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Digital Twins, Green Manufacturing, and the Bioeconomy: BRICS' *Paradigm Shift* Toward Decarbonized, Resource-Efficient Industrial Ecosystems"

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Abstract

This study investigates the intricate relationship between industrial production, human development, and sustainable resource management in BRICS countries from 1996 to 2023, utilizing the MG-ARDL estimation technique. The findings position industrial production as a key catalyst for natural resource rents (TNRR), driving economic outcomes while highlighting the need for balanced growth. Human development emerges as a transformative force, enhancing the efficiency of resource use and promoting long-term sustainability. Green energy technologies stand out as a pivotal factor in reducing reliance on finite resources, signaling a gradual transition to renewable solutions and reinforcing environmental resilience. Economic growth and trade openness further amplify resource-driven revenues, showcasing their potential to harness natural wealth for broader development goals. Conversely, population growth exerts a consistent downward influence on TNRR, reflecting demographic pressures on sustainability. CO2 emissions present complex challenges, requiring targeted policies to mitigate their dual economic and environmental impacts. The study reveals a robust capacity for BRICS nations to swiftly correct resource imbalances, emphasizing the synergy between economic strategies and environmental stewardship. These findings provide actionable insights for policymakers, urging them to align industrial expansion with green innovation and human capital development to achieve a sustainable balance between economic growth and resource conservation.

Keywords : Industrial Production, Human Development, Green Solution, Sustainable Resource Management, BRICS Countries

ملخص

. تستكشف هذه الدراسة العلاقة المعقدة بين الإنتاج الصناعي والتنمية البشرية والإدارة المستدامة للموارد في دول البريكس خلال الفترة من 1996 إلى 2023، باستخدام تقنية تقدير MG-ARDL. وتُظهر النتائج أن الإنتاج الصناعي يُعدّ محفزًا رئيسيًا لعائدات الموارد الطبيعية، إذ يُسهم في تحقيق نتائج اقتصادية إيجابية، مع التأكيد على ضرورة النمو المتوازن. وتبرز التنمية البشرية كقوة تحويلية، تُعزز كفاءة استخدام الموارد وتُسهم في تعزيز الاستدامة على المدى الطويل. وتُعد تقنيات الطاقة النظيفة عاملًا محوريًا في تقليل الاعتماد على الموارد المحدودة، مما يُشير إلى انتقال تدريجي نحو حلول الطاقة المتجددة، ويُعزز المرونة البيئية. كما يُسهم النمو الاقتصادي والانفتاح التجاري في زيادة عائدات الموارد، مما يُبرز إمكاناتها في تسخير الثروات الطبيعية لتحقيق أهداف تنموية أوسع. في المقابل، يُؤثر النمو السكاني سلبًا على عائدات الموارد الطبيعية، مما يعكس الضغوط الديموغرافية على الاستدامة. وتُمثل انبعاثات ثاني أكسيد الكربون تحديات معقدة، تتطلب سياسات مُحددة للتخفيف من آثارها الاقتصادية والبيئية المزدوجة. تكشف الدراسة عن قدرة دول البريكس القوية على تصحيح اختلالات الموارد بسرعة، مؤكدةً على التآزر بين الاستراتيجيات الاقتصادية والإدارة البيئية الرشيدة. وتقدم هذه النتائج رؤى عملية لصناع السياسات، تحثهم على مواءمة التوسع الصناعي مع الابتكار الأخضر وتنمية رأس المال البشري لتحقيق توازن مستدام بين النمو الاقتصادي والحفاظ على الموارد.

الكلمات المفتاحية: الإنتاج الصناعي، التنمية البشرية، الحلول الخضراء، الإدارة المستدامة للموارد، دول البريكس

1. Introduction

The merging of industrialization, human development, and sustainability resource management has emerged as an urgent problem of the 21st century. Industrialization has catalyzed economic growth, technological advancements, and social development(Usman and Balsalobre-Lorente 2022). It has proven crucial in generating employment, enhancing the quality of life, and promoting infrastructure growth (Rasheed et al. 2024). Nonetheless, these accomplishments frequently incur significant environmental expenses. Industrial operations diminish resource availability, aggravate environmental impact, and increase the release of greenhouse gases (GHG), hence aggravating worldwide climate issues. This contradiction is particularly evident in the BRICS nations—Brazil, Russia, India, China, and South Africa—which collectively function as financial centers while safeguarding vital natural resources (Danish et al. 2019).

The BRICS states, comprising over 40% of the worldwide population and providing about 25% of the world's economic output (GDP), constitute a distinctive collective of expanding economies characterized by varied industrial capabilities and abundant natural resources(Samour et al. 2023). China's supremacy in industrial production has established its status as the "globe's factory," whereas Russia's numerous energy assets support its economic endeavors. Brazil's agribusiness and hydrological capacities, India's expanding IT and production industries, and South Africa's mineral economies illustrate the diverse socioeconomic qualities of these countries. Nonetheless, these economic activities have resulted in considerable environmental repercussions, such as deforestation, air and water pollution, and climate change, underscoring the necessity for effective resource utilization(Danish et al. 2019).

The environmental repercussions of modernization are apparent in BRICS countries. China, the foremost worldwide emission of CO_2, predominantly depends on fossil fuels for power, substantially exacerbating pollution in the atmosphere and global warming(Z. Li et al. 2019). The swift reforestation in Brazil, mainly for agriculture, endangers ecosystems and disturbs worldwide carbon cycles. Mine operations in South Africa deplete water supplies and exacerbate land erosion. Manufacturing oversight has become a crucial global issue due to the compounding problems of population expansion, urbanization, and growing energy demands(Lisha et al. 2023a).

Industrial output significantly impacts the growth of humans (Y. W. Li et al. 2023). It creates jobs, fosters creation, and supplies the monetary capital necessary for health care, education, and transportation investments. These elements influence a nation's Human Development Index (HDI), which assesses advancements in health, academic achievement, and income equity. The connection between industry and human growth is intricate and multidimensional. Although industrial operations frequently enhance GDP, they can also worsen social inequities, relocate vulnerable populations, and adversely affect the public's health through degradation and depletion of resources (Wu, Li, and Li 2018).

The disparities in human development within and across BRICS nations illustrate these challenges. Urban areas in Brazil and India have benefited significantly from industrial growth, while rural regions continue to face limited access to education, healthcare, and clean energy (Y. W. Li et al. 2023).). Likewise, the wealth produced by demanding resources sectors in Russia and South Africa has not been relatively allocated, sustaining income disparities and social divisions. Addressing these disparities necessitates incorporating eco-friendly solutions into industrial manufacturing to guarantee sustainable and inclusive human growth (Jahanger et al. 2023).

Sustainable resource management is essential for balancing the conflicting objectives of production, preservation of the environment, and human growth (Samour et al. 2023). Sustainable solutions, such as using renewable energy, energy-efficient technologies, and circular economy practices, offer avenues to alleviate the adverse ecological effects of urbanization (Shahzad et al. 2022). Renewable energy sources such as wind, hydroelectricity, and solar power provide options to petroleum and coal, thereby mitigating greenhouse gas emissions and improving energy security. Advanced technologies, such as robotics, AI, and the rise of the Internet of Things (IoT), can enhance the use of resources, reduce waste, and increase factory productivity (C. Liu et al. 2022).

Despite an expanding corpus of studies on industry growth and sustainability, notable deficiencies remain in comprehending how green approaches can navigate the intricate interplay between manufacturing, human growth, and practical resource management, especially within the BRICS framework. Current research (Liao et al. 2024) frequently analyzes each of these factors separately, concentrating on either the economic advantages of manufacturing or its ecological repercussions while insufficiently considering their interrelated effects on overall human growth findings..

The distinctive economic, social, and environmental characteristics of BRICS states exacerbate these research deficiencies. China's preeminence in green energy expenditures, representing roughly 30% of worldwide solar and wind ability, starkly contrasts with Russia's dependence on natural gas and oil exporting goods, which obstruct its shift towards more environmentally friendly alternatives Brazil's reliance on hydro renders it susceptible to water shortages and climatic fluctuations, whilst India's lofty energy efficiency objectives encounter financial and policy obstacles. The mining industry in South Africa, while economically essential, substantially contributes to biodiversity deterioration and socioeconomic inequities.

Furthermore, the economic and social ramifications of implementing environmentally friendly approaches in BRICS countries have yet to be examined adequately. Although renewable energy and energy efficiency initiatives are frequently lauded for their ecological advantages, their broader implications on working, wealth disparity, and rural growth necessitate additional examination. India's initiative for electric automobiles and innovative electricity systems offers the potential for diminishing city pollution. However, it prompts inquiries regarding its impact on rural power supply and employment generation (Samour et al. 2023). China's swift implementation of renewable energies underscores the necessity to comprehend their effects on social fairness and workforce transformation (Deng, Cao, and Yang 2024).

This investigation aims to rectify these deficiencies by:

1) Recognizing inefficiency in the existing industrial manufacturing methods of BRICS states, namely regarding the use of resources, manufacturing of waste, and harm to the environment.

2. Assessing the viability of green alternatives, including green power, circular economic concepts, and sustainability logistics, in order to reconcile industrial expansion with protecting the environment.

3. Evaluating sustainable manufacturing procedures' societal and economic ramifications, emphasizing their effects on well-being, academic achievement, and financial inequality within BRICS countries.

The study examines how BRICS countries may efficiently adopt environmentally friendly options to align industrial output with sustainable use of resources and human growth objectives. It focuses on the impact of renewable energy technologies, financial complexity, and the application of circular economy approaches for tackling issues such as depletion of resources, emissions, and economic and social disparities. The study seeks practical advice for stakeholders and policymakers by analyzing the societal, technological and policy environments necessary to shift to sustainable industrial procedures.

The study posits that incorporating green solutions into industrial production techniques is feasible for attaining environmentally friendly resource management and human growth in BRICS nations (Bi and Khan 2024). By embracing clean energy sources, enhancing energy utilization, and advocating for the values of the circular economy, these countries may dissociate economic expansion from pollution while advancing social fairness. Furthermore, BRICS nations are distinctly equipped to lead the development of novel approaches that promote worldwide sustainability objectives, owing to their considerable economic power and resource assets (Fan and Wang 2024).

This study utilizes an integrated strategy, integrating concepts from the field of economic science of the environment and public policy to deliver a thorough analysis. It employs empirical evidence, research, and policy evaluations to demonstrate how environmentally friendly solutions can advance the 2030 Agenda for Sustainable Development of the United Nations (SDGs), specifically SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), and SDG 13 (climate action) (Udeagha and Muchapondwa 2023a).

This research offers significant improvements to the dialogue on sustainability and human development. Initially, it connects industrial manufacturing with sustainability resource utilization by analyzing their interaction within the distinct socioeconomic and environmental frameworks of BRICS countries. Secondly, it underscores the capacity of green solutions to revolutionize manufacturing operations, accentuating their wider socioeconomic ramifications, including creating employment, rural electrical power, and how income is distributed. Third, it establishes a structure for aligning industrial output with environmental goals, including policy proposals customized to the difficulties and possibilities within BRICS countries.

The worldwide importance of BRICS nations in the sustainability dialogue is indisputable. Their manufacturing operations significantly impact worldwide environmental objectives and financial stability. China's roleChina's role in expanding clean energy investments provides instructive insights for other developing nations, whereas Brazil's initiatives to incorporate sustainability into agricultural procedures exemplify innovative strategies for reconciling prosperity with sustainability (Bi and Khan 2024) .

The study highlights the significance of international teamwork. BRICS countries may exchange efficient procedures, align policies, and mobilize technological and financial assets to expedite their transitions to economically viable industrialization. These initiatives not only reinforce their status as global sustainability leaders but also offer a model for nations that are developing (Q. J. Wang, Wang, and Chang 2022).

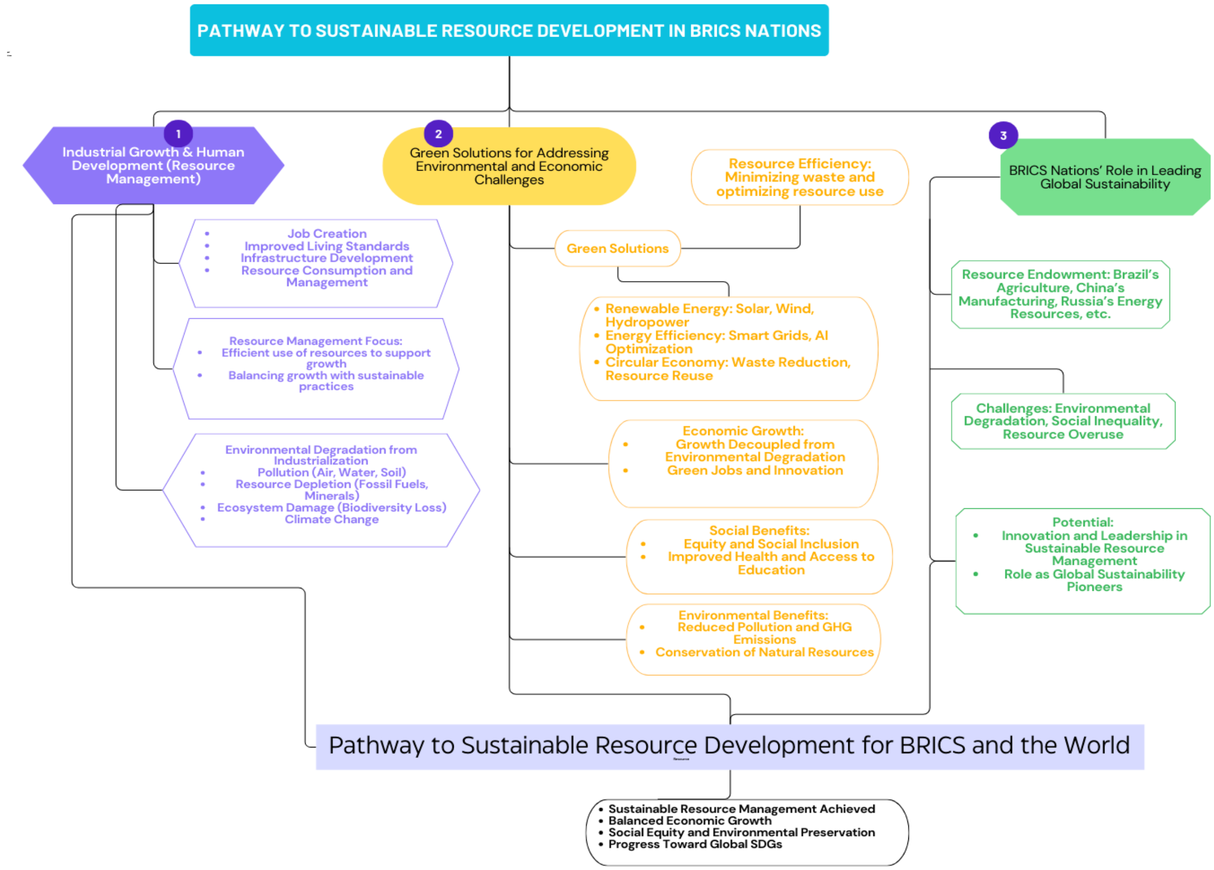

Figure 1.1 Pathway to sustainable Resource Development in BRICS Nations

2. Literature Review

2.1 Overview of the Literature

The connection between industrial output, the growth of humans, and environmentally friendly resource management is being extensively studied. The existing research is scattered, with most investigating specific aspects of such relationships. Despite substantial studies on the adverse environmental impacts of industrial development, the financial implications of natural resource utilization, and the revolutionary impact of renewable energy sources, a holistic structure that unites these dimensions—especially in the BRICS context—has yet to be developed.

Brazil, Russia, India, China, and South Africa—BRICS nations—exemplify the obstacles to reconciling economic growth with social and environmental viability(Nasrollahi et al. 2020) and (Jie et al. 2023) . Highly resource-intensive industries and expanding industrialized activities force these nations to balance economic growth, environmental protection, and development of people. Considering their importance in the worldwide financial and ecological networks, these concerns require a coordinated response (Tamasiga, Onyeaka, and Ouassou 2022) and (C. Wang et al. 2024)(Dogan and Aslan 2017).

Industrial manufacturing and environmental research fall into two categories. First, total natural resource rent (TNR) management and governing are examined for their impact on the economy and sustainable development. Effective utilization of resources is essential for BRICS industrial growth while limiting environmental damage and financial instability. Effective leadership is crucial for sustained growth in the industry since resource rent exploitation increases vulnerability. The subsequent category explores how green energy technology reduces industrial environmental impacts. These innovations are generally recognized for their beneficial environmental benefits, but their effects on human growth and allocation of resources are rarely examined.

TNR leadership in the countries of the BRICS region is being researched for its effects on economic development, industry expansion, and the environment. Studies show that highly resource-intensive economies, like Russia's oil export and Brazil's expansion of agriculture, boost the economy but harm ecosystems. China leads in sustainable energy adoption, demonstrating greener energy's ability to minimize carbon emissions. The interaction of these innovations with human growth goals, including health care, schooling, and equal wages, is understudied.

This review synthesizes these dispersed research domains, revealing correlations, differences, and crucial gaps. It suggests ways BRICS economies can improve industry sustainability by merging TNR management and green energy adoption findings. Developing methods that balance industry productivity, sustainable development, and equitable society requires this integrated approach. The assessment emphasizes the need for comprehensive solutions to BRICS nations' distinct obstacles and opportunities in achieving sustainable growth through this integration.

2.2 "Nexus: The Influence of Total Natural Resource Rent on Industrial Output and Development"

H1 : Industrial production positively boosts Total Natural Resource Rent (TNRR)

Total natural resource rent (TNR) – an economic yield from resources like natural gas, petroleum, mineral substances, and forestry — is fundamental in influencing the industrial sectors of BRICS countries. These nations, possessing a wealth of natural assets, depend on the efficient administration of TNR to enhance industrial output while reducing environmental harm (Rasheed et al. 2024). The divergent results of the exploitation of resources among these countries underscore the essential equilibrium necessary between optimizing industrial production and maintaining a sustainable environment (Miao et al. 2022).

The BRICS nations leverage their natural resources to drive industrial production and generate export earnings. For example, Russia's financial system relies on energy-exporting goods, whereas Brazil's farming industry, which is frequently sourced from areas of deforestation, underpins its manufacturing and processing sectors. The mining industry of South Africa, primarily focused on the extraction of gold and platinum, supports its manufacturing industry, while India's energy-intensive businesses are primarily reliant on coal (Tiwari, Shahbaz, and Adnan Hye 2013) and (Nenavath 2022).). China leverages its extensive factories to utilize various natural resources, maintaining its worldwide manufacturing supremacy (K. Du, Cheng, and Yao 2021). The dependence of the BRICS countries on rents for resources generates substantial economic prospects (F. Liu et al. 2022). Nevertheless, it also intensifies the risk of financial stagnation stemming from excessive reliance on unstable resource markets. Russia's vulnerability to variable global energy costs hampers its industrial development, whereas Brazil's growth in agriculture, driven by forest clearing, jeopardizes the environment despite its contribution to agro-industrial exports. Likewise, South Africa's mining operations frequently damage the environment, including water pollution and soil erosion, directly affecting industry sustainability.

Recent research emphasizes the necessity of synchronizing TNR management with industrial production plans to promote sustainable growth (L. Du et al. 2022) and (Zhang and Wang 2019). Technological advances like chains have been utilized to promote openness regarding the handling of resources, hence improving legitimacy and mitigating corruption (Ali et al., 2023). This promotes fair resource allocation and guarantees that corporate profits are redirected into productivity-boosting projects. Artificial intelligence (AI) is becoming a tool for enhancing resource utilization in industrial manufacturing. AI-powered systems can forecast resource consumption, reduce waste, and assess environmental implications, reconciling industrial production with protecting the environment(Lin and Ma 2022). Predictive analytics is employed in the mining and energy sectors to enhance operational efficiency and mitigate excessive asset extraction. Green finance mechanisms significantly influence transformation China's Green Bond programme illustrates the allocation of natural resource rentals to environmentally friendly building initiatives, improving industry productivity and reducing environmental impact (Zhou and Cui 2019).

Furthermore, India's significant investments in green hydrogen technology indicate a transition towards alternative energy sources for industry use, hence diminishing dependence on oil and gas s(Chandel et al. 2016). To optimize the industrial value of TNR, it is essential to reinvest in diversifying and upgrading manufacturing procedures. As exemplified by Brazil's forest certification programs, governance structures demonstrate the potential of natural resource rents to foster technological advancement and stewardship. Shifting to clean energy technology and embracing strategies from the circular economy provide avenues for diminishing resource reliance and bolstering industry resilience. Partnerships across sectors such as government, industry, and academic organizations are becoming progressively essential. Public-private collaborations in China and India propel developments in renewable energy technologies, fostering complementarity among industrial production and protecting the environment. These partnerships guarantee that TNR is both a source of industrial revenue and a driver for technological advancement and sustainability.

The ecological repercussions of the extraction of resources directly influence industrial output in BRICS countries. Forest loss extraction and fracking intensify the degradation of biodiversity, soil erosion, and carbon emissions, disrupting economic supply networks and diminishing the abundance of resources. India and China, confronting significant biological capacity deficiencies, have led to this problem as their resource-intensive industrial sectors struggle with excessive extracting levels. Simultaneously, the mining industry in South Africa exerts a considerable influence on the availability of water, which has profound implications for its industrial activities. Implementing responsible extraction methods and pursuing clean technology is essential for harmonizing industrial production with environmental objectives (Khattak, Khan, and Hussain 2024). China's swift advancement in renewable energy diminishes its industrial carbon emissions while ensuring the sustainability of resources over the long term. India's focus on energy efficiency in industrial operations highlights the increasing acknowledgement of environmentally friendly methods as an edge over rivals.

Total natural resource rent is pivotal in industrial production within BRICS countries, providing considerable economic prospects while presenting notable ecological and governance issues. By implementing solid political frameworks, utilizing digital and green technology, and promoting joint projects, BRICS states may steadily leverage TNR to enhance their economic output. Synchronizing the rental of resources with technological advancement and protecting the environment will be crucial in converting natural richness into industry robustness and continued economic expansion.

2.3 "Harnessing Total Natural Resource Rent (TNR) for Sustainable Human Development"

H2 : Advancements in human development promote better resource management and usage

In resource-abundant economies worldwide, applying Total Natural Resource Rent (TNR) is a vital determinant affecting human growth, frequently assessed by the Human Development Index (HDI). TNR may improve HDI by financing essential public expenditures in medical care, schools, and technology; nevertheless, the connection is intricate and diverse. Oil revenues have been utilized in Saudi Arabia to enhance literacy rates and life expectancy (Doytch 2020). Likewise, BRICS countries like India and Brazil have utilized their resource richness to promote industry, generate employment, and enhance rural electricity supply, indirectly enhancing the Human Development Index (Y. W. Li et al. 2023). Nevertheless, the allocation of these rewards is frequently inequitable, with urban centres generally obtaining more significant advantages, whilst rural regions persist in confronting issues such as diminishing resources, insufficient facilities, and limited availability of essential services. This disparity underscores the necessity for more equal resource allocation strategies to guarantee comprehensive human development.

Although TNR can stimulate the economy, the adverse ecological and social repercussions of mining for resources may diminish its beneficial impact on HDI. Environmental deterioration resulting from actions such as logging, mineral extraction, and industrial emissions has enduring repercussions for human health, food availability, and general well-being. In nations such as India and China, industrial pollution poses a considerable wellness issue, undermining the advantages of TNR and constraining its impact on HDI (Nchofoung, Achuo, and Asongu 2021). Moreover, the socioeconomic disparities arising from plundering natural resources frequently result in local populations, especially in agricultural areas, not receiving equitable benefits from the resulting riches. In South Africa's mining industry, resource riches have primarily advantaged multinational firms and urbanized elites, marginalizing local populations.

Solutions are being investigated to integrate TNR more effectively with human development objectives. Modern technologies, like blockchain and artificial intelligence (AI), provide novel methods to enhance accountability, assess socioeconomic and environmental implications, and ensure equitable resource rent allocation. Blockchain innovation can improve the integrity of TNR transportation, guaranteeing that profits are reinvested in environmentally friendly initiatives (Liao et al. 2024). Artificial intelligence can oversee and alleviate the detrimental ecological and social repercussions associated with resource extraction, facilitating the alignment of resource exploitation with objectives related to sustainable development. Moreover, green finance efforts, including China's Green Bond scheme and India's investments in green hydrogen technology, exemplify how TNR can finance renewable energy endeavours that mitigate harmful emissions while generating employment and promoting diverse economies.

Management is essential for the efficient application of TNR in promoting human development. Norwegian effective strategy of allocating resource rents towards training, energy efficiency, and community development initiatives is a valuable exemplar for resource-abundant countries. By enhancing organizational structures, increasing accountability, and promoting collaboration between the public and private sectors, BRICS states can guarantee that TNR is reinvested in sustainability initiatives that benefit all populations rather than solely urban elites (Rahim et al. 2021). Brazil's certification of forest schemes exemplifies how resource rents can facilitate conservation efforts while fostering technological advancement. The discussion between the public and private sectors in South Africa, focused on enhancing labour conditions in the mining sector, exemplifies how changes in governance can mitigate socioeconomic inequities and foster better outcomes.

In verdict, although TNR possesses significant promise to advance the growth of humans, its advantages must be meticulously regulated to prevent environmental destruction and socioeconomic inequity. Through the implementation of solid governance structures, the utilization of creative innovations, and an equitable division of resource rents, BRICS states may capitalize on their resource richness to promote long-term human growth and enhance HDI for the benefit of all residents. This comprehensive strategy can foster enduring growth, social equality, and its commitment to sustainability. As the Human Development Index (HDI) advances, improved educational and health results foster a transition to a more informed and accountable citizenry that advocates for a more sustainable utilization of natural resources. This societal transformation propels a continuous rise in Total Natural Resource Rent

(TNRR) as elevated Human Development Index (HDI) levels enhance buying power, promoting sustainable and morally supplied resources. This increase in HDI promotes the reallocation of resource rents towards sustainable investments in green technologies, renewable energy, and circular economies (Y. W. Li et al. 2023). This systematic transformation guarantees abundant natural resources are utilized not for immediate profits but as a fundamental basis for equitable, sustainable, and resilient economic development, promoting prosperity for future generations while preserving the ecological balance.

2.4 "Economic Growth and Total Natural Resource Rent (TNR): Unveiling the Connection"

H3 : Economic growth positively influences Total Natural Resource Rent (TNR) by enhancing resource-based revenue creation over time

Organizations have historically depended on rents from natural resources to fund facilities, societal amenities, and vital services that boost GDP (Jahanger et al. 2022). Efficient TNR maintenance can boost other industries outside the extraction of resources. TNR revenue funds medical care, education, and technological advances, which have created long-term economic improvements. Research (Deng, Cao, and Yang 2024) found that innovative TNR management boosts production and industrialization. In BRICS nations (Brazil, Russia, India, China, and South Africa), TNR has driven manufacturing, poverty reduction, and geographic expansion (Awosusi et al. 2022). Russia invests in facilities and welfare programs and spends money on society using its natural gas and petroleum resources. Brazil uses its TNR from agriculture and mining to grow its financial system and boost development.

In contrast, South Africa has expanded its service and manufacturing sectors with resource income. Government quantity, exterior marketplace dynamics, and technology capacity affect TNR and economic growth, complicating the link. Only innovative policy measures that promote sustainability over time above short-term spending can boost revenue growth with TNR.

A significant issue with TNR is economic unpredictability. Organic resource prices are volatile due to external factors such as international conflicts, worldwide demand, and environmental regulation (Erdoğan et al. 2021) . International oil and resource price swings have caused major recessions in BRICS countries, notably Russia and Brazil, increasing their reliance on just one industry. Price volatility causes price fluctuations, impeding financial stability and planning for the future. Government is an additional curse of resources issue(Hussain et al. 2020). New riches from TNR can lead to rent-seeking, mismanagement, and poor utilization of resources. TNR typically fails to lead to equitable growth due to organizational instability, such as weak legal frameworks, low openness and inadequate responsibility. Venezuela and Nigeria despite their oil wealth, Venezuela and Nigeria have experienced financial mismanagement, political instability, and fraud by misallocating resource revenues, hindering inclusive progress (Erdoğan et al. 2021). Responsible management determines whether natural resource rents (TNR) support expansion or worsen the resource curse. Spending rents for resources in productive industries requires accountability and open governance (Baloch & Wang, 2019). The Norwegian Government Pension Fund Global (GPFG) shows how resource riches can be carefully managed to ensure economic stability and diversity, avoiding Dutch disease. Institutional frameworks and governance must be strengthened to mitigate TNR risks, ensure long-term viability and diversify investments in BRICS states (Khattak, Khan, and Hussain 2024).

Abundant in resources, countries must diversify to lessen dependency on renewable resources, cushion pricing fluctuations, and maintain equitable development China's renewable dominance and Brazil's industrial instruction in innovation are examples of reinvested natural resource rents (TNR) into green technologies. Like India's IT services boom, human resources growth is essential for economies based on information. Green mining industries, economic circularity concepts, and technological advances like artificial intelligence, massive data sets, and robotics improve the handling of resources, worker efficiency, and environmental impacts, promoting sustainable development and stability (Lisha et al. 2023b).

2.5 "Innovative Green Energy Solutions for Sustainable Resource Management"

H4 : The adoption of green energy technologies significantly reduces the reliance on natural resources

Renewable energy sources like wind, water power, solar energy, and biofuels help combat global warming, harm the environment and maximize resource utilization (Lisha et al. 2023b). Sustainable solutions to oil and gas minimize the loss of resources and waste. Utilizing them promotes sustainable development and economic development. However, the Total Natural Resource Rent (TNR) administration is crucial to supporting and expediting the green energy revolution(Shao et al. 2021).

Total Natural Resource Rent (TNR) is the financial surpluses from gas, petroleum, gemstones, and forestry exploitation and exporting. TNR is a large portion of the financial resources for numerous nations, especially in the BRICS group (Brazil, Russia, India, China, and South Africa). It goes to social services and facilities and diversifies their economies. If handled well, TNR can support renewable energy technology acceptance and scalability(Lisha et al. 2023b). TNR may help environmentally conscious adopters cover the high investment expenditures of green energy facilities, technological innovation, and maintenance. Abundant in resources nations may promote long-term viability, lessen their reliance on finite energy resources such as coal, and diversify their economy by reinvesting some TNR in environmentally friendly innovations. This strategy solves energy demands and supports sustainable development worldwide. China, a leader in developing wind and solar energy adoption, has invested coal and oil income in clean energy sources. Therefore, China has become a global leader in environmentally friendly energy manufacturing, lowering carbon dioxide emissions and protecting natural resources (H. Liu, Lei, and Zhou 2022).

(Yadav et al. 2024) Naturally resource-rich nations benefit economically from renewable energy sources. Green energy solutions reduce pollutants and boost economic development, including creating jobs, technological advancements, and energy industry specialization. Example: India's National Solar Mission. The country has expedited renewable energy construction with both public and private investments. This change has improved municipal air quality by lowering coal use and creating millions of clean energy opportunities(Zheng, Feng, and Yang 2023). Efficient use of TNR can finance renewable energy projects, create jobs, and promote green sectors, promoting long-term economic development. TNR in environmentally friendly energy policies allows the countries of the BRICS to diversify their economy, reduce oil and gas exports of goods, and move toward environmentally friendly growth. Planning for strategy and expenditures in innovation in technology, training for workers, and transportation are needed for this shift.

In abundant resource-rich economies, switching to energy from renewable sources is difficult. Russia's economy relies heavily on oil and gas exports, challenging energy sector diversification. South Africa's coal-dependent network and high renewable technology costs also limit its energy source transition. Given this, South Africa's Integrated Resource Plan (IRP) strives to broaden its energy mix through more outstanding environmental contributions. BRICS economies generally lack the funds for massive amounts of sustainable energy initiatives. Reinvesting natural resource rents (TNR) in green energy projects can pay for maintenance, technical advances, and fossil fuel departure. These nations may use their mineral richness to generate clean energy and lessen their reliance on gasoline by carefully directing TNR(Razzaq et al. 2021).

Strategically using TNR to construct renewable energies can help nations with abundant resources sustain themselves Good governance ensures that TNR invests in infrastructures and industries that promote long-term revenue diversification and sustainable development rather than short-term consumerism. (Aizawa and Yang 2010) suggest creating sovereign wealth investments and environmental investment funds to use TNR for renewable power. Norway's Government Pension Fund Global (GPFG) shows how nations with abundant resources can use TNR to fund long-term expenditures, including environmentally friendly innovations. Norway has reduced its petroleum volatility in prices and supported a carbon-neutral economy by preserving and investing its wealth of natural resources abroad. Similar financing for renewable energy and green infrastructure in BRICS economies might minimize fossil fuel reliance and finance the switch to clean energy. Such funds could also finance green energy projects, enable public and private sector collaboration, and assist energy storage technologies, which are essential for incorporating clean energy into national networks (Akomea-Frimpong et al. 2022) and (Aizawa and Yang 2010).

Green energy is both a sustainability imperative and an economic possibility, especially for nations with abundant resources. TNR for alternative energy acceptance can help achieve the UN Sustainable Development Goals (SDGs) of clean and reliable electricity, tackling climate change, and economic expansion (Ullah et al. 2023) and (Udeagha and Muchapondwa 2023b). In The Brazilian government has used resource rents from mining and farming to promote biofuels and solar power. Brazil has been a regional leader in renewable energy, and its TNR has helped diversify its energy portfolio away from oil and gas. Green energy solutions allow resource-rich nations to innovate in non-fossil fuel businesses. Renewable energy purchases can boost electric vehicles, energy storage, and innovative grid systems, allowing countries to join the worldwide sustainable economy**.**

2.6 Integrated Approaches to Sustainability

BRICS nations—Brazil, Russia, India, China, and South Africa—must integrate industrial output and social progress with environmentally friendly approaches that reconcile economic growth and sustainability to achieve efficient use of resources. Manufacturing output drives economic growth and damage to the environment. Hence, efficient industry practices that minimize the depletion of resources and pollution are needed (Khattak, Khan, and Hussain 2024). Solar power, resource-efficient production, and sustainable economic concepts are essential to reducing industrialization's adverse environmental effects. China's green production initiatives have shown how manufacturing may be detached from greenhouse gases while boosting technology and development. While certain BRICS nations are making progress, ensuring green industrial practices serve all sectors of society remains difficult. Green technology can alleviate impoverishment, generate jobs, and enhance the health of everyone, making human growth crucial to this shift (Pata, Aydin, and Haouas 2021). India's National Solar Mission shows how renewable energy, jobs, and energy-related poverty reduction can assist industrial progress and human growth. Studies show that minorities often pay the societal costs of industrialization and extraction of resources (Chen, Lee, and Chen 2022) . So that the shift to green utilization of resources is democratic and beneficial to all sections of the community, environmentally friendly manufacturing options must tackle social fairness. BRICS nations must modify their approaches and technical developments to link industrial expansion with developmental agendas and use green advances for sustainable and equitable resource management.

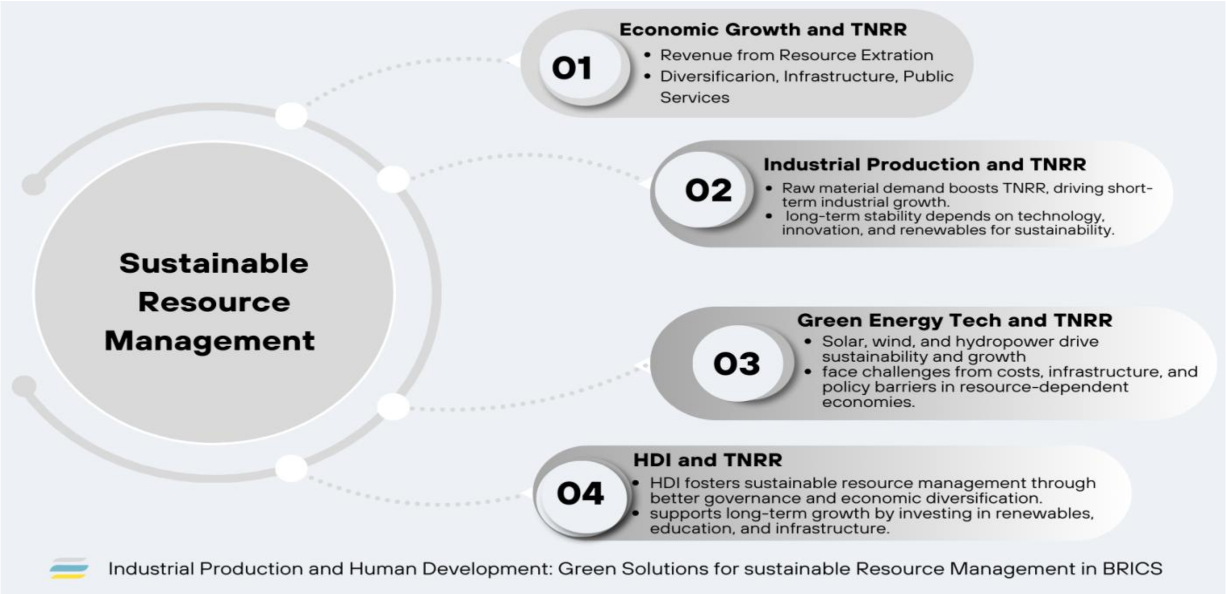

Figure 2.1 Industrial Production and Human development : Green Solutions for Sustainable Resource Management

3. Methodology

Total Natural Resource Rent (TNNR) is influenced by industrial production, HDI, the Green Energy Technology Index, economic expansion, and control variables, including carbon dioxide emissions, trade, and growing populations. The Resource Curse Hypothesis and Environmental Kuznets Curve (EKC) examine resource utilization, economic growth, and sustainability.

The Hypothesis of Resource Curse

The Resource Curse Hypothesis posits that economies dependent on natural resource rents face growth hurdles due to over-extraction, governance issues, and insufficient diversity (Richard M. Auty n.d.). This theory explains:

- Industrial Production (Ind Pro): Resource-intensive sectors generate rents and may hinder diversification.
- Economic Growth (Econ Growth): Examines resource rents' impact on GDP, considering volatility hazards.

Control variables like commerce are added to account for globalization's dual function of increasing or alleviating the resource curse through resource exports or technological transfer.

EKC Environmental Kuznets Curve

The EKC states that environmental degradation rises with economic expansion but falls with cleaner technology and stricter standards(Sinha, Sengupta, and Alvarado 2020) and This theory supports: • Green Energy Technology Index (Green Tech): Highlights renewable energy and innovative contributions to resource efficiency.

- CO_2 Emissions: Measures industrial activity and resource exploitation's environmental impact.

Key control fluctuating population increase drives resource demand and amplifies environmental concerns.

Framework Functionality

This relationship is modelled:

$$TNNR = f(IndPro, HDI, Green\ Energy\ Tech, EconGrowth, CO2, Trade, PopGrowth)$$

Supports the Resource Curse Hypothesis by measuring the socio-economic benefits of resource use. Green Energy Tech and CO_2 illustrate EKC concepts, balancing resource utilization and environmental sustainability.

This concept, using the Resource Curse Hypothesis and EKC, links economic activity, human development, and environmental sustainability to TNNR and reveals the resource-management secrets for sustainable growth.

Model Specification

A linear regression method operationalizes its mathematical appearance:

$$TNNRit = \beta 0 + \beta 1IndProit + \beta 2HDIit + \beta 3GreenTechit + \beta 4EconGrowthit + \beta 5CO_2it + \beta 6Tradeit + \beta 7PopGrowthit + \varepsilon it$$

Where:

- $TNNRit$: Total Natural Resource Rent for country I at time t
- $IndProit$: Industrial production, reflecting the economic reliance on resource extraction
- $HDIit$: Human Development Index, capturing socio-economic benefits
- $GreenTechit$ Green Energy Technology Index, indicating renewable energy and technological advancements
- $EconGrowthit$: Economic growth, representing GDP performance
- CO_2it : CO_2 emissions, serving as a proxy for environmental degradation
- $Tradeit$: Trade openness, capturing globalization effects
- $PopGrowthit$: Population growth, representing demographic pressures
- β0: Intercept term
- β1,β2,…,β7: Coefficients of the respective variables
- εit: Error term capturing unobserved factors

This model, with the Resource Curse Hypothesis and EKC, provides an exhaustive outline for TNNR variables. The equation allows a practical assessment of resource use, economic expansion, and sustainability's ongoing relationship.

Total Natural Resource Rents (TNRR) and related factors in BRICS nations (Brazil, Russia, India, China, and South Africa) from 1996 to 2023 are examined. The variables used in this study are CO_2 emissions (CO2), Economic Growth (EG), and TNRR, which measure the percentage of GDP derived from natural resources (e.g. forests, oil, gas, and minerals) (sourced from WDI). WDI reports industrial production (IND) and trade openness (TR) as percentages of GDP. Green Energy Technology (GET), defined by the OECD diffusion index of environment-related technologies, showcases sustainability innovation. The UNDP Human Development Index (HDI) links socio-economic development to resource usage by measuring health, education, and income. Population increase (PG), annual population increase (%) from WDI, is a control variable. Sustainable development plans are informed by this dataset's environmental, economic, and social perspectives on resource management and development**.**

Table 1: Variable Definitions and Sources

Variables	**Definition**	**Unit**	**Source**
Co2	Carbon intensity of gdp	Kg co_2 per constant 2021 usd	Edgar
Eg[1]	Gdp growth (annual %)	% annual	Wdi
Tnrr	Total natural resources rents (% of gdp)	% of gdp	Wdi
Ind[2]	Industry value added (including construction)	% of gdp	Wdi
Get[3]	Diffusion of environment-related technologies	Index	Oecd
Hdi[4]	Human development index	Index	Undp
Tr[5]	Trade openness (% of gdp)	% of gdp	Wdi
Pg[6]	Population growth (annual %)	% annual	Wdi

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[1] Economic Growth (EG): The yearly GDP growth rate (%) measures a nation's economic growth year over year. This variable measures BRICS economic activity. The World Bank's WDI, or World Development Indicators, offer reliable and precise statistics for cross-country comparisons (World Bank, 2023).

[2] Industries' benefits, including development, as a percentage of GDP show their contribution to economic expansion and the efficient use of resources. WDI data allows comparisons of BRICS industrial development trends.

[3] Green Energy Technology (GET): The research described here monitors the increasing use of environmental technology to measure environmentally friendly innovations. OECD data shows the adoption of BRICS states' green energy.

[4] HDI: Human Development Index. An integrated index of health, education, and income, HDI measures improvements in socioeconomic status. It shows BRICS human development trends from UNDP.

[5] Globally, economic convergence is measured by trade openness, which is the sum of exports and imports as a proportion of GDP. WDI data shows how trade affects economic and environmental trends.

[6] The annual percentage growth of the total population is a control variable that reflects societal shifts and their effects on resource demand and environmental issues. The BRICS states use WDI data for uniformity and availability.

Note: This table supports transparency and replicability in the study of TNRR and its drivers in BRICS economies.

UNIT ROOT TEST

The study employed first- and second-generation unit root evaluation, specifically utilizing the IPS panel unit root test to identify unit roots in a panel series (Im, Pesaran, and Shin 2003). The examination utilizes panel data ADF regression, as illustrated in Equation (5).

$$\Delta y_{it} = \propto_i + \beta_i \bar{y}_{it-1} + \gamma_i y_{t-1} + \sum\nolimits_{j=0}^{k} \delta_{ij} \Delta \bar{y}_{it-1} + \sum\nolimits_{j=0}^{k} \theta_{ij} \Delta y_{it-1} + \varepsilon_{it}$$

In Eq. (6), k represents the specified variables, and y¯it denotes the mean of the cross-sections. Consequently, the CIPS was calculated using the aforementioned equation's CADF assessment statistic.

$$CIPS = N^{-1} \sum\nolimits_{i=1}^{N} CADF_i$$

Equation (7) represents CADFi as the cross-sectional term, while the mean value of CADF calculates CIPS. The null hypothesis posits the fact of unit roots, whereas the alternative hypotheses refute their presence.

Cross-sectional dependence test

Before assessing the various offered estimating techniques, it is essential to investigate cross-sectional dependency (CD). The existence of CD may lead to inaccurate and biased prediction outcomes when first-generation methods are favoured for further analysis. This analysis utilized (Pesaran 2015) to assess the cross-sectional dependence (CD). The CD test statistic is expressed as (8):

$$CD_{LM1} = \sqrt{\frac{1}{N(N-1)}} \sum\nolimits_{i=1}^{N-1} . \sum\nolimits_{j=i+1}^{N} \left(T \hat{\rho_{ij}}^{2} - 1\right)$$

In this scenario, ρijˆ denotes a sample enumeration of the residuals in paired connections, N represents the cross-sectional component of the panel data, and T signifies its time series component.

Cointegration test

Analyzing cross-sectional dependency (CD) is essential before assessing estimate methods, as CD might result in erroneous and biased forecasts when utilizing first-generation methodologies. This study employs the methodology of (Pesaran 2015)) to assess cross-sectional dependence, utilizing the CD test statistic shown in Equation (8):

$$y_{it} = x\acute{}^{it} \beta_i + \acute{z}_{it} \tau_i + e_{it}$$

(Pedroni 1999) cointegration tests account for cross-sectional variability in intercepts and trend coefficients. Similarly, (Kao 1999) test also presumes uniform coefficients and captures particular cross-sections for the initial-stage forecasts.

$$\hat{e}_{it} = \rho \hat{e}_{i,t-1} + \mathcal{V}_{it}$$

Where e ˆ_it represents the estimated residual, and the OLS estimate of ρ is,

$$= \frac{\sum_{i=1}^{n} . \sum_{t=2}^{t} . \hat{e}_{it} \hat{e}_{it-1}}{\sum_{i=1}^{n} . \sum_{t=2}^{t} . \hat{e}_{it}^{\,2}}$$

The cointegration investigation by (Westerlund 2007) examines the long-term link among TNRR, IND, GET, EG, and HDI. This method is suitable and favoured over Pedroni and Kao's panel cointegration tests whenever data exhibits cross-dependence (CD). The formulas for the test statistics in this method are as follows

$$G_t = \frac{1}{N} \sum_{i-1}^{N} . \frac{\acute{\alpha}_i}{SE(\acute{\alpha}_i)}$$

$$G_\alpha = \frac{1}{N} \sum_{i-1}^{N} . \frac{T \acute{\alpha}_i}{\acute{\alpha}_i(1)}$$

$$P_T = \frac{\acute{\alpha}}{SE(\acute{\alpha})}$$

$$P_\alpha = T \acute{\alpha}$$

The group mean statistics, encompassing Gt and Gα, are delineated by equations (12) and (13). The panel's statistics, including Pt and Pα, are shown in equations (14) and (15). The null hypothesis asserts the absence of cointegration, whereas the alternative hypotheses indicate its presence.

Mean group (MG) ARDL

This research utilized the MG-ARDL methodology to investigate the interrelationship among the use of resources, economic expansion, and sustainability, resolving the constraints of conventional panel models. Pooled OLS neglects individual differences by enforcing a constant intercept and slope. Fixed-effects models presume nation-specific captures while sharing variance and slopes, resulting in erroneous estimates when endogenous regressors are present (Baltagi n.d.). The random effects methodology naively assumes model constancy across time . Stationary panel estimate approaches insufficiently account for changing data dynamics and permits structural variation solely as random or fixed effects, notwithstanding the possible disparities in slope parameters among nations. (Pesaran and Smith 1995) demonstrate that, for large T, conventional panel methodologies may yield incorrect and deceptive parameter estimates within a dynamic panel data context.

This study by (Pesaran, Shin, and Smith 1999) examines the short- and long-term links among resource usage, economic growth, and sustainability in the five BRICS states from 1996 to 2023, yielding a dataset of 140 observations. The Mean Group (MG) ARDL model was selected over alternative methods like GMM because it is more appropriate for panel data where T (28 years) surpasses N (5 countries). The MG-ARDL model adeptly handles variables exhibiting mixed stationarity (I(0) and I(1)) and is especially beneficial for datasets with limited sample sizes. Within the MG-ARDL paradigm, the equation for an individual group is as follows:

$$TNRR_{it} = \alpha_i + \sum_{k=1}^{p} .\, \beta_{\mathrm{ik}} TNRR_{it-k} + \sum_{j=0}^{q} .\, \gamma_{ij} x_{it-j} + \epsilon_{it}$$

Here:

- TNRRit : Dependent variable (e.g., resource utilization).
- Xit : Independent variable(s).
- αi : Group-specific intercept.
- βik and γij : Short-run coefficients that vary across groups.
- ϵit : Error term.

The model accounts for heterogeneity by permitting the coefficients βik and γij to fluctuate among groups, illustrating varying correlations between variables.

The enduring correlation among the variables can be established by converting the ARDL model into a cointegration equation:

$$TNRR_{it} = \boldsymbol{\lambda}_i + \frac{\sum_{k=1}^{p} .\, \beta_{\mathrm{ik}}}{\sum_{k=1}^{p} \gamma_{\mathrm{ik}}} x_{it} + +\epsilon_{it}$$

This illustrates the long-term impact of the independent variable x_{it} on the dependent variable $TNRR_{it}$. This illustrates the long-term impact of x_{it} on $TNRR_{it}$ where θi = $\frac{\sum_{k=1}^{p} .\beta_{\mathrm{ik}}}{\sum_{k=1}^{p} \gamma_{\mathrm{ik}}}$ is the long-run coefficient.

$$TNRR_{it} = \alpha_i + \sum_{k=1}^{p} .\, \beta_{\mathrm{ik}} TNRR_{it-k} + \sum_{j=0}^{q} .\, \gamma_{ij} x_{it-j} + \lambda_i (TNRR_{it-1} - \theta_i x_{it-1}) + \epsilon_{it}$$

In this context, $\Delta TNRR_{it}$ and Δx_{it} signify the initial differences between the variables, whereas λi represents the adjustment rate to the long-term equilibrium. θi denotes the long-run coefficient that measures the enduring impact of the independent variable x_{it} on the dependent variable $TNRR_{it}$. The MG-ARDL model is advantageous because it accommodates group variation, allowing each group to exhibit distinct short—and long-term dynamics. This adaptability renders it especially advantageous for evaluating panel data, as the relationships among variables are expected to fluctuate over several cross-sectional units. The MG-ARDL model yields a more precise representation of the overall panel interactions by averaging the group-specific estimates.

4. Empirical Results and discussion

4.1. Data summary

The variable exhibiting the greater mean is lnind (Industrial Production) at 3.3727, indicating its significant impact on Total Natural Resource Rent (TNRR) across data. The lowest mean is lnhdi (Human Development Index) at -0.3804, signifying more constrained variation or sluggish advancement in human development, which may affect the dynamics of TNRR in the sample.

Variable	Observations	Mean	Std. Dev.	Min	Max
Lntnrr	140	1.460533	0.752752	-0.14644	3.068178
Lnind	140	3.372694	0.244859	2.90079	3.861937
Lnhdi	140	-0.38041	0.159805	-0.76572	0.599386

Lnget	140	2.918463	1.049171	0.192479	4.60517
Ineg	140	1.352865	0.836557	-1.6415	2.655413
Intr	140	3.711656	0.330617	2.74955	4.23979
Lnco2	140	0.709499	0.848933	-2.83341	2.2354
Lnpg	140	-0.31127	0.907261	-3.503	0.698079

4.2. Multicollinearity test

Table 3 presents the variance inflation factor (VIF) analysis for the variables chosen in this study. The VIF for each variable is below 10, with an average VIF of 1.67. The reciprocal of VIF indicates a minimal tolerance factor; hence, these values are considered normal, and multicollinearity is absent among the variables.

Table 3. VIF test.

Variable	VIF	1/VIF
Lnhdi	2.37	0.422223
Lnpg	2.14	0.466463
Lnind	1.93	0.518369
Ineg	1.57	0.637682
Intr	1.43	0.701243
Lnget	1.21	0.829124
Lnco2	1.07	0.932611
Mean VIF	1.67	

4.3. Correlation matrices

Correlation evaluation ascertains the form and significance of correlations among variables. Table 4 indicates that lnTNRR exhibits a statistically significant positive connection with lnHDI and lnTR. In contrast, lnTNRR exhibits a negative correlation with lnGET and lnPG. The other variables demonstrate varied associations, illustrating the intricate relationships among industrial output, human development, green energy technologies, economic growth, and population pressures within the framework of sustainable resource management.

Table 4. Correlation metrics.

Variable	Lntnrr	Lnind	Lnhdi	Lnget	Ineg	Intr	Lnco2	Lnpg
Lntnrr	1.000							
Lnind	0.044	1.000						
Lnhdi	0.453	-0.082	1.000					
Lnget	-0.432	0.079	-0.263	1.000				
Ineg	-0.001	0.544	-0.292	0.143	1.000			
Intr	0.615	0.388	0.199	-0.268	0.164	1.000		
Lnco2	0.021	0.031	0.127	-0.124	0.017	-0.062	1.000	
Lnpg	-0.381	-0.262	-0.638	0.050	0.004	-0.159	-0.013	1.000

4.4. Unit Root Test

The PMG ARDL model requires variables to be stationary at level (I(0)) or stationary following the first differencing (I(1)) but not integrated of order 2 (I(2)). Table 5 displays the outcomes of unit root tests for the variables in the present investigation to assess the model's appropriateness.

The Im-Pesaran-Shin (IPS) test results demonstrate that the majority of variables, such as lntnrr, lnind, lnhdi, lnget, intr, and lnpg, are non-stationary at level (I(0)) but achieve stationarity following initial differencing (I(1)). Nonetheless, lnco2 and ineg are determined to be stationary at level (I(0)).

Moreover, the second-generation unit root test (CIPS) findings offer additional validation. The CIPS test indicates that lntnrr, lnind, lnget, intr, and lnpg are stationary at first difference (I(1)), whereas lnco2 and Lneg are stationary at level (I(0)). These findings conform to the criteria of the PMG ARDL approach, confirming its suitability for examining the relationships connecting the variables.

Table 5. Unit root test.

	Im-Pesaran-Shin unit-root test			**CIPS unit-root test**		
	At level	**At 1st Difference**	**Stationarity**	**At level**	**At 1st Difference**	**Stationarity**
Lntnrr	-1.2487	-7.4778***	I(1)	-2.591	-	I(0)
Lnind	0.0858	-5.2261***	I(1)	-1.592	-3.730	I(1)
Lnhdi	6.2919	-0.1583	Non-stationary	-2.075	-2.095	Non-stationary
Lnget	-0.8381	-5.8173***	I(1)	-2.236	-5.472	I(1)
Ineg	-2.0110**	-	I(0)	-4.118	-	I(0)
Intr	- 0.8062	-4.6012***	I(1)	-1.439	-3.643	I(1)
Lnco2	-4.1930***	-	I(0)	-3.793	-	I(0)
Lnpg	1.1762	-7.1205***	I(1)	-1.851	-4.150	I(1)

4.5 Cross-sectional dependency test

(Pesaran 2015) The CSD test was utilized to assess cross-sectional dependency in panel data analysis. Table 6 presents significant p-values at the 1% level for variables including lntnrr, lnind, lnhdi, and lnpg, indicating cross-sectional dependency. This dependency may arise from common factors such as economic convergence, technological advancements, and interdependence among BRICS nations. The statistically negligible p-values for lnget (green energy technology) and lnco2 (CO_2 emissions) imply a lack of cross-sectional dependency, suggesting that these variables may function independently within the examined groups. This independence indicates that initiatives in green energy innovation or emission management within one BRICS nation operate mainly independently and are not significantly influenced by the actions of other member nations.

Table 6: Cross-Section Dependency Test

Variable	**CD-Test**	**P-Value**	**Mean ρ**	**Mean Abs(ρ)**
Lntnrr	10.51	0.000	0.628	0.628
Lnind	7.15	0.000	0.427	0.460
Lnhdi	12.63	0.000	0.755	0.755
Lnget	-0.17	0.866	-0.010	0.212
Ineg	4.52	0.000	0.270	0.302
Intr	3.00	0.003	0.179	0.434
Lnco2	0.33	0.739	0.020	0.172
Lnpg	5.71	0.000	0.341	0.689

4.6 Cointegration test

Cointegration testing is essential for panel data to assess the long-term cointegration of the variables. Table 7 presents the Pedroni test, which analyzes this relationship and indicates strong cointegration based on the t and ADF statistics ((Pedroni 2004). The cointegration tests, such as Dickey-Fuller, Augmented Dickey-Fuller, Unadjusted Dickey-Fuller, and Unadjusted Modified Dickey-Fuller, further validate the presence of cointegration. The Westerlund cointegration test results reveal a long-term association of variables despite a tenuous connection, which will not impact model forecasting, as the ECT term of the MG-ARDL model will exhibit a dynamic adjustment process. This work seeks to determine the presence of an Error Correction Model (ECM) for each panel member, individually or collectively, to rectify the absence of cointegration (Asteriou et al., 2021).

Table 7. Cointegration Test

Pedroni Test for Cointegration	**Panel Test Statistics**	**Group Test Statistics**
Statistic	**Value**	**P-value**
Modified Phillips-Perron t	2.2393	0.0126
Phillips-Perron t	-4.1109	0.0000
Augmented Dickey-Fuller t	-1.9027	0.0285

Kao Test for Cointegration		
	Statistic	**P-value**
Modified Dickey-Fuller t	−3.6787∗∗∗	0.0001
Dickey-Fuller t	−3.1482	0.0008
Augmented Dickey-Fuller t	−2.1597∗	0.0154
Unadjusted modified Dickey-Fuller t	−6.3337∗∗∗	0.0000
Unadjusted Dickey-Fuller t	−3.8707∗	0.0001

Westerlund Test for Cointegration		
	Statistic	**p-value**
Variance ratiot	−1.2883∗∗∗	0.0988

4.7. Mean group ARDL estimation results

The MG-ARDL estimating method offers insights into the short- and long-term dynamics influencing total natural resource rents (tnrr). The study underscores the critical influences of industrial output, human development, renewable energy technology, economic expansion, trade openness, CO2 emissions, and population growth on tnrr.

Over the long run, industrial production exerts a favourable influence on TNRR, with a coefficient of 1.02, signifying a consistent rise in resource rents as output escalates. The short-term effect is more pronounced, exhibiting a coefficient of 3.04 and a p-value of 0.041. This underscores the prompt increase in resource rents propelled by elevated resource demand during early industrialization, particularly in developing countries dependent on manufacturing and energy-intensive industries. The Human Development Index (HDI) positively correlates with Starr, whereby a 1% increase leads to a 1.60% rise in the long term and a 2.15% increase in the short term. These findings indicate that advancements in human development promote improved oversight and usage of natural resources. Green Energy Technology (lnget) indicates a progressive transition towards sustainability, with a 1% increase correlating to a 0.10% reduction in TNNR in the long term and a 0.06% decrease in the short term. This trend signifies embracing environmentally friendly technologies and diminishing reliance on conventional resource rents. Economic Growth (ineg) facilitates resource-based revenue creation, resulting in a 0.29% increase in tnrr in the long term and a minor 0.07% increase in the medium term for each 1% growth. This relationship highlights the significance of economic Growth in improving resource consumption efficiency. Trade openness (intr) greatly enhances tnrr, with a 1% increase resulting in a 0.16% rise in the long term. The short-term effect is especially significant, demonstrating a statistically notable 1.06% rise, underscoring the critical role of trade in generating resource-based economic advantages. Carbon Dioxide Emissions (lnco2) have a complex relationship, wherein a 1% increase results in a marginal 0.02% gain in tnrr in the long term and a little 0.09% decrease in the short term. This result indicates a gradual shift towards more sustainable practices affecting resource utilization patterns. Population Growth (lnpg) significantly impacts resource rents, with a 1% increase leading to a 0.55% decline in the long term and a substantial 0.50% loss in the short term. These findings underscore the significance of population dynamics in resource management techniques.

The error correction term (ECT) is negative and statistically significant (-1.017), indicating a strong long-term equilibrium link among the variables. This signifies a swift adjustment process, with almost 102% of any imbalance rectified each year, demonstrating dynamic and efficient rebalancing mechanisms within the system.

The MG-ARDL results highlight the interrelation of economic, environmental, and demographic factors in influencing TNR, establishing a basis for evidence-based legislation to improve sustainable resource utilization.

Table 8.1 MG-ARDL Estimation of the BRICS-5: Long-Run Coefficients (LR)

Variable	Coefficient	Standard Error
Lnind	1.018508	2.555678
Lnhdi	1.600978	1.90863
Lnget	-0.1018802	0.125176

Ineg	0.293005	0.277133
Intr	0.1604471	0.575131
Lnco2	0.018954	0.065054
Lnpg	-0.5481578	0.281463

Notes: *, **, * indicate the significance at the 10%, 5% and 1% confidence levels, respectively.**

Table 8.2 MG-ARDL Estimation of the BRICS-5: Short-Run Coefficients (SR)

Variable	**Coefficient**	**Standard Error**
Ect	**-1.017139**	**0.207763**
Lnind (D1)	**3.038043**	**1.485437**
Lnhdi (D1)	**2.149465**	**2.458321**
Lnget (D1)	**-0.0596892**	**0.041927**
Ineg (D1)	**0.0670007**	**0.105020**
Intr (D1)	**1.064111**	**0.422829**
Lnco2 (D1)	**-0.094727**	**0.095331**
Lnpg (D1)	**-0.4992458**	**0.240314**

Notes: *, **, * indicate the significance at the 10%, 5% and 1% confidence levels, respectively.**

4.8. Hausman test

The study uses(Hausman 1978) test to differentiate between the mean group and the PMG estimator. Table 9 indicates that the p-value of the statistic was statistically significant. The p-value is below 0.05, signifying the rejection of the null hypothesis, which suggests that the coefficient variations between the MG and PMG estimations are statistically significant. Consequently, the findings indicate that the PMG estimator lacks consistency under the alternative hypothesis. Consequently, the null hypothesis is accepted, indicating that the coefficient difference is not systematic. Husman's test indicates that the pooled mean group outperforms the mean group, therefore validating the acceptance of pooled mean group results.

Table 9. Hausman test.

Variable	**(b) MG**	**(B) PMG**	**Difference (b - B)**	**S.E.**
lnind L1	1.018508	-0.8264603	1.844968	2.542554
lnhdi L1	1.600978	1.485364	0.1156141	1.866007
lnget L1	-0.1018802	-0.1137024	0.0118222	0.1240583
ineg L1	0.293005	0.3329929	-0.0399879	0.2764135
intr L1	0.1604471	1.348852	-1.188405	0.5658007
lnco2 L1	0.018954	0.0606424	-0.0416884	0.0618357
lnpg L1	-0.5481578	-0.1162076	-0.4319502	0.2805068

Hausman Test
chi2(4) 26.34
Prob > chi2 : 0.0004

5. Discussion

The MG-ARDL estimation method has illuminated short- and long-term total natural resource rent dynamics. This examination shows intricate economic, ecological, and sociological links. These links significantly affect resource policy and management judgments in BRICS countries (Brazil, Russia, India, China, and South Africa), which face similar economic expansion, sustainable development, and resource utilization concerns. The fluctuations of each important variable are examined in this part to emphasize its significance and provide a more complete picture based on the study's findings and contemporary literature.

Industrial production and total natural resource rents (TNRR) are complexly related to financial, ecological, and developmental problems in Brazil, Russia, India, China, and South Africa. Industrial output boosts TNRR over time by raising demand for renewable resources, especially in nations like Russia and Brazil, where fossil fuel and mineral exploitation are key to GDP action (Ran et al. 2023) . Fast industrialization in China and India has raised demand for raw resources, energy, and infrastructure, raising TNRR (Shi et al. 2024). In early industrial development, such as in India and South Africa, manufacturing productivity and resource rents develop swiftly, increasing the need for resources in the immediate future (Khattak, Khan, and Hussain 2024). According to (Erdoğan, Yıldırım, and Gedikli 2020)), in their comparison of Brazil and Russia, trade openness and FDI significantly impact exported resources and rental production. The environment and sustainability programs are changing quickly, with China and India embracing greener technology that may lower resource rents. Trade and urbanization drive consumer appetite for raw materials, which maintains a beneficial connection between industry output and resource rents. However, new environmental laws and a worldwide move toward cleaner forms of energy could dampen projected developments. Industrial development drives resource rents, but economic, technological, and policy considerations will affect TNRR in BRICS countries (Samour et al. 2023) .

Recent BRICS studies (Rahim et al. 2021) shows that successful natural resource usage improves human growth. Governance, institutional quality, and infrastructure improve with HDI, improving the management of resources and usage. According to (Y. W. Li et al. 2023) HDI improvements also lead to higher technological uptake and resource utilization in BRICS nations, especially in abundant resources in Brazil and Russia, where improved infrastructure for society mitigates resource extraction's environmental impact. As HDI rises, improved education and health outcomes educate citizens and encourage sustainable utilization of resources, which boosts TNRR over time. HDI increases boost incomes that can be spent, stimulating patronage of higher-value, sustainably derived resources, ensuring that resource rents support economic growth rather than short-term plunder.

Green energy technologies are transforming BRICS countries, especially China and India. As highlighted by (Khattak, Khan, and Hussain 2024),), green power decreases fossil fuel exploitation and natural resource rents. Sustainability issues and global agreements like the Paris Agreement encourage governments to develop greener technologies. Making investments in clean energy infrastructures balance with oil and gas rent declines in the short term, generating new sectors and boosting the economy. Long-term impacts reveal that nations like China and Brazil, actively pursuing energy efficiency plans, have fewer non-renewable resources in their national revenue (Ganda 2024). This reduces fossil fuel TNRR, which has become crucial for sustainable economic growth. As renewable energies become increasingly incorporated into the power mix, traditional rents for resources will decline, changing global resource economics (Yadav et al. 2024).

The industrial revolution and infrastructural development stimulate resource demand, which explains the positive association between economic growth and TNRR in BRICS nations (Rahim et al. 2021). Resource management rents rise as India and China grow economically and need more energy, natural resources, and inputs for industry. (Gyamfi, Agozie, and Bekun 2022), found a strong correlation between economic development and the mining of resources. Long-term TNRR rises are more significant than short-term increases because continuous economic expansion improves resource utilization and rents through improved management and technological advances. Russia's economic growth is driven by crude oil and natural gas consumption, which boosts TNRR. Over time, countries like Brazil have focused more on diversity, putting money into skills and knowledge-driven sectors to minimize reliance on conventional resource rents and boost financial stability.

Trade openness affects Total Natural Resource Rents (TNRR) in BRICS countries, especially resource-exporting Brazil and Russia. Integration into the global economy has helped these nations exploit their natural resources.(Rahim et al. 2021) note that global demand, especially from China, has increased TNRR in these countries. Trade liberalization boosts resource extraction and exports by encouraging foreign investment. Trade openness increases resource rents quickly, but the long-term advantages may shrink when nations like South Africa and India migrate toward industrial and high-value-added industries(Ul-Haq et al. 2024).

There is an intricate link between CO2 emissions and TNRR. In the short term, industrial activity and economic growth increase pollutants and TNRR. However, (Bi and Khan 2024) and (Cai et al. 2023) remark that patterns over time vary as India and China limit coal mining to minimize emissions (Xu and Lin 2019). This shift into green technologies shows how legislation can reduce environmental damage and ensure resource sustainability.

In fast-rising BRICS countries like India and South Africa, population expansion lowers TNRR. Increased demands for resources often result in overuse and depleted resources. (Xuan, Jiang, and Fang 2023) say irresponsible extractive practices worsen these issues. Government officials must prioritize resource efficacy, environmentally friendly consumption, and efficient management techniques to balance growing populations and protection (Xuan, Jiang, and Fang 2023).

6. Conclusion

From 1996 to 2023, BRICS data examines the relationship between industrial production, human development, green energy tech, economic growth, and sustainable resource management. The Pesaran cross-sectional dependence test showed high variable dependency. Given cross-sectional dependency, the IPS and CIPS procedures were used to confirm the variables' stability, suggesting they were stationary at the initial level or initial difference. The study examined the long-term correlation between the dependent and independent variables using Kao, Pedroni, and Westerlund's cointegration methods. All three methods show long-term cointegration between variables. The PMG-

ARDL approach was used to evaluate independent factors' short- and long-term effects on dependent variables according to the data's unique characteristics and study goals. The MG-ARDL analysis shows how industrial productivity, human development, and green energy tech in BRICS nations affect sustainable resource management.

Industrial output, human development, and sustainable resource management in the BRICS (Brazil, Russia, India, China, and South Africa) exhibit the difficulties of modern economic growth. Industrial output still drives total natural resource rents (TNRR), but human development and green technology influence its long-term sustainability. These economies continue to become more industrial, driving the need for natural resources, especially in Russia and Brazil, where oil, gas and mining are vital to the economy. Compared to China and India, rapid industrialization has increased the need for ingredients, energy, and infrastructure, boosting TNRR .As industrial output rises, balancing economic expansion with the conservation of resources becomes harder. This is where social advances matter. As BRICS countries improve health, education, and governance , they improve resource management. Human development improves the effectiveness of resources, sustainability gathering, and higher-value sectors by educating citizens and improving institutions. In Brazil and Russia, social and legislative changes are improving the management of resources, which increases TNRR's stability over time and lowers dependence excessively on traditional resource extraction .

China and India's push to green renewable energy sources signifies a significant change in BRICS source of strength priorities. Green power cuts the consumption of fossil fuels and alters the economy, offering new growth potential. This shift may lower energy-related rents in the near term, but it will support economic expansion in the long term. This changing dynamic supports environmental goals like the Paris Agreement and the worldwide trend toward cleaner energy. BRICS countries are decreasing resource rent dependence by committing to cleaning technology, which will change how they manage resources.

The link between industrial output and resource rental is amplified by economic development, trade openness, and FDI. TNRR rises rapidly in Brazil and Russia due to rising trade and exported resources . The long-term effects are mitigated by diversifying into higher-value sectors and services, as shown in Brazil, which is becoming more durable and less dependent on basic resource exports.

Population expansion, which increases the demand for natural resources, makes sustainable resource management difficult in BRICS countries, particularly India and South Africa. Population growth in these nations strains natural resources, causing depletion and unsustainable extraction. Resource demand and inefficient management can worsen resource depletion. To prevent population growth from outpacing resource use, BRICS nations must promote resource efficiency, sustainable consumption, and technological innovation.

BRICS countries may achieve sustainable resource management by combining industrial production, human development, and green technology. As industrialization increases the demand for natural resources, TNRR's long-term survival depends on these nations' capacity to embrace cleaner, more efficient technologies and implement sustainable economic development strategies. Human development components like administration and transportation will boost resource management and lessen industrialization's adverse ecological effects. By adopting green energy solutions and diversifying their economies, BRICS countries can assure long-term prosperity and address global environmental problems.

7. Policy recommendation

Industries development, development of people, and environmentally friendly innovations must be integrated in the BRICS countries (Brazil, Russia, India, China, and South Africa) to guarantee sustainable resource management. Policy suggestions to maximize the utilization of natural resources and achieve socioeconomic and ecological sustainability:

Increase Renewable Energies and Carbon-neutral Technology Transitions

BRICS nations, particularly China and India, should invest in wind, hydro, and solar power technology and promote batteries for energy innovations. Carbon incentives for fuel should be phased out and directed to clean energy sources. Sustainable technology incentives, such as tax rebates for corporations investing in environmental responsibility, would accelerate the shift to greener power sources, supporting global environmental targets like the Paris Agreement.

Optimize Resource Utilization with Sustainable Circular Economy

Concepts BRICS states should promote recycling, reclamation, and adapting to optimize the utilization of resources. Institutions must encourage closed-loop manufacturing processes and enforce product lifetime, ability to be repaired, and capacity for recycling rules. Rigorous waste prevention and e-waste disposal legislation would reduce the utilization of resources and boost green industry employment creation, tackling the depletion of resources and pollution.

Improve Efficiency in Resource Government and Institutions

Governing frameworks must evolve with human growth. The BRICS ought to make investments in strong institutional structures that assure accountability, openness, and resource efficiency. Implement extensive external factors, resource preservation, and environmentally friendly legislation with vigorous enforcement. Public involvement in extracting resources and development decisions promotes managing resources. Boost Sustainability Training and strengthening capacities.

Environmental training and higher learning in environmental sustainability sectors like renewable energy and resource management must be funded by BRICS nations. Countries should collaborate with worldwide organizations, colleges and universities, and business organizations to share expertise and build capability. A competent labour will be needed to apply environmentally friendly procedures across businesses and use the environment more efficiently. Broaden economies to reduce extracting resources dependence. Manufacturing drives the consumption of resources, but BRICS countries have to branch out into higher-value companies like technological devices and biotechnological fields and clean the manufacturing sector. Investing in research development and creativity will change the emphasis from base material exports to goods with value, making the economy more resilient and sustainable. Encourage Global Cooperation and Sustainable Trade. Collaboration and cooperation should help BRICS countries use resources sustainably. Trade policies should prioritize sustainable technology imports and renewable power exports while minimizing extractive exports' adverse environmental effects. Trade agreements must include environmental sustainability clauses to protect future generations of humanity from resource extraction. Build Strong Population Planning and Urban Development Strategies Rapid demographic growth in India and South Africa strains the availability of resources. Administrations should fund public transit, energy-efficient construction, and garbage elimination to promote environmentally friendly urbanization. Population planning, medical services, and education will coordinate the use of resources and environmentally friendly practices.

Encourage Private Enterprise Sustainable Initiatives Healthy socioeconomic transformation relies heavily on private industry. Authorities should set unambiguous standards for sustainability to encourage green business practices. Private sector priorities will align with long-term sustainability goals through collaboration between the public and private sectors to fund developments in green technologies and sustainable companies. These policy proposals can help BRICS nations balance industrial expansion and preservation of the environment through sustainable resource management. Environmental technology, advancement of humanity, and good governance will position BRICS countries as champions in the worldwide transformation to sustainable economic structures. They can boost national prosperity and the global sustainability aim by means of these initiatives.

8. Limitations and future research

Barriers to examining environmentally friendly resource utilization within BRICS nations encompass data discrepancies, obstacles to adopting renewable energies, and significant dependence on energy-intensive sectors. Innovative methodologies, including machine learning and massive amounts of data for tracking resources and forecasting, may rectify data deficiencies and enhance decision-making. Studies should investigate adaptation strategies that flexibly react to technological progress, geographical inequalities, and sociopolitical changes. Furthermore, analyzing the amalgamation of community-driven projects and autonomous government may provide novel avenues for equitable handling of resources. Examining cross-sector partnerships, including public-private relationships in environmentally friendly projects, and promoting region resource-sharing arrangements might enhance sustainability performance. Analyzing the influence of developing financial structures, such as green financing and carbon markets, in conjunction with evaluating policy efficacy, can facilitate the development of novel, practical approaches.

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