models Asafu-Adjaye et al. (2016), and Ali et al. (2021) lead to increases in CO2 emissions and the ecological footprint, highlighting that more open trade environments might lead to greater industrial activity and transportation, thus increasing environmental degradation. However, in Model (Pratiwi and Wulansari, 2022), positive shocks to TO are associated with an increased load capacity factor, implying that trade can enhance resource use efficiency and sustainability by facilitating technology transfer and better resource management practices. In contrast, negative shocks to TO tend to reduce the ILCF in Model (Abidi and Nsaibi, 2024), suggesting that disruptions in trade may help conserve resources or reduce pressure on resource use temporarily.

Natural Resource Rents (NRR) exhibit significant asymmetric effects on environmental outcomes. Positive shocks to NRR in Models Asafu-Adjaye et al. (2016), and Ali et al. (2021) lead to higher CO2 emissions and a larger ecological footprint, likely due to the environmental harm associated with resource extraction activities. On the other hand, in Model (Pratiwi and Wulansari, 2022), positive shocks to NRR are linked to an increase in the load capacity factor, suggesting that natural resource exploitation can contribute to more efficient resource utilization. However, negative shocks to NRR reduce the ILCF in Model (Abidi and Nsaibi, 2024), indicating that when natural resource rents decrease, there may be a reduced strain on resource capacity, potentially aiding sustainability efforts.

4.3 Directional causality assessment with DH causality

The causality analysis (see Table 5) reveals a complex network of bidirectional and unidirectional relationships among key variables such as CO2 emissions, technological innovation, natural resource rent, trade openness, economic growth, and clean energy expansion. Bidirectional causality is observed between CO2 emissions and technological innovation, as well as between CO2 emissions and natural resource rent. Similar bidirectional links exist between trade openness and natural resource rent, as well as between natural resource rent and economic growth. Technological innovation, trade openness, and clean energy expansion are also deeply interconnected through bidirectional causality. Unidirectional relationships include the influence of technological innovation on economic growth and the impact of trade openness on CO2 emissions. Clean energy expansion also has significant unidirectional effects on both CO2 emissions and economic growth. Moreover, natural resource rent influences clean energy expansion, while trade openness impacts economic growth, further emphasizing the intricate interdependence between economic and environmental factors. When examining the load capacity factor (LCF), similar patterns of bidirectional and unidirectional causality emerge, reinforcing the idea that technological, economic, and environmental variables mutually influence each other in shaping sustainable development outcomes.

5 Discussion

The results of the study clarify a complex nexus between technological innovation and environmental sustainability in

TABLE 4 Output of long-run and short-run asymmetric coefficients.

Variables	Mode [1] CO2	Model [2] EF	Model [3] LCF	Model [4] ILCF
Panel –A: long-run asymmetric coefficients				
Y	0.1401 (0.061)[-2.295]	0.1788 (0.044)[-4.063]	−0.2759 (0.009)[-30.655]	0.103 (0.024)[4.291]
Y2	−0.056 (0.042)[1.333]	−0.293 (0.027)[10.851]	0.2546 (0.003)[84.866]	−0.079 (0.063)[-1.253]
REC^{+}	−0.167 (0.014)[11.928]	−0.247 (0.011)[22.454]	−0.2524 (0.003)[84.133]	0.088 (0.03)[-2.933]
REC^{-}	−0.139 (0.055)[2.527]	−0.1866 (0.012)[15.55]	−0.1645 (0.007)[23.5]	0.088 (0.028)[-3.142]
TI^{+}	0.069 (0.026)[-2.653]	0.2978 (0.038)[-7.836]	0.2984 (0.039)[-7.651]	−0.142 (0.012)[11.833]
TI^{-}	0.079 (0.028)[-2.821]	0.2441 (0.017)[-14.358]	0.1683 (0.06)[-2.805]	−0.164 (0.038)[4.315]
$T0^{+}$	0.176 (0.051)[-3.45]	0.1933 (0.03)[-6.443]	0.2869 (0.006)[-47.816]	−0.067 (0.036)[1.861]
$T0^{-}$	0.15 (0.034)[-4.411]	0.2661 (0.035)[-7.602]	0.2075 (0.05)[-4.15]	−0.15 (0.04)[3.75]
NRR^{+}	0.104 (0.036)[-2.888]	0.2971 (0.041)[-7.246]	0.1819 (0.006)[-30.316]	−0.117 (0.054)[2.166]
NRR^{-}	0.101 (0.019)[-5.315]	0.2974 (0.018)[-16.522]	0.2126 (0.01)[-21.26]	−0.056 (0.018)[3.111]
Panel –B: Short-run asymmetric coefficients				
Y	0.0429 (0.013)[-3.3]	0.0889 (0.008)[-11.112]	0.0754 (0.044)[-1.713]	−0.0383 (0.045)[0.851]
Y2	−0.0404 (0.011)[3.672]	−0.0816 (0.023)[3.547]	−0.0943 (0.042)[2.245]	0.0262 (0.03)[-0.873]
REC^{+}	−0.0352 (0.006)[5.866]	−0.0913 (0.062)[1.472]	−0.0875 (0.007)[12.5]	0.0386 (0.002)[-19.3]
REC^{-}	−0.0493 (0.036)[1.369]	−0.075 (0.028)[2.678]	−0.0967 (0.033)[2.93]	0.04 (0.017)[-2.352]
TI^{+}	0.0269 (0.055)[-0.489]	0.0983 (0.012)[-8.191]	0.0941 (0.018)[-5.227]	−0.0277 (0.03)[0.923]
TI^{-}	0.0503 (0.013)[-3.869]	0.084 (0.038)[-2.21]	0.0785 (0.034)[-2.308]	−0.0427 (0.043)[0.993]
$T0^{+}$	0.0401 (0.043)[-0.932]	0.0787 (0.006)[-13.116]	0.1005 (0.017)[-5.911]	−0.034 (0.028)[1.214]
$T0^{-}$	0.0248 (0.025)[-0.992]	0.0715 (0.027)[-2.648]	0.0936 (0.045)[-2.08]	−0.0468 (0.037)[1.264]
NRR^{+}	0.0292 (0.047)[-0.621]	0.0897 (0.058)[-1.546]	0.099 (0.042)[-2.357]	−0.0498 (0.029)[1.717]
NRR^{-}	0.0452 (0.036)[-1.255]	0.1001 (0.006)[-16.683]	0.0998 (0.006)[-16.633]	−0.0442 (0.009)[4.911]
C	7.7144 (0.043)[179.404]	30.8722 (0.049)[630.044]	22.0521 (0.041)[537.856]	18.6202 (0.04)[465.505]
Eq (−1)	−0.214 (0.058)[3.689]	−0.2355 (0.031)[7.596]	−0.2139 (0.049)[4.365]	0.2042 (0.021)[-9.723]

BRIC + T nations. Taken together, these findings suggest technology is central to mitigating carbon dioxide emissions as a whole, given the consistent negative bivariate relationship that links technological innovation with CO2 avoidance across models. This is in line with extant literature that underscores the importance of technological innovation to improve energy efficiency and render industrial processes cleaner (Raghutla and Chittedi, 2023; Bhat, 2018; Khattak et al., 2024; Rostami and Salehi, 2024). Green technology practices by the BRICS countries have been demonstrated to contribute significantly to environmental degradation mitigation through enhanced energy efficiency and reduced emissions (Zhang and Yasin, 2024). Technological change had the same sign, but it was also statistically significant and negative across the models. This is consistent with conclusions reached by other research that green innovation plus high institutional quality can significantly help reduce the ecological footprint. Similarly, there is a negative effect of the inverted load capacity factor, which indicates that technological advancement reduces resource use intensity and enhances sustainable development (Ahmad et al., 2023). The positive coefficients of the variables in Model 3, however, suggest that technological innovation can also contribute to greater efficiency in resource utilization, and this would thus increase biocapacity/ecological footprint ratios, which means that with slight public effort for a combined impact, although tech advancements are sustainable in the bigger picture when it comes to optimizing resource usage from any handle we own and cannot afford let slip. The literature argues that technical innovation has this dual role (Ullah et al., 2023a; Huang, 2024), on the one hand to decrease emissions and achieve environmental goals, but also have positive impact in terms of sustainable growth.

Diversified strategies can be employed to enhance the footprint of tech innovation in the BRIC + T nations. First, even more environmentally sustainable outcomes arise when investments are increased in green technologies and renewable energy as a result of successful technological innovation. Results also have confirmed that the integration of technological innovation with renewable energy utilization causes carbon emissions to be reduced significantly, and sustainable development will flourish (Ullah et al., 2023b; Dam et al., 2024). Not only this, but the implementation of more stringent environmental laws and the

TABLE 5 DH causality test” CO_2.

	CO2	TI	TO	CE	NRR	Y
Panel –A: for carbon emission as proxy for environmental sustainability						
CO2		(2.2678)*	0.967	1.0425	(6.2295)***	(4.8225)***
		[2.3902]	[1.0192]	[1.0988]	[6.5659]	[5.0829]
TI	(3.4378)**		(3.9266)**	0.8416	1.7162	(4.425)**
	[3.6234]		[4.1387]	[0.8871]	[1.8089]	[4.664]
TO	(4.5058)**	0.9128		(2.2582)*	(5.9032)***	(4.8926)***
	[4.7491]	[0.9621]		[2.3801]	[6.222]	[5.1568]
CE	1.4516	1.6206	0.9872		1.8894	(6.2454)***
	[1.53]	[1.7081]	[1.0405]		[1.9915]	[6.5827]
NRR	(5.7938)***	(5.0786)***	(5.9521)***	(1.9224)*		(2.5164)*
	[6.1067]	[5.3528]	[6.2735]	[2.0262]		[2.6523]
Y	1.2348	(6.1859)***	(4.3432)**	(2.425)*	(4.2826)**	
	[1.3015]	[6.52]	[4.5777]	[2.556]	[4.5139]	
Panel –B: for ecological footprint as proxy for environmental sustainability						
	EF	TI	TO	CE	NRR	Y
EF		(3.8023)**	(2.4665)*	(3.4314)**	1.4835	(2.5802)*
		[4.0076]	[2.5997]	[3.6167]	[1.5636]	[2.7195]
TI	(3.3039)**		(6.1817)***	1.5185	(2.2667)*	(2.848)**
	[3.4823]		[6.5155]	[1.6006]	[2.3891]	[3.0018]
TO	1.6386	(2.9861)**		(1.9107)*	(4.2709)**	1.7747
	[1.7271]	[3.1474]		[2.0139]	[4.5016]	[1.8705]
CE	(6.1083)***	(6.0552)***	1.1625		1.2401	(2.1455)*
	[6.4382]	[6.3822]	[1.2253]		[1.3071]	[2.2614]
NRR	1.4516	(5.2529)***	(1.9606)*	(5.8809)***		(3.6822)**
	[1.53]	[5.5365]	[2.0665]	[6.1985]		[3.881]
Y	1.1307	(3.9447)**	(4.814)***	(5.5536)***	(4.4133)**	
	[1.1917]	[4.1577]	[5.0739]	[5.8535]	[4.6517]	
Panel –C: for Load capacity factor as proxy for environmental sustainability						
	LCF	TI	TO	CE	NRR	Y
LCF		(4.0775)**	(5.2922)***	(3.9458)**	1.7832	1.0031
		[4.2977]	[5.578]	[4.1588]	[1.8795]	[1.0573]
TI	(6.2688)***		(2.933)**	(3.8363)**	(2.6726)*	(3.6238)**
	[6.6073]		[3.0914]	[4.0435]	[2.817]	[3.8194]
TO	1.1891	(2.0414)*		(4.9893)***	0.8172	(2.4176)*
	[1.2533]	[2.1516]		[5.2587]	[0.8613]	[2.5481]
CE	(2.3963)*	(3.3719)**	1.1105		1.8416	(3.2029)**
	[2.5257]	[3.554]	[1.1704]		[1.9411]	[3.3759]
NRR	(2.3645)*	(6.0903)***	(2.2646)*	(4.8469)***		(5.0414)***
	[2.4921]	[6.4192]	[2.3869]	[5.1087]		[5.3136]

(Continued on following page)

TABLE 5 (*Continued*) DH causality test" CO$_2$.

	CO2	TI	TO	CE	NRR	Y
Y	(5.4165)***	1.458	(2.119)*	(4.8342)***	0.8182	
	[5.709]	[1.5367]	[2.2334]	[5.0952]	[0.8624]	
Panel –C: for Inverted Load capacity factor as proxy for environmental sustainability						
	ILCF	TI	TO	CE	NRR	Y
ILCF		(2.6418)*	(3.6748)**	(5.9957)***	(4.5749)**	(2.5897)*
		[2.7845]	[3.8732]	[6.3195]	[4.8219]	[2.7296]
TI	1.4558		(2.8862)**	(3.1147)**	(3.3751)**	(6.2826)***
	[1.5345]		[3.0421]	[3.2829]	[3.5573]	[6.6219]
TO	(1.9659)*	(5.034)***		(5.4059)***	(3.136)**	(4.7853)***
	[2.0721]	[5.3058]		[5.6978]	[3.3053]	[5.0437]
CE	(3.1445)**	(3.4962)**	(5.5441)***		(6.255)***	(3.5759)**
	[3.3143]	[3.685]	[5.8434]		[6.5928]	[3.769]
NRR	(6.0329)***	(5.2975)***	1.0807	(5.4176)***		1.8607
	[6.3587]	[5.5836]	[1.1391]	[5.7101]		[1.9612]
Y	(3.8894)**	(5.5387)***	(2.3889)*	(5.4739)***	1.6514	
	[4.0995]	[5.8378]	[2.5179]	[5.7695]	[1.7406]	

promotion of an eco-friendly lifestyle can also escalate the benefits derived from technological development. At the national level, improving the environmental regulation of BRICS countries has contributed to reducing the negative effects this can have on green growth. Furthermore, the BRIC + T nations can better implement technological advances by developing an integrated partnership with other countries leading in IT. Such countries can effectively deal with environmental challenges and sustainable development by learning from each other's best practices, as well as developments taking place in the new technological age. Literature also highlights the potential for a positive impact from joint actions in technological innovation and green policies on environmental quality (Adebayo et al., 2023).

The positive signs of coefficients for Trade Openness (TO) across different models indicate the significant influence on CO2 emissions and environment footprints. This shows a positive correlation; that is, the higher trade volumes, and so do industrial transportation activities, the more environmental degradation there is. This suggests a complicated interplay between several factors in the BRIC + T, with trade openness leading to benefits for India and harm for China but not within other countries. The features of industrial activity and energy consumption explain the positive relationship trade openness has with CO2 emissions since, in reality, growth is indeed driven by increased economic activities from opening up for trade. Fossil fuels mostly power these activities, hence the increased levels of greenhouse gas emissions. This is consistent with the findings of Grossman and Krueger (1991), who pointed out the emphasis that trade liberalization can lower environmental quality in so far as the industrial growth generated by it primarily uses non-renewable energy sources. The study also shows that trade openness is associated with higher ecological footprints. He argues that it is probably driven by the environmental costs of extending industrial activities and the transportation infrastructure necessary for increasing trade. For instance, Gebert and de Mello-Sampayo (2024) asserts that trade can increase environmental degradation without strict (er) environmental policies. Nonetheless, the positive signs in Model 4 hint at the possibility that trade may well facilitate investment decisions conducive to more sustainable resource use (i.e., a greater inverse load capacity factor). In this case, the high level of environmentally friendly technologies and practices transferred through trade towards resource efficiency by reducing environmental impact. This is also in line with evidence provided by Frankel and Rose (2005) suggesting that trade can help the environment as it allows for the diffusion of green technologies. Model 3 implies that a higher load capacity factor might encourage trade through improved resource utilization. One possible reason is that more trade brings technological transfers and innovations, which might help in making production processes more efficient by reducing wastage. Empirically, positive aspects of the trade include technology transfer and resource efficiency. For example Siddiqui (2015), and Managi (2004) advocated for technical change/directed technological progress inducing environmentally friendly economic growth.

Analysis of different environmental indicators (CO2 emissions, EFs, LCF and ILCF) with Natural Resource Rents (NRR) reveals varied relationships among BRICS + T countries. Results reveal that NRR has a positive and significant effect on CO2 emissions in different models, denoting the possible presence of cointegration by detracting with positive coefficients using DSUR, CUP-FM and

CUP-FM methodology. In other words, CO2 emissions grow with higher natural resource rents due to the carbon-intensive processes of extraction and use that lie behind all natural resource-based wealth (Huang et al., 2023; Cai et al., 2023). The extraction involves a great deal of energy use and often the burning of fossil fuels, which causes more greenhouse gas emissions. The literature of Shah et al. (2023), Lu and Wang (2023) and Amin et al. (2024) postulated that the over-exploitation of resources in the drive to generate revenue on a bigger scale provides environmental degradation, mostly as higher CO2 emissions. This finding is consistent with prior work that has argued natural resource dependence leads to higher emission levels by under-investment in clean technologies, greater reliance on resource extraction for economic growth (CRCG), and lack of forward-looking sustainable strategies (Danish et al., 2019; Balsalobre-Lorente et al., 2018). Also, greater natural resource rents are positively associated with an enhanced ecological footprint, suggesting that countries that have performed worse from an ecological standpoint are not necessarily those more dependent on natural resource rents (Qing et al., 2024; Magazzino, 2024; Satrovic et al., 2024). Study findings supported by the environmental destruction resulting from resource extraction (such as those through deforestation, habitat loss and soil erosion) increase a nation's ecological footprint (Amer et al., 2024; He et al., 2024). This, of course, measures the ecological demand that human activities are putting on the planet, and it is magnified by the intensive extractive use of resources in resource-rich BRICS + T nations. This finding is in line with the literature, which suggests that economies based on natural resources push their environments more, therefor degrade it to a higher degree.

The negative coefficients in the regression models highlight a fundamental ecological truth: when resources are drawn upon more heavily and rapidly, then this ecosystem's capacity to support the population sustainably is also reduced (Ni et al., 2022; Akadiri et al., 2022). This is a concerning dynamic as it implies that higher resource rent leads to lower environmental sustainability of the productive capacity, which can be reported in one way by referring back again to the inverse relationship between NRR and LCF. This connection is not just a matter of statistical record but an illustration of the wider implications for environmental mismanagement and resource depletion. Numerous studies, see (Wang Q. et al., 2024; Sun C. et al., 2024; Inuwa et al., 2024; Du et al., 2024; Ali et al., 2024; Jin et al., 2024), in ecological and economic literature have established the heavy toll that resource extraction, despite its obvious short-run benefits, can exact upon environmental integrity over the long run. The misuse or overuse of a natural resource can lead to its depletion and the resulting destruction or degradation of an ecosystem, eventually making it less capable of sustaining life. Nowhere is it more apparent than in situations such as overfishing, where fish stocks are depleted faster than they can recover naturally, or mining, which leaves landscapes denuded and polluted for future farming or conservation possibilities.

The reduction of LCF also relates to wider uncertainties regarding environmental sustainability. Resilience is the ability of an ecosystem to recuperate quickly after being distressed. The greater surge of NRR and fewer changes in LCF lead to weakness/threatening the resilience of the ecosystem, which makes the ecosystems more susceptible to stressors–such as climate change, diseases or over-exploitation-that can exceed their tipping points and cause a transition towards an irreversible degraded state. The long-term resilience of an ecosystem is a key to the support system for human populations as well as biodiversity. Nonetheless, the current depletion of resources to higher NRR levels at a pace that undermines resilience. Additionally, the one-off economic benefits from natural resource rents are a short-term focus that may overlook sustainable management. Given these political realities, in many BRICS + T nations, extracting resources for short-term financial gain will be 'more attractive' to governments than ensuring sustainable livelihoods and long-term environmental protection. This short informal focus is reflected in a declining LCF, whereby the immediate gains from natural resource exploitation are incrementally accrued at the expense of both ecosystem health and resilient provision to dependent populations.

By definition, positive NRR coefficients suggest a potentially adverse tradeoff between economic benefits and environmental costs, given the findings about the ILCF. This relationship is consistent with the dual-edged nature of resource exploitation, particularly in BRICS + T nations, which have abundant natural resources and stringent economic growth commitments (Caglar et al., 2024). This would lead to financial flow, employment opportunities and foreign exchange accruing through a number of fees as economic benefits. These financial benefits are essential in financing initiatives, e.g., infrastructure projects, social programs and technological developments leading to better rates of growth for a country. Nevertheless, this economic pursuit often comes at a hefty environmental price. This points to a trade-off between the generation of economic benefits through more efficient transformation and restoration of natural resources on the one hand but at an environmental degradation cost in achieving many such transformations-restoration. It disrupts ecosystems and sustains biodiversity loss, as well as generates air pollution, which reduces the carrying capacity of this environment when the ecosystem's natural resiliency is eroded (Cai et al., 2024; Ahakwa and Tackie, 2024; Shahbaz et al., 2024).

BRICS + T countries all need to manage the tricky balance between growing their economies based on natural resources and maintaining stocks of natural capital and high ecological quality in the future. It is not easy to choose between economic growth and environmental sustainability due to the complex calculation pitting the more immediate economic exigencies against future disposition and the potential cost of environmental disaster. Increased resource rents, for example, may offer a lifeline in terms of capital with which to achieve poverty alleviation and infrastructural development. Nevertheless, the environmental degradation inherent within such exploitation can ultimately thwart these very developmental aspirations by degrading natural resources upon which communities depend for their livelihoods. Moreover, the "resource curse" is a useful concept here as countries with an abundance of natural resources have historically seen relatively lower economic growth and human development outcomes compared to those whose primary resource base consists of manufactured goods. Numerous antecedents can explain this paradox, such as governance challenges, rent-seeking activities, and the so-called resource curse. Such may be the case where short-term economics are targeted, and long-term economic benefits along with environmental sustainability are disregarded, which is hinted at by an existing strong positive relation between NRR and ILCF. In cases where the environmental costs of resource exploitation exceed economic benefits, the result can be a development impact that is net negative in terms of depleted natural capital, compromised ecosystem health and heightened social and economic vulnerability.

6 Conclusion and policy suggestions

6.1 Conclusion

The motivation behind this study lies in understanding the critical relationship between technological innovation, trade openness, natural resources, clean energy, and environmental sustainability in BRICS + T nations. These nations are significant players in the global environmental arena, and addressing their contributions to carbon emissions and ecological degradation is vital for achieving Sustainable Development Goals (SDGs), especially SDG 13, which emphasizes climate action. The key findings of the study indicate that technological innovation plays a crucial role in reducing CO2 emissions and improving environmental sustainability through cleaner industrial processes and energy efficiency. Trade openness has a dual impact, with increased trade leading to higher emissions in some cases and facilitating the transfer of green technologies. Clean energy adoption consistently shows a positive effect, lowering emissions and enhancing sustainability, while natural resource rents can both contribute to environmental degradation and offer financial means for sustainability investments. The Environmental Kuznets Curve (EKC) hypothesis is supported, revealing that economic growth initially worsens environmental outcomes but can eventually lead to improvements as higher incomes promote sustainable practices. Overall, the study underscores the complexity of balancing economic growth with environmental sustainability and the importance of integrated policies across these variables to achieve long-term ecological balance.

6.2 Policy suggestions

The study highlights that environmental sustainability in BRICS + T nations is profoundly influenced by technological innovation, clean energy adoption, trade openness, and natural resource management. Policymakers should adopt a holistic strategy integrating these factors, with a particular focus on advancing clean energy technologies and fostering innovation. For instance, Brazil’s successful programs to reduce deforestation, like the Amazon Fund, demonstrate how targeted policies can mitigate environmental degradation. Similarly, China’s massive investments in renewable energy infrastructure and its leadership in solar technology innovation showcase the potential for clean energy to lower CO_2 emissions and improve ecological footprints.

Policies should encourage investments in renewable energy projects, such as India’s National Solar Mission, which has significantly expanded the country’s solar capacity while creating green jobs. Trade openness must be guided by frameworks that facilitate the transfer of green technologies, as evidenced by South Africa’s Renewable Energy Independent Power Producer Procurement Programme (REIPPPP), which has attracted foreign investment and accelerated the transition to sustainable energy sources. These examples underline the need for strategic regulatory measures to promote environmentally beneficial trade practices while discouraging industries with high pollution levels.

Addressing income inequalities and ensuring inclusive economic growth is equally critical. Poor governance of natural resource rents can increase environmental harm, as seen in countries overly dependent on fossil fuel revenues. Effective resource management practices, like Russia’s initiatives to improve efficiency in oil extraction and reduce flaring, demonstrate how natural resource utilization can align with sustainability objectives.

By implementing such targeted and evidence-backed policies, BRICS + T economies can not only achieve their Sustainable Development Goals (SDGs) but also lead by example in harmonizing economic growth with environmental stewardship. As these nations, among the largest greenhouse gas emitters, adopt cleaner and greener practices, they can significantly mitigate global climate change, improve global air quality, and set a precedent for other developing nations to follow, paving the way for a sustainable future.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://databank.worldbank.org/source/world-development-indicators.

Author contributions

JS: Conceptualization, Methodology, Formal Analysis, Writing–review and editing, Supervision. MQ: Data curation, Investigation, Software, Visualization, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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