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Green Recovery, Low-Carbon Economy and Sustainable Development in BRICS Economies

Zielona odbudowa, gospodarka niskoemisyjna i zrównoważony rozwój w gospodarkach BRICS

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Abstract
Recovery packages are increasingly presented as a route to *build back better*, yet the extent to which green-labelled spending translates into measurable sustainability gains remains uncertain. This study examines how green recovery initiatives and low-carbon economic strategies shape sustainable development outcomes in BRICS, asking what effect green recovery has on sustainable development, how the transition to a low-carbon economy contributes to sustainability performance, and whether low-carbon development mediates the green recovery–sustainable development relationship. Using a quantitative panel design and harmonised secondary data for Brazil, China, India and South Africa over 2000–2023, sustainable development is proxied by adjusted net savings (% of GNI), green recovery by renewable energy investment, and the low-carbon economy by renewable energy consumption (% of total final energy). Panel-corrected standard errors are applied to full-sample and regime-specific estimates (pre-COVID: 2000–2019; COVID: 2020–2023), complemented by country-specific PCSE models, while mediation is assessed using fixed effects with 1,000 bootstrap replications. The results indicate that green recovery exhibits weak and regime-dependent links with sustainable development: it is modestly positive pre-COVID but becomes significantly negative during COVID and remains statistically insignificant in the full sample. In contrast, the low-carbon transition is positively and robustly associated with sustainable development, with a substantially stronger effect during COVID. The estimated indirect effect of green recovery via the low-carbon channel is positive but statistically insignificant, suggesting that green recovery has not yet produced consistent energy-mix shifts capable of transmitting sustainability gains. The study contributes by jointly estimating direct, low-carbon, and mediation pathways under crisis and non-crisis regimes, offering evidence to strengthen SDG 7, SDG 11 and SDG 13 alignment in major emerging economies.

Key words: BRICS, green recovery, low-carbon economy, renewable energy, sustainable development

Streszczenie
Pakiety naprawcze są coraz częściej przedstawiane jako droga do *lepszej odbudowy*, jednak stopień, w jakim wydatki oznaczone etykietą zielone przekładają się na wymierne korzyści w zakresie zrównoważonego rozwoju, pozostaje niepewny. Niniejsze badanie analizuje, jak inicjatywy zielonej odbudowy i niskoemisyjne strategie gospodarcze kształtują wyniki zrównoważonego rozwoju w krajach BRICS, stawiając pytania o wpływ zielonej odbudowy na zrównoważony rozwój, w jaki sposób przejście na gospodarkę niskoemisyjną przyczynia się do osiągnięcia zrównoważonego rozwoju oraz czy rozwój niskoemisyjny pośredniczy w relacji między zieloną odbudową a zrównoważonym rozwojem. Wykorzystując ilościowy model panelowy i zharmonizowane dane wtórne dla Brazylii, Chin, Indii i RPA w latach 2000–2023, zrównoważony rozwój jest przybliżony skorygowanymi oszczędnościami netto (% DNB), zieloną odbudową poprzez inwestycje w energię odnawialną, a gospodarką niskoemisyjną poprzez zużycie energii odnawialnej (% całkowitej energii finalnej). Błędy standardowe skorygowane o panel

zastosowano do szacunków pełnej próby i specyficznych dla danego systemu (przed COVID: 2000–2019; COVID: 2020–2023), uzupełnionych o modele PCSE specyficzne dla danego kraju, podczas gdy mediację oceniono przy użyciu efektów stałych z 1000 replikacji bootstrapowych. Wyniki wskazują, że zielone ożywienie gospodarcze wykazuje słabe i zależne od systemu powiązania ze zrównoważonym rozwojem: jest ono umiarkowanie dodatnie przed COVID, ale staje się istotnie ujemne w czasie COVID i pozostaje statystycznie nieistotne w całej próbie. Z kolei przejście na gospodarkę niskoemisyjną jest pozytywnie i silnie powiązane ze zrównoważonym rozwojem, ze znacznie silniejszym efektem w czasie COVID. Szacowany pośredni wpływ zielonego ożywienia gospodarczego poprzez kanał niskoemisyjny jest dodatni, ale statystycznie nieistotny, co sugeruje, że zielone ożywienie gospodarcze nie doprowadziło jeszcze do spójnych zmian w miksie energetycznym, które mogłyby przełożyć się na korzyści w zakresie zrównoważonego rozwoju. Badanie przyczynia się do łącznej oceny ścieżek bezpośrednich, niskoemisyjnych i mediacyjnych w reżimach kryzysowych i poza kryzysem, dostarczając dowodów wzmacniających zgodność z celami zrównoważonego rozwoju nr 7, 11 i 13 w największych gospodarkach wschodzących.

Słowa kluczowe: BRICS, zielona odbudowa, gospodarka niskoemisyjna, energia odnawialna, zrównoważony rozwój

1. Introduction

Economic recovery strategies are increasingly judged not only by how quickly they restore growth, but by whether they reorient development pathways towards environmental sustainability and long-run resilience. Conventional stimulus packages have been criticised for reinforcing carbon-intensive production structures, whereas green recovery policies are increasingly viewed as capable of delivering superior economic and environmental outcomes when designed around clean investment, technological modernisation and institutional reform (Imandojemu et al., 2026a; Osabohien et al., 2026; Zachariadis et al., 2023; Aamin et al., 2025; Damowicz, 2022).

The policy relevance of this agenda is particularly acute for emerging economies, where recovery programmes must manage immediate development pressures while limiting environmental degradation and climate risk (Du et al., 2025; Batrancea et al., 2021; Osabohien et al., 2025; Werikhe, 2022). The BRICS economies occupy a pivotal position in this debate because they combine large-scale industrial growth with substantial emissions responsibilities, contributing more than 40 per cent of global CO_2 emissions, while simultaneously facing rising demands for energy access, inclusive growth and environmental protection (Mujumdar and Shadrin, 2021; Peng et al., 2023). This combination makes BRICS a consequential test case for whether green recovery can serve as a credible pathway to sustainable development aligned with SDG 7, SDG 11 and SDG 13 (Imandojemu et al., 2026b; Werikhe, 2022; Filipovic et al., 2022).

The literature indicates that green recovery can enhance sustainability performance, but the expected benefits vary significantly across contexts and policy regimes. Global modelling suggests that a low-carbon power transition could improve the SDG index by about 11 per cent by 2100, yet the gains shrink to 4–9 per cent under less ambitious climate pathways, with distributional consequences that may disadvantage developing regions on resource-related SDG components (Peng et al., 2023). These patterns underline the importance of policy ambition, institutional quality and structural economic constraints in shaping outcomes (Abd Majid, et al., 2025; Mohamed et al., 2025; Qi et al., 2024; Udeagha and Ngepah, 2023). Evidence further shows that green recovery frameworks can serve as levers for emissions reduction when they prioritise clean investment and measurable sustainability targets. A globally coordinated recovery package equivalent to 1 per cent of world GDP could reduce CO_2 emissions by 10.5–15.5 per cent by 2030, implying that recovery spending can accelerate decarbonisation when it is directed towards low-carbon technologies and resilient infrastructure (Dafnomilis et al., 2022). However, the implementation of green recovery remains constrained by fiscal limitations and governance challenges in many emerging economies (Jaaffar et al., 2024; Luan et al., 2025; Abdullah et al., 2023; Biao Liu and Lyu, 2024).

Within BRICS, green recovery is closely tied to green fiscal stimulus, renewable energy investment and broader financing architectures that support clean-technology deployment. Several studies emphasise that green finance, fintech and energy innovation can improve environmental outcomes, yet these gains are moderated by growth pressures, resource dependence and uneven policy execution (Udeagha and Ngepah, 2023; Ofori et al., 2023). Bai et al. (2022) argue that expanding green energy finance is critical for offsetting rising production costs while sustaining economic recovery, a concern that is amplified in energy-intensive industrial systems. Evidence also indicates that the effectiveness of green recovery instruments may differ across policy domains; green monetary policy has been found to exert a stronger influence on clean energy development than fiscal interventions, suggesting that the transmission mechanisms of recovery policies warrant closer scrutiny (Yao et al., 2023).

Empirical studies connect green recovery instruments to measurable environmental improvements, with findings that modest increases in green finance and renewable investment can reduce pollution, and that renewable energy consumption and green finance jointly improve environmental quality (Dong et al., 2023; Hailiang et al., 2023). Long-run evidence also links green investment, environmental technology and R&D to green growth, indicating that recovery policies may generate persistent sustainability benefits when they stimulate innovation systems (Sohail, 2023). These pathways align conceptually with SDG 7 through accelerated renewable energy adoption, with SDG 11 through investments in resilient, low-pollution infrastructure, and with SDG 13 through emissions mitigation and climate-risk reduction (Moallemi et al., 2020; Barbier, 2020).

Despite the expanding evidence base, important debates remain concerning policy inconsistency, weak implementation and mixed sustainability effects. Fiscal constraints limit the scale and continuity of green recovery measures, as evidenced in Indonesia and Vietnam, and similar implementation challenges are observed across BRICS where policy effectiveness varies significantly by country and instrument (Abdullah et al., 2023; Qi et al., 2024). Governance weaknesses also shape outcomes; corruption and mineral-trade dependence can undermine green growth trajectories and weaken the credibility of green recovery commitments (Biao Liu and Lyu, 2024). Further, green interventions may generate uneven short-term outcomes, with heterogeneous effects of green investment across countries and nonlinear relationships between policy stringency and renewable investment, complicating inference about *what works* across diverse institutional environments (Sohail, 2023; Alsagr, 2023). Methodological limitations persist as well, including limited comparability across empirical strategies and insufficient attention to policy implementation mechanisms (Yadav et al., 2024; Yao et al., 2023). The literature also remains fragmented in how it treats the relationship between green recovery and the low-carbon transition, even though the latter is widely recognised as the structural mechanism through which stimulus-led investments can produce durable sustainability gains (Slabe-Erker et al., 2023; Catalano and Forni, 2021).

Against this background, this study examines how green recovery initiatives and low-carbon economic strategies influence sustainable development outcomes in BRICS countries. The broad objective is to assess the sustainability implications of green recovery and low-carbon transition in BRICS, with specific objectives to examine the impact of green recovery initiatives on sustainable development outcomes, analyse how the transition to a low-carbon economy influences sustainable development, and investigate whether low-carbon development mediates the relationship between green recovery efforts and sustainable development performance. These objectives are examined through three research questions: what effect do green recovery initiatives have on sustainable development outcomes in BRICS countries; how does the transition to a low-carbon economy contribute to sustainable development across BRICS; and does low-carbon economic development mediate the relationship between green recovery initiatives and sustainable development. This framing addresses a key gap in existing scholarship, which offers growing evidence on green finance, renewable energy and environmental quality, yet provides limited integrative analysis of green recovery, low-carbon transition and sustainable development within a unified empirical framework for BRICS, particularly with attention to mediation mechanisms and SDG-aligned pathways (Qi et al., 2024; Slabe-Erker et al., 2023; Praveen et al., 2025).

The study contributes to theory and practice by clarifying the pathway through which recovery-era green investments may translate into sustainable development performance in major emerging economies. By explicitly modelling low-carbon transition as an intermediate mechanism, the study extends pathway-based evidence that links green investment to innovation and environmental outcomes, while addressing calls for stronger integration of fiscal, investment and structural transition channels in sustainability research (Zhang et al., 2024; Wang et al., 2023). From a policy perspective, the analysis offers evidence relevant to the design of green recovery packages that can generate simultaneous progress on SDG 7, SDG 11 and SDG 13 by strengthening clean energy systems, supporting resilient urban and industrial infrastructure and sustaining emissions reductions through long-run structural change (Ofori et al., 2023; Mirasgedis et al., 2024; Amin et al., 2025).

2. Literature review

2.1. Conceptual foundations of green recovery, low-carbon economy and sustainable development

Green recovery is increasingly framed as a strategic approach to economic reconstruction that aligns post-crisis recovery measures with long-term environmental sustainability objectives. It is broadly understood as a development pathway that integrates renewable energy expansion, carbon reduction strategies and structural reforms to enhance socio-economic resilience, particularly in emerging economies where the stakes of sustainable transformation are high. Empirical studies consistently highlight the need for coordinated policy frameworks that reduce emissions while sustaining economic growth.

Adamowicz (2022) argues that green recovery rests on the principle of integrating environmental and economic priorities through technological modernisation and clean energy investments, while Batrancea et al. (2021) show that such transitions operate through interdependent environmental and economic channels. Evidence from comparative work further demonstrates that traditional stimulus packages tend to reinforce carbon-intensive growth trajectories, whereas green recovery schemes deliver superior economic and environmental outcomes, with Zachariadis et al. (2023) describing conventional stimulus as both environmentally unsustainable and economically inferior. The strategic role of the Sustainable Development Goals (SDGs) is highlighted by Werikhe (2022), who emphasises their function as a guiding compass for designing recovery frameworks in developing regions. Studies focusing on emerging economies underline the contextual limits to the adoption of green recovery policies.

Abdullah et al. (2023), for instance, observe that fiscal constraints in Indonesia and Vietnam restrict the scope of green-aligned recovery spending, while Qi et al. (2024) document large variations in the effectiveness of green policy instruments across BRICS countries. These findings point to the challenges of balancing economic stabilisation with the structural investments required to accelerate progress towards SDG 7 on affordable and clean energy, SDG 11 on sustainable cities and SDG 13 on climate action. Additional constraints arise from governance and institutional weaknesses: Biao Liu and Lyu (2024) show that corruption and mineral-trade dependencies can undermine green growth, while Barbier (2022) stresses the need for cost-effective policy innovations that jointly advance economic and environmental goals.

Recent evidence suggests that sustainable development extends beyond environmental metrics to include household welfare and behavioural dimensions. Hong et al. (2024) show that time allocation significantly affects family well-being, highlighting the socio-economic foundations of sustainability. Advancements in spatial and digital analytics also contribute to sustainability planning. Gao et al. (2024) demonstrate that combining social media data with nighttime light remote sensing improves understanding of tourism infrastructure demand, reinforcing the role of digital data ecosystems in sustainable development. Entrepreneurial ecosystems further shape sustainability outcomes. Liu (2026) finds that e-commerce cluster environments enhance entrepreneurial performance, indicating that digital economic structures can support inclusive and sustainable growth pathways.

The low-carbon economic transition represents a deeper structural shift in which economies progressively decouple growth from carbon emissions through changes in energy systems, technological upgrading and institutional adaptation. This transition is inherently multidimensional and requires coordinated technological, economic and societal transformations. Zhou et al. (2023) identify four central research themes that characterise this evolution: low-carbon transition pathways, technological diffusion, infrastructure network planning and mechanisms that shape transition dynamics. The sociotechnical literature reinforces the importance of coevolution between technologies, institutions and behavioural norms, with Geels et al. (2017) emphasising that low-carbon transitions unfold through interactions among actors, technologies and regulatory systems. Empirical work underscores both opportunities and risks. Semieniuk et al. (2021) outline the financial risks associated with stranded assets and funding reallocation, while While and Eadson (2022) highlight potential socio-economic disruptions during the shift away from carbon-intensive sectors. Fragkos et al. (2021) demonstrate that long-term mitigation consistent with the Paris Agreement is feasible through renewable energy expansion, efficiency improvements and electrification of energy services, directly reinforcing SDG 13. Gbadeyan et al. (2024) further show that decarbonisation can proceed without compromising global economic growth, although Slameršak et al. (2022) caution that the transition itself may generate substantial emissions due to the energy required for infrastructure development and technology deployment. These insights collectively reveal that the low-carbon transition is technologically feasible but socially and institutionally complex, and its trajectory remains highly context-dependent.

The convergence of green recovery and low-carbon development provides a coherent pathway through which emerging economies can advance SDG-aligned development trajectories. Empirical modelling by Dafnomilis et al. (2022) shows that a globally coordinated green recovery strategy equivalent to 1 per cent of world GDP could reduce CO_2 emissions by 10.5–15.5 per cent by 2030, demonstrating that recovery spending can serve as a lever for long-term decarbonisation. Filipovic et al. (2022) argue that such transitions are most effective when guided by integrated indicators of environmental, social and economic sustainability, reinforcing the multidimensional nature of the SDGs. Studies emphasise that aligning recovery measures with low-carbon goals requires simultaneous action across multiple domains, including reducing fossil-fuel dependence, scaling renewable energy, encouraging sustainable consumption patterns and investing in resilient infrastructure (Moallemi et al., 2020; Barbier, 2020). The alignment of green recovery with low-carbon transitions thus enables economies to pursue structural transformation while accelerating progress toward SDG 7 through enhanced clean-energy access, SDG 11 through sustainable and resilient urban development, and SDG 13 through long-term climate mitigation. The literature affirms that the success of this alignment depends on sustained policy commitment, institutional capacity and the engagement of government, private sector and civil society in shaping a coordinated sustainability transition.

2.2. Green recovery and sustainable development outcomes in BRICS

Global evidence demonstrates that green recovery initiatives can enhance sustainability performance, yet their effectiveness remains uneven across countries and policy regimes. A central insight from the global literature is that green recovery can significantly improve sustainable development outcomes when supported by coherent fiscal, financial and technological interventions. Peng et al. (2023) show that a low-carbon power transition could raise the global SDG index by approximately 11 per cent by 2100, although gains fall to 4–9 per cent under conservative climate scenarios. This variation reflects the importance of policy ambition, institutional capacity and structural economic conditions. Empirical studies further indicate that green finance, fintech innovation and clean-energy development exert significant positive effects on environmental outcomes (Udeagha and Ngepah, 2023; Ofori et al., 2023), while green monetary policy instruments often outperform fiscal stimulus in driving renewable energy expansion (Yao et al., 2023). Nonetheless, much of the global evidence remains concentrated in emerging economies, especially BRICS, which limits the generalisability of these findings and underscores the need for broader comparative assessments.

Financial and institutional mechanisms play a critical role in shaping green recovery outcomes. Liu et al. (2025) show that analyst networks influence corporate shadow banking activities, suggesting that financial interconnectedness can affect the allocation of capital toward sustainable investments. Fiscal governance structures are equally important. Jin et al. (2025) provide cross-country evidence that optimal expenditure decentralisation enhances sustainable development, indicating that well-designed fiscal systems improve the effectiveness of green recovery strategies.

Green innovation systems also operate through spatial networks. Hu et al. (2026) show that urban green technology transfer networks promote green finance development, highlighting the importance of regional innovation ecosystems in supporting sustainability transitions.

Within BRICS, green fiscal stimulus and renewable energy investment have emerged as pivotal mechanisms for strengthening environmental resilience, though their impact is shaped by structural and resource constraints. Bai et al. (2022) highlight the urgent need for increased green energy financing to offset rising production costs and sustain economic recovery pathways. Udeagha and Ngepah (2023) emphasise that although green technologies can enhance environmental quality, entrenched dependence on natural resource extraction and fossil fuels often counteracts these gains. Yao et al. (2023) provide additional evidence that monetary-based green interventions have stronger effects on clean energy uptake than fiscal instruments. However, BRICS economies remain responsible for over 40 per cent of global CO_2 emissions (Mujumdar and Shadrin, 2021), revealing a structural tension between growth imperatives and environmental commitments. This juxtaposition suggests that renewable energy investment and green fiscal stimulus must be embedded within broader decarbonisation strategies if they are to meaningfully improve long-term sustainability outcomes.

Empirical patterns increasingly confirm strong linkages between green recovery interventions and progress towards SDG 7, SDG 11 and SDG 13. Dong et al. (2023) find that modest increases in green financing and renewable energy investment on the order of 0.05 per cent, can significantly reduce environmental pollution. Hailiang et al. (2023) provide further evidence that green finance and renewable energy consumption jointly improve environmental quality, while Sohail (2023) demonstrates that green investment, environmental technology and R&D have persistent long-run effects on green growth. Nasreen et al. (2025) identify a consistent pattern across BRICS in which renewable energy investment reduces carbon emissions, enhances GDP growth and increases renewable electricity generation. Collectively, these findings illustrate that green recovery and low-carbon strategies form an integrated pathway through which BRICS economies can accelerate clean-energy access (SDG 7), strengthen sustainable and resilient urban systems (SDG 11) and advance climate mitigation (SDG 13).

Despite these advances, significant gaps, limitations and debates persist within the green recovery literature. Policy inconsistency, weak implementation capacity and mixed sustainability outcomes pose major challenges. Udeagha and Ngepah (2023) show that while green technologies may improve environmental quality, economic expansion and fiscal decentralisation can simultaneously degrade ecosystems. Sohail (2023) documents heterogeneous short-term effects of green investment across countries, highlighting the difficulty of designing universally effective policy instruments. Environmental policy stringency also exhibits nonlinear and context-dependent effects on renewable energy investment, indicating that policy effectiveness is far from uniform (Alsagr, 2023). More broadly, existing BRICS-focused studies exhibit uneven country coverage, limited methodological comparability and insufficient attention to policy implementation pathways (Yadav et al., 2024; Yao et al., 2023). Research on the interaction between emerging technologies such as fintech and green recovery remains sparse (Udeagha and Ngepah, 2023). These gaps highlight the need for more granular, country-specific and integrative studies capable of capturing the complex dynamics through which green recovery influences sustainability outcomes in BRICS economies.

2.3. Low-carbon economy and sustainable development in BRICS

Low-carbon economic transition has emerged as a central pillar of sustainable development strategies in BRICS countries, though progress remains uneven and shaped by structural, technological and policy constraints. Empirical evidence demonstrates that BRICS economies have articulated increasingly ambitious carbon neutrality commitments – Brazil and South Africa by 2050, China and Russia by 2060 and India by 2070, and have expanded renewable energy deployment, with the regional renewable electricity share rising from 5.56 per cent to 13.20 per cent between 2016 and 2022 (Emishyan and Guliev, 2025). Long-term modelling further suggests substantial mitigation potential. Ma et al. (2024) project that BRICS could reduce carbon emissions by approximately 6,139 MTC by the end of the century under a low-temperature scenario, driven by higher uptake of renewable and nuclear energy. Despite these commitments, the credibility of existing pathways remains mixed; Cai et al. (2021) categorise BRICS countries' Nationally Determined Contributions as ranging from *Insufficient* to *Highly Insufficient*, underscoring the gap between political ambition and implementation capacity. Achieving a low-carbon transition will require scaled-up investments, adoption of circular economy principles and reforms in climate-friendly international trade (Sampene et al., 2021).

Technological innovation remains central to low-carbon transitions. Zheng et al. (2024) analyse a novel high-temperature superconducting maglev transport system, demonstrating the potential of advanced transport technologies to reduce emissions and improve energy efficiency. Adoption of low-carbon technologies is shaped by multiple interacting factors. Ji et al. (2026) show that technological, organisational, environmental and human dimensions jointly determine the adoption of autonomous driving in new energy vehicles.

Energy–digital integration is also emerging as a key transition pathway. Xiao et al. (2026) develop an integrated framework for low-carbon data centre siting using renewable energy synergy, illustrating how digital infrastructure can align with clean energy systems. Behavioural factors also influence low-carbon outcomes. Jiang et al. (2026) demonstrate that normative misperception affects low-carbon travel behaviour, indicating that social norms and perception biases play a role in sustainability transitions. Digital transformation further supports sustainability. Gao et al. (2026) show that digital transformation enhances value co-creation in manufacturing enterprises, reinforcing its importance in improving sustainability performance.

The broader literature conceptualises low-carbon transition as a multidimensional and systemic restructuring process embedded in technological, institutional and socio-economic change. Fragkos et al. (2021) demonstrate that major economies can pursue mitigation pathways consistent with limiting global warming through expanded renewable energy, efficiency improvements and rapid electrification. Qiu et al. (2024) emphasise the necessity of integrating physical energy systems, market incentives and regulatory strategies to sustain decarbonisation efforts. Zhou et al. (2023) identify transition pathways, technology diffusion, infrastructure planning and enabling mechanisms as the core research themes shaping low-carbon development. Importantly, these studies converge on the view that transition processes extend beyond technological substitution and require coordination across policy, market and social dimensions. Such complexity is particularly acute in developing economies where low grid capacity, technology gaps and financing constraints persist (Babayomi et al., 2022).

Country-specific studies provide further insight into how BRICS economies pursue low-carbon strategies within their socio-economic contexts. Khosla et al. (2020) show that successful technology transitions in India, China and Brazil rely on coordinated innovation policies that integrate domestic R&D, manufacturing and demand-creation strategies. Pigato et al. (2020) document China's transformation from a technology importer to a global leader in renewable energy and electric vehicle production, illustrating the potential of sustained industrial and policy support. These findings reinforce the conclusion that low-carbon pathways are not uniform but highly path-dependent, shaped by institutional capacity, national development priorities and sectoral structures.

Empirical evidence also highlights strong associations between low-carbon indicators and sustainability outcomes across environmental, technological and social domains. Wang et al. (2024) demonstrate that low-carbon practices significantly enhance business sustainability, with technological innovation acting as a key mediating factor. Evidence from supply-chain analysis shows similar patterns: Das and Jharkharia (2019) find that low-carbon supply-chain practices improve environmental performance through enhanced governance and product design. Lizana et al. (2021) provide evidence from the education sector, documenting a 10 per cent improvement in school environmental performance and a 20 per cent increase in sustainable practices among families following low-carbon interventions. Proskuryakova (2023) identifies total material requirement, CO_2 emissions, lifecycle emissions and operational costs as critical indicators for evaluating transition progress, while Peñasco et al. (2021) show that decarbonisation policies produce positive environmental and technological outcomes, albeit with short-term competitiveness trade-offs.

Progress across SDG-related dimensions is evident but uneven. Emishyan and Guliev (2025) report increases in renewable electricity and simultaneous reductions in coal consumption across BRICS, contributing to SDG 7 on clean energy. Bangura (2024) highlights divergent SDG 13 performance, with China showing substantial advances through corporate social responsibility initiatives while Brazil exhibits limited progress. Amin et al. (2025) find that research and development expenditure, green energy deployment and technological innovation contribute to CO_2 emission reductions of between 0.211 and 0.329 per cent. However, the transition remains constrained by structural pressures. Amin et al. (2025) show that a 1 per cent increase in economic growth leads to a 0.499 per cent rise in CO_2 emissions, while resource rents elevate emissions by 0.840 per cent. Emishyan and Guliev (2025) caution that rapid withdrawal from non-renewable energy sources may generate economic instability, including higher electricity prices and potential capital flight.

Taken together, the literature portrays low-carbon transition in BRICS as a dynamic but challenging process marked by promising technological gains and persistent structural barriers. Emerging evidence affirms that meaningful progress toward SDG 7, SDG 11 and SDG 13 is possible, yet contingent on stronger policy coherence, long-term investment strategies and national pathways that balance development imperatives with climate commitments.

2.4. Mediation linkages between green recovery and sustainable development through low-carbon transition

Low-carbon transition functions as a mediating mechanism between green recovery policies and sustainable development because it represents the structural pathway through which stimulus-led investments translate into long-term emissions reduction, resource efficiency and environmental resilience. This mediation logic is grounded in the recognition that recovery measures alone do not guarantee sustainability unless they induce systemic changes in energy systems, infrastructure and production structures. Slabe-Erker et al. (2023) show that effective transition requires infrastructural redesign and data-driven policy frameworks capable of steering economies away from carbon-intensive trajectories, while Catalano and Forni (2021) demonstrate that combining carbon pricing with targeted green public investment produces stronger transition effects than isolated interventions. Dwarkasing (2023) emphasises that the mediating role of low-carbon transition must also address structural inequalities to avoid uneven social outcomes, and Johnson et al. (2020) argue that sustained policy coherence is necessary to prevent lock-in to high-emission development paths. These studies collectively show that low-carbon transition provides the conceptual bridge linking short-term recovery policies to long-run sustainability outcomes.

A growing body of empirical research employs mediation or pathway-based analytical frameworks to examine the mechanisms through which environmental and economic variables interact. Wang et al. (2023) show that technological innovation negatively mediates the relationship between industrialisation and renewable energy intensity, highlighting the role of innovation systems in shaping clean energy progress. Bétila (2023) finds that renewable energy consumption mediates the relationship between economic freedom and carbon emissions across 138 countries, revealing how institutional quality affects environmental outcomes indirectly. Praveen et al. (2025) provide further evidence that green technology constitutes a statistically significant mediating channel in the link between green finance and green growth, with effect sizes between 0.004 per cent and 0.019 per cent for each 1 per cent increase in green finance. These findings confirm that mediation frameworks offer deeper understanding of the indirect pathways that underpin environmental-economic transitions.

Digital financial systems are increasingly recognised as mediating channels. Xia et al. (2025) demonstrate that spatial data and graph neural networks can predict digital financial inclusion, suggesting that digital finance strengthens access to sustainability-oriented funding. Monetary innovation also plays an indirect role. Jiang and Yuan (2026) find that China's digital currency (e-CNY) pilot promotes consumption upgrading, implying that financial digitalisation can influence sustainable consumption patterns. Institutional and cognitive factors also mediate sustainability outcomes. Yang et al. (2025) show that emerging market multinational enterprises respond to institutional pressures through cognitive entrepreneurship, highlighting the role of institutional adaptation in sustainability transitions.

Indirect linkages between green investment and sustainability outcomes are increasingly evident. Zhang et al. (2024) show that green investments stimulate corporate green innovation by easing financial constraints, especially in competitive industries. Zhongping et al. (2023) demonstrate that green financial flows improve both economic performances, measured by GDP per capita, and environmental outcomes, measured by CO_2 emissions. Chițimiea et al. (2021) document rising organisational adoption of green investment strategies linked to resource efficiency and environmental stewardship, while Ahir and Mahida (2025) highlight the role of green financial instruments in enhancing risk resilience and promoting transparency in sustainability reporting. The consistency of these findings across corporate, financial and national scales indicates that indirect effects form a substantive component of green recovery dynamics.

In BRICS economies, green recovery stimulates low-carbon transition through investment channels, fiscal supports and clean-technology adoption mechanisms. Nasreen et al. (2025) show that sustained renewable energy investments reduce carbon emissions while increasing GDP, reinforcing the dual economic–environmental benefits of transition policies. Sohail (2023) provides further evidence that green investment, environmental technology and R&D exert positive long-run effects on green growth in BRICS, while Ofori et al. (2023) emphasise the critical role of technological innovation and green resource investment in enabling structural shifts toward sustainability. These mechanisms include foreign direct investment in clean sectors, targeted fiscal incentives, and policy frameworks that expand clean-energy deployment and strengthen environmental regulation.

The mediating role of low-carbon transition has important implications for SDG alignment in BRICS. Clean-energy investments advance SDG 7 by improving access to affordable and sustainable energy; they support SDG 11 by promoting resilient, low-pollution urban systems; and they strengthen SDG 13 by driving long-term decarbonisation. Ofori et al. (2023) show that clean energy enhances environmental sustainability and human development, while Mirasgedis et al. (2024) demonstrate that mitigation actions in buildings generate spillovers that reinforce progress on SDGs 3, 7, 8, 11 and 13. Amin et al. (2025) quantify these effects, reporting that R&D expenditure, green energy deployment and green technological innovation reduce CO_2 emissions by 0.329 per cent, 0.211 per cent and 0.148 per cent respectively. These findings confirm that mediation through low-carbon transition strengthens multi-SDG alignment by linking green recovery interventions to long-term environmental and socio-economic gains.

3. Materials and methods

3.1. Research design and scope of the study

This study adopts a quantitative panel research design to examine the effects of green recovery and low-carbon economic transition on sustainable development in the BRICS economies. The panel structure allows for the joint exploitation of cross-country and time-series variation, enabling the control of unobserved country-specific heterogeneity and improving the efficiency of parameter estimates. The empirical scope covers Brazil, China, India, and South Africa over the period 2000–2023. Russia is excluded from the analysis due to uncertainties associated with the ongoing Russia–Ukraine war, which has disrupted statistical reporting and reduced transparency, alongside persistent data gaps in green recovery indicators, particularly renewable energy investment data.

Although Russia represents a major economic, energy, and environmental actor within the BRICS bloc, its inclusion presents substantial methodological challenges. Since 2022, the conflict and related international sanctions have affected institutional reporting systems, resulting in discontinuities, delayed releases, and missing observations across several macroeconomic and environmental indicators. These disruptions reduce data transparency and compromise the consistency and comparability of Russia's statistics with those of other BRICS members. Because the present study relies on balanced panel estimation and comparable time-series data, including Russia could introduce measurement bias and weaken the robustness of the empirical results. Consequently, its exclusion is a methodological decision aimed at preserving data reliability and ensuring more credible cross-country inference rather than a substantive judgment about its economic importance.

The study period encompasses multiple global economic cycles, including the pre-pandemic phase and the COVID-19 crisis period, which allows for the assessment of both structural and shock-driven dynamics in green recovery, low-carbon transition, and sustainable development. To capture these regime-specific effects, the analysis is conducted for the full sample as well as for two sub-periods: pre-COVID (2000–2019) and during COVID (2020–2023).

3.2. Theoretical framework

The analytical foundation of this study is anchored in Ecological Modernisation Theory and Green Growth Theory. Ecological Modernisation Theory posits that environmental protection and economic growth are not mutually exclusive and that technological innovation, institutional reform, and structural economic transformation can foster environmental improvement alongside sustained economic expansion. Within this framework, green recovery initiatives such as renewable energy investment, clean infrastructure development, and environmentally oriented fiscal programmes represent practical mechanisms through which economic systems internalise environmental objectives. The theory supports the view that regulatory coordination and green investment can stimulate innovation and reorient production structures in favour of sustainability.

Green Growth Theory complements this perspective by asserting that long-run economic expansion can be achieved through low-carbon development strategies that prioritise resource efficiency, clean technologies, and environmentally responsible production. In the context of BRICS economies, green recovery programmes serve as instruments for stimulating economic activity while reducing carbon intensity and enhancing energy efficiency. This theoretical lens provides the justification for modelling the low-carbon economy as a mediating channel through which green recovery influences sustainable development.

By integrating both theoretical perspectives, the study conceptualises green recovery as the policy-driven catalyst that initiates a transition towards a low-carbon economic structure, which in turn supports sustainable development outcomes. Sustainable development is operationalised using Adjusted Net Savings (ANS), which internalises investment in human capital, depletion of natural capital, and environmental damages. Ecological Modernisation Theory provides the institutional and innovation-oriented logic, while Green Growth Theory offers the economic rationale for sustaining growth under binding environmental constraints. Together, they provide a coherent framework for analysing how BRICS economies can leverage green recovery and low-carbon strategies to align growth trajectories with SDG 7, SDG 11, and SDG 13.

3.3. Data sources, variable measurement, and justification of sustainable development indicator

The study relies on harmonised secondary data obtained from internationally recognised databases. Sustainable development is measured using Adjusted Net Savings (% of GNI) from the World Development Indicators. Green recovery is proxied by renewable energy investment as a percentage of total investment from the International Renewable Energy Agency. The low-carbon economy is captured by renewable energy consumption as a share of total final energy consumption from the World Development Indicators. Control variables include GDP per capita (constant 2015 USD), industrialisation measured by manufacturing value added as a share of GDP, and energy consumption measured in kilograms of oil equivalent per capita.

Adjusted Net Savings is adopted as the principal dependent variable because it provides a comprehensive and forward-looking measure of sustainable development. It captures not only gross capital formation but also deductions for natural resource depletion and environmental degradation. This makes ANS particularly suited for assessing the sustainability implications of green recovery and low-carbon strategies, as it reflects the extent to which current economic activity preserves future productive capacity. The indicator aligns closely with the objectives of SDG 7, SDG 11, and SDG 13, and directly internalises the hidden costs of environmentally damaging growth. The study employs the ANS series that incorporates particulate emission damages, as this variant most fully captures the environmental and public-health externalities that green recovery and low-carbon policies seek to address. For robustness, supplementary estimations are also conducted using the ANS series that excludes particulate emission damage to ensure that results are not driven by mechanical overlap in pollution measurement. Table 1 presents the detailed descriptions, measurements, and data sources for all variables used in the analysis.

Table 1. Description, measurement, and sources of variables, source: Authors' compilation

Variable	Description	Measurement / Proxy	Data Sources	Linked To SDG
Sustainable Development (SD)	Measures environmental–economic sustainability performance in BRICS	• Adjusted Net Savings (% of GNI)	WDI;	SDG 12 and 13
Green Recovery (GR)	Reflects green-oriented recovery policies and investments aimed at supporting clean energy transition and sustainable economic rebuilding	• Renewable energy investment (% of total investment)	IRENA	SDG 7, 9 and 13
Low-Carbon Economy (LC)	Shows the extent of transition to a carbon-efficient, climate-friendly economy	• Renewable energy consumption (% of total final energy)	WDI	SDG 7 and 13
GDP per Capita (GDPPC)	Level of economic development	Constant 2015 USD	WDI	SDG 8
Industrialisation (IND)	Structure of the economy and level of industrial activity	Manufacturing value added (% of GDP)	WDI	SDG 9
Energy Consumption (ENC)	Total energy use per capita	kg of oil equivalent per capita	WDI; IEA	SDG 7 and 12

3.4. Model specification

Recent advances in modelling techniques provide useful tools for analysing complex sustainability systems. Tian et al. (2026) develop a dynamic Stackelberg game model with heterogeneous expectations, demonstrating the relevance of complex system modelling for economic-environmental interactions. Similarly, Huo (2025) proposes a finite-difference least-squares Monte Carlo approach, highlighting methodological innovations applicable to financial and sustainability modelling. To address the core research objectives, three econometric models are specified. All variables enter the models in natural logarithmic form to stabilise variance and allow for elasticity-based interpretation of coefficients.

Model 1: Impact of Green Recovery on Sustainable Development

$$\ln SD_{it} = \beta_0 + \beta_1 \ln GR_{it} + \beta_2 \ln ENC_{it} + \beta_3 \ln GDPPC_{it} + \beta_4 \ln IND_{it} + \mu_i + \varepsilon_{it} \quad (1)$$

This model evaluates the direct effect of green recovery on sustainable development while controlling for energy consumption, income level, and industrial structure.

Model 2: Impact of Low-Carbon Economy on Sustainable Development

$$\ln SD_{it} = \beta_0 + \beta_1 \ln LC_{it} + \beta_2 \ln GDPPC_{it} + \beta_3 \ln IND_{it} + \mu_i + \varepsilon_{it} \quad (2)$$

This specification isolates the role of the low-carbon transition in shaping sustainable development outcomes, conditional on economic development and industrial structure.

Model 3: Mediation Framework with Low-Carbon Economy as Mediator

The mediation mechanism is implemented through a two-step system:

Step 1, the mediator equation:

$$\ln LC_{it} = \gamma_0 + \gamma_1 \ln GR_{it} + \gamma_2 \ln ENC_{it} + \gamma_3 \ln GDPPC_{it} + \gamma_4 \ln IND_{it} + \eta_i + \varepsilon_{it} \quad (3)$$

Step 2, the outcome equation:

$$\ln SD_{it} = \delta_0 + \delta_1 \ln GR_{it} + \delta_2 \ln LC_{it} + \delta_3 \ln ENC_{it} + \delta_4 \ln GDPPC_{it} + \delta_5 \ln IND_{it} + \eta_i + v_{it} \quad (4)$$

The indirect effect is computed as $\gamma_1 \times \delta_2$, the direct effect as δ_1, and the total effect as the sum of the direct and indirect effects. This framework permits an explicit assessment of whether the low-carbon transition constitutes a transmission mechanism through which green recovery shapes sustainable development.

3.5. Estimation strategy and diagnostic procedures

The dataset constitutes a small-N, moderate-T panel with four countries observed over 24 years. Pre-estimation diagnostics confirm that econometric conditions are suitable for reliable inference. Multicollinearity is negligible, with variance inflation factors for all regressors falling well below conventional critical thresholds. The Breusch–

Pagan/Cook–Weisberg test indicates no evidence of heteroskedasticity, while Pesaran's cross-sectional dependence tests confirm the absence of contemporaneous correlation across countries in both core models.

Based on these diagnostics, Panel-Corrected Standard Errors are adopted as the principal estimation technique. PCSE is well suited to panels with a small number of cross-sections and a moderate time dimension, and it produces efficient and consistent standard errors in the presence of potential serial correlation and contemporaneous dependence. Estimations are conducted for the full sample as well as for the pre-COVID and COVID sub-periods. In addition, country-specific PCSE regressions are estimated to capture heterogeneity in institutional structure, energy systems, and industrial composition across BRICS economies.

For the mediation analysis, fixed effects estimation with bootstrapped standard errors is employed. The use of bootstrapping with 1,000 replications ensures reliable inference for the indirect effects, which often exhibit non-normal sampling distributions. No alternative dynamic estimators are applied, as the PCSE framework, combined with robust diagnostics and sub-sample analysis, provides sufficient econometric rigour for the study's objectives.

4. Results and discussion

4.1. Presentation of results

4.1.1. Descriptive statistics

Table 2 reports the descriptive statistics for sustainable development (SD), green recovery (GR), low-carbon economy (LC), energy consumption (ENC), GDP per capita (GDPPC) and industrialisation (IND) across the BRICS economies. For the full sample, SD, proxied by adjusted net savings (% of GNI), averages about 17.0 per cent with substantial dispersion (standard deviation of 10.2) and a wide range from 1.8 to 34.1. This indicates that, while some BRICS economies have begun to internalise environmental depreciation into their savings behaviour, others still operate at relatively low levels of sustainability. GR exhibits a mean of roughly 1,119.8 (with a very large standard deviation of 1,949.1), reflecting marked heterogeneity in renewable energy investment across the bloc, with observations close to zero in some years and very high investment episodes in others.

LC, measured by the share of renewable energy in total final energy consumption, has a full-sample mean of 27.5 per cent (standard deviation 15.4), ranging from 7.6 to 50 per cent. This suggests that while some BRICS countries have made substantive progress towards a low-carbon energy mix, others remain heavily dependent on fossil fuels. Average energy consumption per capita (ENC) is about 1,519 kg of oil equivalent, with values spanning from 393.4 to 2,850.9, again pointing to sharp differences in energy intensity and consumption levels across countries and over time. GDPPC averages around USD 5,530 (constant 2015 prices), with a broad spread between lower-middle-income and upper-middle-income conditions in the bloc. Industrialisation (IND), proxied by manufacturing value added as a share of GDP, has a full-sample mean of 18.0 per cent, with values ranging from about 10.3 to 32.0 per cent, signalling variation in structural transformation and the relative size of manufacturing.

Table 2. Descriptive statistics, source: Authors' computation

Variable	Full Sample		Brazil		China		India		South Africa	
	Mean (SD)	Min (Max)	Mean (SD)	Min (Max)	Min (Max)	Mean (SD)	Mean (SD)	Min (Max)	Mean (SD)	Min (Max)
SD	17.01979	1.76	8.07	1.76	27.61	22.30	25.45	20.01	6.94	3.38
	(10.18)	(34.06)	(3.87)	(14.38)	(3.83)	(34.06)	(3.33)	(30.35)	(2.56)	(11.45)
GR	1119.831	0.04	3040.93	5.56	203.26	23.16	875.71	12.06	359.42	0.04
	(1,949.13)	(13,762.60)	(3,066.77)	(13,762.60)	(261.34)	(1,329.07)	(785.05)	(2,994.65)	(457.14)	(1,716.71)
LC	27.50	7.6	45.48	41.3	16.31	11.3	38.34	32.5	9.87	7.6
	(15.41)	(50.00)	(2.24)	(50.00)	(5.48)	(29.60)	(5.08)	(47.10)	(2.26)	(16.20)
ENC	1519.178	393.38	1326.71	1081.36	1881.57	898.08	549.26	393.38	2319.17	1938.31
	(736.53)	(2,850.94)	(144.47)	(1,522.42)	(578.45)	(2,850.94)	(114.94)	(754.18)	(216.47)	(2,738.08)
GDPPC	5530.36	756.70	8305.04	6817.78	6720.21	2237.44	1378.78	756.70	5717.39	4700.88
	(3,090.65)	(12,484.20)	(861.25)	(9,366.74)	(3,278.20)	(12,484.20)	(462.91)	(2,270.91)	(468.40)	(6,170.88)
IND	17.95	10.33	12.33125	10.33	29.52375	25.5	15.44458	13.02	14.4875	11.73
	(7.09)	(31.99)	(1.60)	(15.10)	(2.23)	(31.99)	(1.21)	(17.30)	(2.62)	(19.07)

Country-specific statistics reveal clear structural asymmetries. Brazil records relatively low SD (mean approximately 8.1) compared with China (about 22.3) and India (about 25.5), while South Africa shows the lowest average SD (around 6.9). In terms of green recovery, Brazil stands out with the highest mean renewable energy investment (about 3,041), consistent with episodic large-scale investment programmes, while India and South Africa exhibit more moderate averages and China shows relatively modest GR levels despite its large economy. On the low-carbon dimension, Brazil and India display relatively high LC shares (means around 45.5 and 38.3 per cent respectively), reflecting their reliance on hydro and other renewables, whereas China and South Africa exhibit lower LC shares (about 16.3 and 9.9 per cent), consistent with their more carbon-intensive energy systems. ENC is highest in South Africa and China, underscoring their more energy-intensive industrial and electricity structures, while India has the lowest energy consumption per capita. GDP per capita is highest in Brazil and South Africa, intermediate in China, and lowest in India, mirroring broader development disparities within the bloc. Finally, China has the highest degree of industrialisation (IND around 29.5 per cent of GDP), while Brazil, India and South Africa have more modest manufacturing shares, underscoring differences in production structures and value-added composition.

4.1.2. Correlation analysis

The correlation matrix for the full sample (Table 3) provides initial insights into the association between sustainable development, green recovery, low-carbon transition and key macro-structural variables in BRICS. SD is strongly and positively correlated with industrialisation (lnIND, r = 0.711), suggesting that higher manufacturing value added is associated with better environmental–economic sustainability performance. This pattern may reflect the potential for technologically advanced and more efficient industrial structures to internalise environmental costs and support adjusted net savings. By contrast, SD is negatively correlated with energy consumption (lnENC, r = −0.430) and GDP per capita (lnGDPPC, r = −0.508), indicating that higher energy use and higher income levels have historically coincided with more resource-intensive and potentially unsustainable growth trajectories in the bloc. The weak negative correlation with GR (lnGR, r = −0.102) and the modest positive association with LC (lnLC, r = 0.106) suggest that the sustainability benefits of green recovery spending and the low-carbon energy transition are emerging but are not yet fully reflected in the adjusted savings indicator over the sample period.

The correlations among the explanatory variables are also informative. GR is moderately and positively associated with LC (r = 0.483), which is consistent with the expectation that higher renewable energy investment contributes to a greater share of renewables in final energy consumption. LC is strongly and negatively correlated with ENC (r = −0.743) and GDPPC (r = −0.330), indicating that economies with a higher renewable share tend to display lower per capita energy consumption and, in this sample, somewhat lower income levels. ENC and GDPPC are highly positively correlated (r = 0.860), reflecting that higher-income BRICS economies also tend to consume more energy per capita. These patterns highlight potential multicollinearity concerns, especially between GDPPC and ENC, and indicate that the transition to a low-carbon economy in the bloc remains at an early stage, with income growth still closely tied to rising energy use.

Table 3. Correlation analysis for the full sample, source: Authors' computation

	lnSD	**lnGR**	**lnLC**	**lnENC**	**lnGDPPC**	**lnIND**
lnSD	1.000					
lnGR	-0.102	1.000				
lnLC	0.106	0.483	1.000			
lnENC	-0.430	-0.289	-0.743	1.000		
lnGDPPC	-0.508	0.055	-0.330	0.860	1.000	
lnIND	0.711	-0.382	-0.319	0.143	-0.040	1.000

Country-specific correlation matrices (Tables 4–7) underline the heterogeneity of the green recovery–low-carbon–sustainability nexus within BRICS. For Brazil, SD is strongly and positively correlated with industrialisation (r = 0.821) but negatively associated with ENC (r = −0.457) and GDPPC (r = −0.344). The strong positive correlation between ENC and GDPPC (r = 0.983) emphasises the energy-intensive nature of Brazilian growth. The positive correlation between GR and ENC (r = 0.533) suggests that periods of higher renewable investment are also associated with higher overall energy consumption, possibly reflecting expansionary phases of the energy system.

Table 4. Correlation Analysis for Brazil, source: Authors' computation

	lnSD	**lnGR**	**lnLC**	**lnENC**	**lnGDPPC**	**lnIND**
lnSD	1					
lnGR	-0.027	1.000				
lnLC	0.082	0.418	1.000			
lnENC	-0.457	0.533	0.174	1.000		
lnGDPPC	-0.344	0.580	0.203	0.983	1.000	
lnIND	0.821	-0.231	0.169	-0.700	-0.636	1.000

In China, SD is again highly correlated with industrialisation (r = 0.830) and negatively associated with GDPPC (r = −0.462), consistent with a pattern in which rapid income growth has been linked to environmental pressures. LC is strongly negatively correlated with ENC (r = −0.810) and GDPPC (r = −0.725), indicating that China's movement towards a low-carbon energy mix is more pronounced in periods of relatively lower energy consumption and lower per capita income within the sample. The strong positive correlation between ENC and GDPPC (r = 0.984) reinforces the tight link between economic expansion and energy demand in China's growth model.

Table 5. Correlation Analysis for China, source: Authors' computation

	lnSD	**lnGR**	**lnLC**	**lnENC**	**lnGDPPC**	**lnIND**
lnSD	1					
lnGR	-0.348	1.000				
lnLC	-0.169	-0.113	1.000			
lnENC	-0.323	0.078	-0.810	1.000		
lnGDPPC	-0.462	0.155	-0.725	0.984	1.000	
lnIND	0.830	-0.252	0.210	-0.703	-0.807	1.000

For India, SD exhibits a strong positive correlation with industrialisation (r = 0.696) and negative associations with LC (r = −0.214), ENC (r = −0.102) and GDPPC (r = −0.113). The correlation structure among GR, LC, ENC and GDPPC is particularly strong: GR is highly positively correlated with ENC (r = 0.775) and GDPPC (r = 0.757), while LC is sharply negatively correlated with ENC (r = −0.897) and GDPPC (r = −0.868). These patterns reflect an energy-constrained development path where periods of rapid growth and recovery are associated with higher energy use and lower renewable shares, and where the low-carbon transition is still in its formative phase.

Table 6. Correlation Analysis for India, source: Authors' computation

	lnSD	**lnGR**	**lnLC**	**lnENC**	**lnGDPPC**	**lnIND**
lnSD	1.000					
lnGR	-0.021	1.000				
lnLC	-0.214	-0.733	1.000			
lnENC	-0.102	0.775	-0.897	1.000		
lnGDPPC	-0.113	0.757	-0.868	0.992	1.000	
lnIND	0.696	-0.410	0.365	-0.669	-0.690	1.000

In South Africa, SD remains positively correlated with industrialisation (r = 0.558) but is negatively correlated with GR (r = −0.514) and GDPPC (r = −0.316), and positively associated with ENC (r = 0.497). The strong negative correlation between LC and GDPPC (r = −0.937) reveals that higher per capita income coincides with a more carbon-intensive energy mix, reflecting the dominance of coal in South Africa's energy system. GR is negatively correlated with LC (r = −0.464) and ENC (r = −0.530), indicating that greater green recovery expenditure has not yet translated into a higher renewable share or lower energy consumption in the sample period. Across all four economies, the consistently strong positive correlation between SD and IND underscores the central role of industrial structure and upgrading in shaping sustainable development outcomes in BRICS.

Table 7. Correlation analysis for South Africa, source: Authors' computation

	lnSD	**lnGR**	**lnLC**	**lnENC**	**lnGDPPC**	**lnIND**
lnSD	1.000					
lnGR	-0.514	1.000				
lnLC	0.103	-0.464	1.000			
lnENC	0.497	-0.530	-0.284	1.000		
lnGDPPC	-0.316	0.542	-0.937	0.248	1.000	
lnIND	0.558	-0.767	0.771	0.183	-0.855	1.000

4.1.3. Cross-sectional dependence tests

The Pesaran cross-sectional dependence (CD) tests provide further confirmation that the chosen empirical strategy is appropriate for the BRICS panel. For Model 1, the CD statistic is 0.775 with an associated p-value of 0.4385 and an average absolute correlation of 0.135. The high p-value implies that the null hypothesis of cross-sectional independence cannot be rejected, and the relatively low average absolute correlation suggests that residuals across the BRICS economies are only weakly correlated. For Model 2, the CD statistic is −1.063 with a reported p-value greater than 0.10, again indicating no significant cross-sectional dependence in the residuals. Together, these results suggest that common shocks or strong contemporaneous spillovers across BRICS do not dominate the error structure in the estimated models. Consequently, first-generation panel estimators that assume weak cross-sectional correlation remain valid, particularly when combined with robust variance–covariance estimators that accommodate any mild remaining dependence and serial correlation.

4.1.4. Unit root, multicollinearity and heteroskedasticity diagnostics

The panel unit root results reported in Table 8, based on the Im–Pesaran–Shin (IPS) and Levin–Lin–Chu (LLC) tests, indicate a combination of stationary and non-stationary series. For SD, both IPS and LLC statistics are significant at levels (IPS = −2.2642, LLC = −1.8177), implying that lnSD is stationary, I(0). Green recovery (lnGR) is also stationary at level, with both IPS (−2.9576) and LLC (−3.7223) rejecting the null of a unit root at conventional significance levels. In contrast, low-carbon economy (lnLC), energy consumption (lnENC), GDP per capita (lnGDPPC) and industrialisation (lnIND) show mixed evidence. The IPS test fails to reject the null at levels for lnLC, lnENC, lnGDPPC and lnIND, but strongly rejects it after first differencing, indicating that these variables are integrated of order one, I(1). The LLC test suggests that lnLC becomes stationary at level, while lnENC, lnGDPPC and lnIND require first differencing before stationarity is achieved. Taken together, these results point to a mixed order of integration, with lnSD and lnGR behaving as I(0) processes and the remaining variables predominantly I(1). Importantly, no variable appears to be integrated of order two, which is a necessary condition for the validity of the panel cointegration framework adopted in the subsequent analysis.

Table 8. Unit Root Tests source: Authors' computation

Variable	Im–Pesaran–Shin		Levin–Lin–Chu	
	I(0)	I(1)	I(0)	I(1)
lnSD	-2.2642***		-1.8177**	
lnGR	-2.9576***		-3.7223***	
lnLC	0.7488	-4.7032***	-2.2251***	
lnENC	-0.2360	-5.7312***	-2.5727***	
lnGDPPC	0.9025	-2.1365**	0.5910	-5.4825***
lnIND	1.4835	-4.8891***	0.9403	-5.8508***

Immediately after assessing stationarity, multicollinearity was examined using the Variance Inflation Factor (VIF). For Model 1, which includes lnGR, lnENC, lnGDPPC and lnIND as regressors for lnSD, the individual VIF values are 6.96 for lnENC, 6.40 for lnGDPPC, 1.86 for lnGR and 1.19 for lnIND, with a mean VIF of 4.10. These values are below the commonly cited critical threshold of 10, indicating that multicollinearity is moderate rather than severe. The higher VIFs for lnENC and lnGDPPC are consistent with the strong positive correlation between energy consumption and income (r = 0.860), and reflect the fact that both variables capture related aspects of the scale and intensity of economic activity in BRICS. However, the magnitudes are not sufficiently large to invalidate the regression results, especially when robust estimation techniques are employed.

In Model 2, which focuses on lnLC, lnGDPPC and lnIND as regressors, multicollinearity is minimal: VIFs are 1.28 (lnLC), 1.15 (lnGDPPC) and 1.14 (lnIND), with a mean VIF of 1.19. This suggests that the explanatory variables in the low-carbon specification are sufficiently distinct in statistical terms, allowing reliable identification of their separate effects on sustainable development.

The Breusch–Pagan/Cook–Weisberg heteroskedasticity test complements these diagnostics by examining the constancy of the error variance. For Model 1, the test yields a chi-square statistic of 5.45 with a p-value of 0.0195, leading to rejection of the null hypothesis of homoskedasticity. This indicates that the variance of the residuals varies systematically with the fitted values of lnSD, which is unsurprising in a heterogeneous panel comprising economies at very different levels of income, energy use and structural transformation. In Model 2, the corresponding chi-square statistic is 2.03 with a p-value of 0.1539, implying that the null of constant variance cannot be rejected at conventional levels. While this suggests more stable error variance in the low-carbon specification, the evidence of heteroskedasticity in Model 1 justifies the adoption of robust standard errors (for example, Panel-Corrected Standard Errors (PCSE), which automatically corrects for panel heteroskedasticity).

4.1.5. Panel Cointegration Test

The Pedroni and Kao panel cointegration tests reported in Tables 9 and 10 provide evidence on the existence of long-run equilibrium relationships between sustainable development and its green recovery and low-carbon determinants in BRICS. For Model 1, which links lnSD to lnGR, lnENC, lnGDPPC and lnIND, the Pedroni Phillips–

Perron t-statistic (−2.317, p = 0.010) and the Augmented Dickey–Fuller (ADF) t-statistic (−2.429, p = 0.008) reject the null of no cointegration, whereas the modified Phillips–Perron t-statistic is not significant at conventional levels. The Kao test results are somewhat mixed for the adjusted statistics, but the unadjusted modified Dickey–Fuller (−5.258, p = 0.000) and unadjusted Dickey–Fuller (−3.709, p = 0.000) statistics strongly reject the null of no cointegration. Taken together, these findings indicate that Model 1 variables share a common stochastic trend and converge to a stable long-run relationship, even though some individual test statistics are less decisive.

Table 9. Pedroni and Kao Panel Cointegration results for Model 1, source: Authors' computation

	Statistic	**p-value**
Pedroni Cointegration Test		
Modified Phillips–Perron t	0.851	0.197
Phillips–Perron t	-2.317	0.010
Augmented Dickey–Fuller t	-2.429	0.008
Kao Cointegration Test		
Modified Dickey–Fuller t	0.658	0.255
Dickey–Fuller t	-0.058	0.477
Augmented Dickey–Fuller t	0.654	0.257
Unadjusted modified Dickey–Fuller	-5.258	0.000
Unadjusted Dickey–Fuller t	-3.709	0.000

For Model 2, which focuses on the low-carbon economy channel (lnLC, lnGDPPC and lnIND as regressors for lnSD), the cointegration evidence is even stronger. The Pedroni Phillips–Perron t-statistic (−2.079, p = 0.019) and ADF t-statistic (−1.661, p = 0.048) reject the null of no cointegration at the 5 and 10 per cent levels respectively, while the modified Phillips–Perron statistic remains insignificant. The Kao test yields a significant modified Dickey–Fuller statistic (−2.191, p = 0.014) and Dickey–Fuller statistic (−2.370, p = 0.009), with the unadjusted modified Dickey–Fuller (−4.434, p = 0.000) and unadjusted Dickey–Fuller (−3.129, p = 0.001) statistics again providing strong support for cointegration. These results suggest a robust long-run equilibrium link between sustainable development, low-carbon transition, economic development and structural change in BRICS. The combined evidence from the unit root, cross-sectional dependence, multicollinearity, heteroskedasticity and cointegration diagnostics therefore validates the use of long-run panel estimators for both the green recovery and low-carbon specifications, and supports the subsequent analysis of how green recovery strategies and low-carbon transitions contribute to sustainable development in the BRICS economies.

Table 10. Pedroni and Kao Panel Cointegration Results for Model 2, source: Authors' computation

	Statistic	**p-value**
Pedroni Cointegration Test		
Modified Phillips–Perron t	0.248	0.402
Phillips–Perron t	-2.079	0.019
Augmented Dickey–Fuller t	-1.661	0.048
Kao Cointegration Test		
Modified Dickey–Fuller t	-2.191	0.014
Dickey–Fuller t	-2.370	0.009
Augmented Dickey–Fuller t	-1.525	0.064
Unadjusted modified Dickey–Fuller	-4.434	0.000
Unadjusted Dickey–Fuller t	-3.129	0.001

4.1.6. Estimation results across models

Tables 11 to 15 report the core estimation results for the BRICS panel, examining how green recovery policies and the low carbon transition shape sustainable development outcomes. Although the empirical framework is framed around sustainable development (SD), the indicator used – adjusted net savings as a share of GNI – reflects the degree to which economic activity preserves or depletes natural capital. It is therefore closely connected to long term environmental health and, by implication, to the burden of pollution related diseases.

Panel corrected standard errors (PCSE) are employed for the main models in order to address heteroskedasticity and contemporaneous correlation, while country specific PCSE estimations capture structural and institutional heterogeneity across Brazil, China, India and South Africa. A fixed effects model with bootstrapped standard errors is used for the mediation analysis, where the low carbon economy variable (LC) is specified as a mediator of the green recovery (GR)–sustainable development relationship.

*4.1.7. **Model 1**: Effect of green recovery on sustainable development*
4.1.7.1. Full sample and pandemic subsamples (PCSE)
The PCSE estimates in Table 11 show that, for the full BRICS sample, green recovery expenditure has a small and statistically insignificant effect on sustainable development. The coefficient on lnGR is positive (0.032) but not significant, suggesting that, over the full period, green oriented recovery spending has not yet generated a systematic improvement in the adjusted net savings indicator. This is consistent with the notion that climate focused investment, especially when relatively recent or small in scale, may take time to translate into measurable gains in natural capital preservation and pollution control.
Energy consumption (lnENC) is negative and highly significant in the full sample regression (−0.525, $p<0.01$), indicating that higher per capita energy use is associated with lower sustainable development. Given the fossil intensive energy mix in several BRICS economies, this result implies that energy demand continues to exert downward pressure on environmental quality and, by extension, on environmental health. Industrialisation (lnIND) emerges as a strong positive and highly significant predictor of SD (1.751, $p<0.01$). This suggests that, in BRICS, more advanced industrial structures, proxied by higher manufacturing value added, are associated with better adjusted savings performance, possibly because of greater technological efficiency, stricter regulation, and more capacity to invest in cleaner production. GDP per capita (lnGDPPC) is negative but insignificant in the full sample, indicating that income growth on its own does not guarantee improvements in environmental sustainability.
The temporal split between pre-Covid and Covid years reveals important regime shifts. In the pre-Covid period, the coefficient on lnGR is positive and weakly significant (0.0436, $p<0.10$), which implies that before the pandemic, higher green recovery spending was associated with modest improvements in sustainable development. At the same time, lnENC remains negative (−0.329, $p<0.10$) and lnIND strongly positive (1.655, $p<0.01$), while lnGDPPC becomes negative and weakly significant (−0.279, $p<0.10$). This pattern suggests that, in relatively normal times, green oriented investment can partially counteract the sustainability costs of energy intensive and income driven growth, provided that industrial upgrading continues.
During the Covid period the configuration changes sharply. The coefficient on lnGR turns large and negative (−0.220, $p<0.01$). This indicates that, in the crisis context, higher recorded green recovery spending is associated with lower sustainable development. A plausible interpretation is that pandemic era recovery programmes labelled as green were either insufficiently scaled or were used to stabilise existing energy and industrial systems rather than to restructure them, resulting in no immediate gain in natural capital preservation. Energy consumption becomes even more damaging for SD during Covid (lnENC = −2.128, $p<0.01$), while the sign on lnGDPPC reverses and becomes strongly positive (0.577, $p<0.01$). This suggests that, during the pandemic, income growth was largely observed in years where sustainable development also improved, possibly due to selective recovery of more resilient, less resource intensive sectors. Industrialisation remains positive and highly significant (1.987, $p<0.01$) and the model fit rises markedly ($R^2 = 0.963$), reflecting stronger co movement between industrial structure, income and the sustainability indicator in this short, turbulent period.

Table 11. Regression results using PCSE full sample, pre-Covid and Covid, source: Authors' computation

	(1)	(2)	(3)
VARIABLES	**Full Sample**	**Pre-COVID**	**During-COVID**
lnGR	0.0320	0.0436*	-0.220***
	(0.0217)	(0.0234)	(0.0702)
lnENC	-0.525***	-0.329*	-2.128***
	(0.172)	(0.177)	(0.300)
lnGDPPC	-0.139	-0.279*	0.577***
	(0.130)	(0.143)	(0.128)
lnIND	1.751***	1.655***	1.987***
	(0.102)	(0.0985)	(0.226)
Constant	2.396***	2.355***	8.990***
	(0.416)	(0.409)	(1.668)
Observations	96	80	16
R-squared	0.800	0.809	0.963
Number of c_id	4	4	4

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

Overall, Model 1 shows that green recovery has, at best, modest beneficial effects on sustainable development in normal times and may be misaligned with sustainability objectives in crisis conditions. Energy consumption consistently undermines sustainability, whereas industrialisation appears to be a key channel through which BRICS can reconcile growth with long term environmental and health objectives.

4.1.7.2. Country-specific heterogeneity

The country specific PCSE estimates in Table 12 highlight substantial heterogeneity in how green recovery and structural drivers influence sustainable development within the BRICS bloc.

In Brazil, lnGR is statistically insignificant and close to zero, indicating no discernible direct effect of green recovery spending on SD. Energy consumption has a very large negative and highly significant effect (lnENC = −9.639, $p<0.01$), while GDP per capita is strongly positive (10.89, $p<0.01$) and industrialisation is also positive and significant (3.863, $p<0.01$). This combination suggests that Brazilian sustainable development is heavily shaped by the balance between income driven fiscal space and the environmental damage associated with a highly energy intensive economy. The lack of a measurable effect of green recovery indicates that climate related investment has not yet been sufficient to offset the environmental costs of energy use in a way that improves adjusted savings and environmental health in the short to medium term.

China presents a different configuration. The coefficient on lnGR is small and not significant, so green recovery spending again shows no direct impact on SD. Energy consumption is positive but not statistically significant (0.479), while industrialisation is strongly positive and significant (1.732, $p<0.01$). GDP per capita is negative but insignificant. These results imply that in China, progress in sustainable development is tightly linked to the quality and depth of industrial transformation rather than to short run changes in energy use or green recovery outlays. The strong positive effect of lnIND indicates that more advanced and possibly higher technology manufacturing structures support improved natural capital preservation and, by implication, a more favourable environmental health trajectory.

In India, lnGR is negative but insignificant, echoing the absence of a direct green recovery channel observed in the other BRICS members. Neither lnENC nor lnGDPPC is significant, while lnIND again emerges as a strong positive driver of SD (2.071, $p<0.01$). This suggests that, for India, the route to sustainable development, improvement in environmental quality lies in the upgrading of industrial capabilities rather than in incremental changes in green recovery spending or energy consumption per se.

South Africa shows a more complex pattern. The coefficient on lnGR is positive but insignificant, so the green recovery variable again lacks explanatory power. Energy consumption (2.512, $p<0.05$) exerts a positive and statistically significant effect on SD, in contrast to the negative effect observed in the full sample and in Brazil. One interpretation is that in South Africa, higher energy use is associated with years when investment in infrastructure and industrial capacity also rises, improving adjusted savings despite the carbon intensive nature of the energy mix. GDP per capita is negative and insignificant, while industrialisation is positive but not statistically significant at conventional levels. The relatively low R^2 for South Africa (0.498) suggests that important omitted institutional and social factors, such as inequality, regulatory effectiveness, and health system capacity, shape the link between development, environmental quality and health outcomes.

Table 12. Country-specific estimates, source: Estimated and compiled by the authors

	(1)	(2)	(3)	(4)
VARIABLES	**BRAZIL**	**CHINA**	**INDIA**	**SOUTH_AFRICA**
lnGR	-0.00125	-0.00963	-0.0154	0.0388
	(0.0489)	(0.0145)	(0.0164)	(0.0358)
lnENC	-9.639***	0.479	-0.225	2.512**
	(3.286)	(0.425)	(0.533)	(1.217)
lnGDPPC	10.89***	-0.215	0.472	-0.868
	(3.301)	(0.322)	(0.330)	(2.108)
lnIND	3.863***	1.732***	2.071***	1.153
	(0.678)	(0.531)	(0.244)	(0.997)
Constant	-36.69***	-4.223***	-4.311***	-13.30
	(9.500)	(1.612)	(1.430)	(14.63)
Observations	24	24	24	24
R-squared	0.800	0.835	0.756	0.498
Number of c_id	1	1	1	1

Standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Taken together, the country specific results reveal that the influence of green recovery on sustainable development, and hence on environmental quality prospects, is context dependent. In all four BRICS economies green oriented spending has not yet produced a statistically detectable direct effect on SD, whereas energy use, income and industrialisation play central roles, with signs and magnitudes that vary according to the underlying energy mix, institutional quality and stage of structural transformation.

4.1.8. ***Model 2:*** *Effect of the low carbon economy on sustainable development*

4.1.8.1. Full sample and pandemic subsamples (PCSE)

Model 2 focuses on the low carbon economy channel, using the share of renewable energy in total final energy consumption as the key explanatory variable. The full sample PCSE estimates in Table 13 show a clear and robust positive association between the low carbon transition and sustainable development. The coefficient on lnLC is positive and highly significant (0.253, $p<0.01$), indicating that a higher renewable share is associated with higher adjusted savings and a more favourable environmental economic balance. This result aligns with the expectation that scaling up renewables supports reductions in pollution, slows the depletion of natural capital and, over time, contributes to improved environmental health.

GDP per capita enters with a negative and highly significant coefficient (−0.405, $p<0.01$), implying that, in the absence of a strong low carbon transition, higher income levels tend to be associated with more intensive natural resource use and environmental depletion in BRICS. Industrialisation remains strongly positive and significant (1.673, $p<0.01$), confirming its role as a key driver of sustainable development when it is supported by cleaner technologies and more efficient production processes.

The pre-Covid subsample again reveals a more moderate but consistent pattern. The coefficient on lnLC remains positive and significant (0.169, $p<0.05$), while lnGDPPC is negative and highly significant (−0.435, $p<0.01$) and lnIND is strongly positive (1.568, $p<0.01$). This suggests that, before the pandemic, progress in the low carbon transition already contributed to improved sustainable development, but income growth was still largely associated with environmental pressures.

During Covid, the positive effect of the low carbon economy on SD becomes much stronger, with the coefficient on lnLC rising to 0.646 ($p<0.01$). At the same time, GDP per capita retains a negative and highly significant coefficient (−0.574, $p<0.01$), and industrialisation has an even larger positive impact (2.508, $p<0.01$). These results indicate that, in the pandemic period, shifts towards renewable energy were particularly effective in supporting sustainable development, possibly because they coincided with structural adjustments away from the most carbon intensive activities. The high R^2 (0.963) suggests that during Covid, variations in SD are closely tied to changes in renewable deployment, industrial structure and income. From an environmental health perspective, this reinforces the notion that crises can accelerate transitions that reduce pollution exposure and future disease burdens when they are used to reorient energy systems towards renewables.

Table 13. Regression results using PCSE full sample, pre-Covid and Covid, *source: estimated and compiled by the authors*

	(1)	**(2)**	**(3)**
VARIABLES	**Full**	**Pre-COVID**	**During-COVID**
lnLC	0.253***	0.169**	0.646***
	(0.0711)	(0.0751)	(0.116)
lnGDPPC	-0.405***	-0.435***	-0.574***
	(0.0529)	(0.0609)	(0.0235)
lnIND	1.673***	1.568***	2.508***
	(0.0910)	(0.0921)	(0.116)
Constant	0.469	1.264**	-1.452**
	(0.565)	(0.612)	(0.645)
Observations	96	80	16
R-squared	0.772	0.773	0.963
Number of c_id	4	4	4

Standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

4.1.8.2. Country-specific heterogeneity

The country specific PCSE estimates for Model 2 (Table 14) reveal striking heterogeneity in the relationship between the low carbon transition, income, industrialisation and sustainable development.

In Brazil, the coefficient on lnLC is negative and weakly significant (−2.364, $p<0.10$), while lnGDPPC is positive and highly significant (2.323, $p<0.01$) and lnIND is strongly positive (5.357, $p<0.01$). This counterintuitive result suggests that, over the sample period, increases in the renewable share are associated with lower adjusted savings. One explanation is that expansions in renewables may have taken place during periods of macroeconomic stress or fiscal consolidation when broader investment in natural capital and social infrastructure was constrained. Alternatively, the increase in renewables may have been too modest to offset the environmental damage from other sectors, leading to a negative short run association. In contrast, income growth and industrial upgrading support sustainable development, implying that Brazil's progress in environmental health relevant outcomes relies more on structural and fiscal space than on the measured change in the renewable energy share.

For China, lnLC is negative but insignificant, which indicates that fluctuations in the renewable share do not have a clear independent effect on SD in the period considered. GDP per capita is also insignificant, while industrialisation is strongly positive and significant (2.015, $p<0.01$). This reinforces the pattern seen in Model 1, where China's sustainable development performance is primarily driven by the depth and quality of industrial transformation. The absence of a significant effect of lnLC may reflect the fact that China's renewable expansion has occurred alongside continued operation of large fossil fuel capacity, meaning that the renewable share moves more slowly relative to total energy system changes.

In India, lnLC is negative and insignificant, lnGDPPC is positive but insignificant, and lnIND remains strongly positive and significant (1.810, $p<0.01$). This again indicates that the low carbon transition has not yet generated a distinct statistical signal for sustainable development, and that industrialisation is the main channel through which India can improve environmental and health relevant outcomes. The insignificant coefficients on lnLC and lnGDPPC may reflect the early stage of the renewable transition and the strong influence of other social and institutional constraints on sustainable development.

South Africa presents a particularly interesting configuration. The coefficient on lnLC is large and negative (−2.481, $p<0.01$), indicating that increases in the renewable share are associated with lower SD. GDP per capita is also negative and weakly significant (−3.527, $p<0.10$), whereas industrialisation is strongly positive (2.009, $p<0.01$). These results suggest that South Africa's recent renewable expansion may have occurred in a context of economic contraction and fiscal stress, for example in response to energy crises, such that higher renewable shares coincide with periods of weaker overall sustainability performance. At the same time, industrial upgrading still contributes positively to SD. From an environmental health standpoint this highlights that, without broad based economic resilience and institutional capacity, renewable deployment alone may not be sufficient to improve long term sustainability indicators.

Across the four BRICS economies, Model 2 shows that the low carbon transition is clearly beneficial for sustainable development at the aggregate level, especially during the Covid period, but its country level effects are shaped by macroeconomic conditions, energy system legacies and institutional capacity. In some settings, renewables appear to be expanding under conditions of economic stress, which may temporarily weaken their association with improvements in natural capital and environmental health.

Table 14. Country-specific estimates using PSCE, source: estimated and compiled by the authors

	(1)	**(2)**	**(3)**	**(4)**
VARIABLES	**BRAZIL**	**CHINA**	**INDIA**	**SOUTH AFRICA**
lnLC	-2.364*	-0.0790	-0.258	-2.481***
	(1.434)	(0.155)	(0.284)	(0.665)
lnGDPPC	2.323***	0.0831	0.162	-3.527*
	(0.844)	(0.136)	(0.137)	(1.964)
lnIND	5.357***	2.015***	1.810***	2.009***
	(0.692)	(0.679)	(0.314)	(0.535)
Constant	-23.41***	-4.010	-1.941	32.65*
	(8.224)	(3.859)	(2.675)	(19.11)
Observations	24	24	24	24
R-squared	0.755	0.815	0.751	0.625
Number of c_id	1	1	1	1

Standard errors in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$

4.1.9. Mediation analysis: low-carbon economy as mediator of the green recovery–sustainable development nexus

The mediation model reported in Table 15 evaluates whether the low carbon economy acts as an intermediate channel through which green recovery influences sustainable development. The estimated indirect effect of lnGR on SD through lnLC is positive (0.012) but statistically insignificant, with a bootstrapped standard error of 0.010, a Z-statistic of 1.18 and a p-value of 0.240. The 95 per cent confidence interval (−0.008, 0.033) includes zero, which confirms that the mediating role of the low-carbon economy is not statistically supported in the BRICS sample.

This result implies that, over the sample period, the effect of green recovery spending on sustainable development, to the extent that it exists, is not transmitted systematically through measured changes in the renewable energy share. Instead, any influence of green recovery policies on environmental economic sustainability and, by extension, on environmental health is likely to operate through other channels such as industrial restructuring, regulatory

reforms, technology adoption or improvements in public financial management. The absence of a significant mediation effect also indicates that climate focused investments have not yet been deployed at sufficient scale, or with sufficient consistency, to shift the energy mix in a way that is detectable in this panel framework.
Taken together, the results from Models 1 and 2, combined with the mediation analysis, highlight three key insights that are relevant for the broader agenda of green finance and environmental quality. First, energy consumption remains a central determinant of sustainability, reinforcing the importance of decoupling energy use from pollution and natural capital depletion. Second, industrialisation, when supported by cleaner technologies and robust institutions, can enhance sustainable development rather than undermine it. Third, climate focused investments in green recovery and the low-carbon transition have begun to shape sustainability outcomes at the aggregate BRICS level, especially during the Covid period, but their effectiveness is highly heterogeneous across countries and has not yet translated into a clear mediating pathway through the renewable energy share. For such investments to generate measurable reductions in pollution related diseases, they will need to be scaled up, better targeted, and complemented by reforms that ensure that gains in energy and industrial systems are aligned with long term environmental and health objectives.

Table 15. Fixed Effects (FE) with bootstrapping for mediation, source: estimated and compiled by the authors

	Observed coefficient	Bootstrap std. err.	Z	P>z	Normal based	
					[95% conf.	interval]
_bs_1	0.012	0.01	1.18	0.24	-0.008	0.033
	Observations	96		Replications	1,000	

Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1

4.2. Discussion of results

Our study's central aim, is to examine how green recovery initiatives and low-carbon economic strategies shape sustainable development outcomes in BRICS economies. By analysing both the direct effects of green recovery spending and the role of the low-carbon transition, as well as testing whether low-carbon development mediates the recovery–sustainability relationship, the study seeks to clarify the mechanisms through which post-crisis policy responses translate into long-term environmental and economic sustainability. The discussion therefore situates the findings within the broader context of SDG 7 on clean energy, SDG 11 on sustainable cities, and SDG 13 on climate action, and evaluates their implications for policy design, structural transformation, and future research in emerging economies. Our findings provide three clear answers to the study's research questions. First, green recovery initiatives exhibit, at best, weak and regime-dependent links with sustainable development in BRICS: the association is modestly positive before COVID-19 but turns significantly negative during COVID-19, and is statistically indistinguishable from zero in the full-period estimates. Second, the low-carbon transition, proxied by the renewable share of final energy, is positively and robustly associated with sustainable development in the full sample and becomes markedly stronger during COVID-19. Third, the mediation hypothesis is not supported: the indirect effect of green recovery on sustainable development through the low-carbon channel is positive but statistically insignificant. The novelty lies in jointly estimating the direct green recovery–sustainability link, the low-carbon–sustainability link, and a mediation pathway while also explicitly probing pre-COVID versus COVID regimes and country-level heterogeneity within BRICS. Interpreted through SDG lenses, the results imply that progress towards SDG 7 and SDG 13 is more consistently reflected in improved sustainable development performance than green-labelled recovery spending alone, while the mixed crisis-period dynamics signal that SDG 11-aligned resilience depends on the quality of structural reorientation rather than the scale of short-run stimulus.
Placed against existing evidence, the pattern of weak average effects for green recovery but stronger effects for low-carbon transition is consistent with scholarship that emphasises delayed payoffs and contextual constraints in green recovery implementation. The limited full-period impact of green recovery aligns with arguments that sustainable recovery requires coordinated policy and investment systems rather than nominally green expenditures (Adamowicz, 2022; Batrancea et al., 2021) and echoes the claim that conventional stimulus can be environmentally inferior to green schemes when recovery packages do not materially reconfigure carbon-intensive structures (Zachariadis et al., 2023). The crisis-period reversal also resonates with evidence that fiscal constraints and policy design weaknesses can limit the effectiveness of green-aligned recovery in emerging contexts (Abdullah et al., 2023) and with findings that green policy effectiveness varies substantially across BRICS settings (Qi et al., 2024). By contrast, the consistently positive association between the low-carbon economy and sustainable development coheres with the broader transition literature that links renewable expansion, efficiency, and electrification to sustainability and mitigation outcomes (Fragkos et al., 2021; Gbadeyan et al., 2024), while also reflecting the SDG-oriented view that recovery and transition strategies are most effective when guided by integrated sustainability indicators and policy coherence (Werikhe, 2022; Filipovic et al., 2022). The absence of statistically significant mediation is also compatible with arguments that the translation of recovery policies into long-run outcomes depends on deeper

infrastructural redesign, governance quality, and policy mixes rather than single-channel energy shares (Slabe-Erker et al., 2023; Catalano and Forni, 2021).

The pre-COVID positive association between green recovery and sustainable development suggests that, under relatively stable macroeconomic conditions, renewable investment can contribute to preserving national wealth once natural capital depletion and environmental damages are internalised in the outcome metric. This is consistent with evidence that green finance and renewable investment can reduce pollution and improve environmental quality (Dong et al., 2023; Hailiang et al., 2023), and that green investment and R&D support longer-run green growth (Sohail, 2023). The mechanism implied by the results is that recovery-oriented green investment may improve sustainable development when it supports technology upgrading and more resource-efficient production, which is directly relevant to SDG 13 through reduced climate externalities and to SDG 7 through greater renewable capacity and consumption. The weak full-sample coefficient, however, indicates that such gains are not automatic and may be diluted by uneven implementation, competing budget priorities, and the persistence of carbon-intensive energy demand, reflecting the constraints emphasised for emerging economies (Abdullah et al., 2023) and the context dependence of BRICS policy effectiveness (Qi et al., 2024).

The COVID-period negative association between green recovery and sustainable development warrants a policy-relevant interpretation rather than a literal conclusion that *green spending harms sustainability*. In crisis settings, green recovery spending may be simultaneously tasked with stabilisation, social protection, and emergency energy security, potentially producing short-run effects that do not translate into immediate improvements in adjusted net savings. Where recovery packages support incumbent energy and industrial systems, they can entrench carbon-intensive pathways even when labelled as green, which parallels concerns about carbon lock-in and the need for sustained coherence in transition policy (Johnson et al., 2020; Zachariadis et al., 2023). The stronger negative effect of energy consumption during COVID further suggests that when the energy mix remains fossil-intensive, higher energy use rapidly erodes sustainable development by amplifying depletion and pollution damages captured in the adjusted net savings indicator. This directly speaks to SDG 13, because climate mitigation depends on decoupling energy use from emissions, and to SDG 11, because the sustainability of urban systems hinges on cleaner energy supply and reduced pollution intensity, not only on aggregate consumption (Moallemi et al., 2020; Barbier, 2020).

In contrast to green recovery, the low-carbon economy variable displays a stable and strengthening positive association with sustainable development, especially during COVID. This suggests that shifts in the energy mix towards renewables are more tightly connected to the preservation of comprehensive wealth than short-run recovery expenditure is. The implication for SDG 7 is direct: increasing renewable energy consumption supports cleaner and potentially more reliable energy systems, and the strong COVID-period effect suggests that periods of disruption may accelerate energy restructuring when renewables become integral to resilience strategies. The implication for SDG 13 is equally direct, since renewable penetration is a core mitigation lever in long-run transition pathways (Fragkos et al., 2021; Gbadeyan et al., 2024). However, the negative and significant GDP per capita coefficients in Model 2 indicate that, absent sufficient low-carbon progress, higher income can coincide with greater depletion pressures, consistent with evidence that growth and resource rents increase emissions in emerging contexts (Amin et al., 2025). This reinforces the interpretation that development trajectories compatible with SDG 11 and SDG 13 require structural change and not only income expansion.

The country-specific estimates underscore the heterogeneity emphasised in the literature, with implications for the design of SDG-aligned policy mixes. In Model 1, the insignificance of green recovery across all four countries suggests that renewable investment as a share of total investment has not yet reached a scale, consistency, or policy complementarity sufficient to shift comprehensive sustainability metrics in any single country, which is consistent with the argument that green recovery effectiveness varies and depends on local institutional and structural conditions (Qi et al., 2024). Brazil's very large negative energy-consumption effect and strong positive income and industrialisation coefficients suggest that sustainable development performance is dominated by the tension between energy intensity and the fiscal and technological capacity associated with higher income and manufacturing upgrading, echoing the emphasis on energy financing needs and structural constraints (Bai et al., 2022). China and India show comparatively strong industrialisation effects, aligning with the view that transition progress often hinges on coordinated innovation systems and industrial capabilities (Khosla et al., 2020; Pigato et al., 2020). South Africa's positive energy coefficient in Model 1 but negative renewable-share coefficient in Model 2 implies that energy-system stress and macroeconomic conditions may be confounding the short-run relationship between renewables and comprehensive sustainability, which is consistent with warnings that transition costs and instability risks can affect observed outcomes in the near term (Emishyan and Guliev, 2025).

The mediation results offer an important *so what* for policy design. Although green recovery and low-carbon transition are conceptually linked in the literature as mutually reinforcing pathways (Dafnomilis et al., 2022; Filipovic et al., 2022), the estimated indirect effect is not statistically different from zero, suggesting that renewable energy consumption does not yet function as a consistent transmission channel through which green recovery improves sustainable development in BRICS. This is compatible with evidence from pathway-based studies showing that mediation often depends on the strength and maturity of the intermediate mechanism, such as technological innovation systems or renewable intensity, rather than merely the presence of green spending (Wang et al., 2023; Bétila, 2023; Praveen et al., 2025). It also matches arguments that policy mixes combining carbon pricing and public investment, together with data-driven and infrastructural redesign, are typically required for transition effects to materialise (Catalano and Forni, 2021; Slabe-Erker et al., 2023). For SDG alignment, the implication is that recovery packages may advance SDG 7 and SDG 13 only when they measurably alter the energy mix and technology adoption trajectory, and they may advance SDG 11 only when they are embedded in urban and industrial resilience strategies that avoid inequitable outcomes (Dwarkasing, 2023).

A key strength of this study is its integrated empirical design that simultaneously tests the direct effects of green recovery and low-carbon transition and evaluates a mediation pathway, while also distinguishing pre-COVID and COVID regimes and reporting country-specific heterogeneity within BRICS. This responds to concerns in the literature about uneven country coverage and limited comparability in BRICS-focused work (Yadav et al., 2024) and supports more credible SDG-relevant interpretation by showing when and where relationships strengthen or reverse. The use of panel-corrected standard errors is also appropriate for small-N, moderate-T settings, improving inference reliability in the presence of potential contemporaneous correlation. A further strength is the use of adjusted net savings as an outcome, which provides a comprehensive sustainability metric that is conceptually suited to evaluating long-run wealth preservation central to SDG 11 and SDG 13, while remaining sensitive to the structural conditions that shape SDG 7 progress.

Several caveats are important. First, the COVID subsample is necessarily short, and coefficient reversals in that period should be interpreted as indicative of crisis dynamics rather than definitive long-run relationships. Second, proxies may not capture the full policy content of *green recovery*, particularly where fiscal packages include regulatory reform, institutional strengthening, or targeted innovation support not reflected in renewable investment shares, a limitation consistent with calls for more granular policy analysis (Yao et al., 2023; Qi et al., 2024). Third, the mediation test is constrained by the chosen mediator, renewable energy consumption share, which may adjust slowly in large energy systems and may not capture other plausible transmission routes, such as green innovation, infrastructure quality, or governance improvements emphasised in pathway-based research (Wang et al., 2023; Slabe-Erker et al., 2023). Fourth, the heterogeneous country results indicate that omitted structural features, including energy-market design, institutional capacity, and resource dependence, can shape observed associations, consistent with evidence that resource rents and growth pressures can undermine decarbonisation progress (Amin et al., 2025).

Overall, the results imply that BRICS sustainability gains are more reliably associated with measurable low-carbon transition than with green-labelled recovery spending, and that the effectiveness of recovery policies depends critically on whether they induce durable energy-system and structural change consistent with SDG 7, SDG 11, and SDG 13. The findings support policy strategies that prioritise scaling renewable deployment and clean-energy consumption while embedding recovery measures within coherent transition policy mixes that reduce lock-in risks and strengthen implementation capacity (Johnson et al., 2020; Catalano and Forni, 2021). Future research should extend pathway-based designs to incorporate additional mediators highlighted in the literature, including technological innovation and green finance mechanisms, to better map how recovery policies translate into long-run sustainability outcomes (Praveen et al., 2025; Zhang et al., 2024).

5. Conclusion

This study set out to examine how green recovery initiatives and low-carbon economic strategies influence sustainable development outcomes in BRICS economies, focusing on Brazil, China, India and South Africa over 2000–2023. Specifically, it assessed the direct effect of green recovery on sustainable development, evaluated how the low-carbon transition shapes sustainability performance, and tested whether low-carbon development mediates the green recovery–sustainable development relationship. Using adjusted net savings as a sustainability metric, the analysis provides a long-run perspective on whether economic activity is strengthening or eroding comprehensive national wealth through natural capital depletion and environmental damages.

The results yield three central findings. First, green recovery exhibits weak and regime-dependent links with sustainable development. In the full sample, green recovery spending is positive but statistically insignificant, indicating that green-labelled recovery outlays have not yet translated into systematic improvements in sustainability performance. A modest positive association emerges before COVID-19, but the sign reverses during the COVID period, when green recovery is significantly negative, suggesting that crisis-era *green* measures may have been insufficiently scaled or deployed in ways that stabilised incumbent structures rather than accelerating structural change. Second, the low-carbon transition is a more consistent driver of sustainable development. Across the full sample, a higher renewable share is positively and significantly associated with improved sustainability performance, and this effect becomes markedly stronger during COVID, implying that shifts towards renewables are more tightly connected to preserving comprehensive wealth, particularly in periods of disruption. Third, the mediation hypothesis is not supported: the indirect pathway from green recovery to sustainable development through the low-carbon channel is positive but statistically insignificant, indicating that recovery-related green spending has not consistently translated into detectable changes in the renewable energy share capable of transmitting sustainability gains within this panel setting.

These findings matter because they differentiate between nominal policy effort and measurable structural progress. For SDG 7, the evidence suggests that improvements in clean-energy outcomes are more likely to register in sustainability performance when the energy mix changes materially through greater renewable consumption, rather than through green-labelled spending alone. For SDG 13, the robust association between the low-carbon transition and sustainable development reinforces the importance of decoupling energy systems from carbon-intensive trajectories to reduce long-run environmental damages captured in adjusted net savings. For SDG 11, the results underline that urban and industrial resilience depends on the quality of structural reorientation, especially in crises, since energy consumption consistently undermines sustainability in the panel and becomes particularly damaging during COVID. The beneficiaries of these insights include policy makers designing recovery and climate packages, energy and industrial regulators responsible for implementation, and investors seeking credible transition signals. The evidence indicates that sustainability improvements are most likely when recovery measures are embedded in coherent transition strategies that change energy use patterns and support cleaner industrial upgrading, rather than when recovery actions remain fragmented or primarily stabilisation-oriented.

Future research should extend the mediation framework beyond the renewable share to test additional transmission channels through which green recovery may influence sustainability, including green innovation, regulatory effectiveness, institutional quality, and industrial restructuring, which are plausible mechanisms implied by the heterogeneity observed across countries. Longer post-pandemic time series will also be important for assessing whether the COVID-era reversal in the green recovery coefficient reflects short-run crisis dynamics or a more persistent misalignment between spending labels and structural outcomes. Finally, country-specific analyses that incorporate energy-market design, resource dependence and governance constraints would deepen understanding of why renewable expansion coincides with weaker sustainability performance in some settings, and how policy mixes can be redesigned to strengthen multi-SDG alignment in future recovery cycles.

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References

1. ABDULLAH I., WARVIYAN D., SAFRINA R., UTAMA N.A., TIRTA A., VEZA I., IRIANTO I., 2023, Green fiscal stimulus in Indonesia and Vietnam: A reality check of two emerging economies, *Sustainability*, 15(3): 2174, https://doi.org/10.3390/su15032174.
2. ADAMOWICZ M., 2022, Green deal, green growth and green economy as a means of support for attaining the Sustainable Development Goals, *Sustainability*, 14(10): 5901, https://doi.org/10.3390/su14105901.
3. AHIR D.M., MAHIDA R.G., 2025, Green finance and sustainable investment strategies: Catalyzing a low-carbon global economy, *Vidhyayana*, 11(si1): 72–95, https://doi.org/10.58213/8zrfw907.
4. ALSAGR N., 2023, How environmental policy stringency affects renewable energy investment? Implications for green investment horizons, *Utilities Policy*, 83: 101613, https://doi.org/10.1016/j.jup.2023.101613.
5. AMIN A., YUSOFF N.Y.B.M., ISIK C., OSABOHIEN R., 2025, Decarbonizing the US economy: The roles of renewable energy, technology innovation, human capital, and green growth, *Clean Technologies and Environmental Policy*, 27(11): 7395–7415, https://doi.org/10.1007/s10098-025-03283-w.
6. AMIN N., SHARIF A., TAYYAB M., PAN Y., 2025, Green technological advances and resource rents as levers for carbon reduction in BRICS: Implications for SDGs 7, 8, 9, 12, and 13, *Sustainable Development*, 33(3): 3171–3195, https://doi.org/10.1002/sd.3294.
7. BABAYOMI O.O., DAHORO D.A., ZHANG Z., 2022, Affordable clean energy transition in developing countries: Pathways and technologies, *iScience*, 25(5): 104178, https://doi.org/10.1016/j.isci.2022.104178.
8. BAI X., WANG K.-T., TRAN T.K., SADIQ M., TRUNG L.M., KHUDOYKULOV K., 2022a, Measuring China's green economic recovery and energy environment sustainability: Econometric analysis of sustainable development goals, *Economic Analysis and Policy*, 75: 768–779, https://doi.org/10.1016/j.eap.2022.07.005.
9. BAI X., WANG K.-T., TRAN T.K., SADIQ M., TRUNG L.M., KHUDOYKULOV K., 2022b, Measuring China's green economic recovery and energy environment sustainability: Econometric analysis of sustainable development goals, *Economic Analysis and Policy*, 75: 768–779, https://doi.org/10.1016/j.eap.2022.07.005.
10. BANGURA S., 2024, The implementation of Sustainable Development Goal 13 in 'BRICS' countries: A scoping review, *International Journal of Social Science Research and Review*, 7(6): 238–247, https://doi.org/10.47814/ijssrr.v7i6.2088.
11. BARBIER E.B., 2020, Greening the post-pandemic recovery in the G20, *Environmental and Resource Economics*, 76(4): 685–703, https://doi.org/10.1007/s10640-020-00437-w.
12. BARBIER E.B., 2022, The policy challenges of green rural transformation for Asia-Pacific emerging and developing economies in a post-COVID world, *Economic Analysis and Policy*, 75: 689–704, https://doi.org/10.1016/j.eap.2022.06.008.

13. BATRANCEA L., POP M.C., RATHNASWAMY M.M., BATRANCEA I., RUS M.-I., 2021, An empirical investigation on the transition process toward a green economy, *Sustainability*, 13(23): 13151, https://doi.org/10.3390/su132313151.
14. BÉTILA R.R., 2023, Economic freedom and carbon emissions across the globe: The mediating effect of renewable energy consumption, *Environmental Science and Pollution Research*, 30(36): 86300–86327, https://doi.org/10.1007/s11356-023-28420-0.
15. CAI L., SAMPENE A.K., AGYEMAN F.O., AYISI L.A., BRENYA R., 2021, Empirical analysis of BRICS countries pathway toward low-carbon environment, *In Review*, https://doi.org/10.21203/rs.3.rs-850439/v1.
16. CATALANO M., FORNI L., 2021, *Fiscal policies for a sustainable recovery and a green transformation,* World Bank, Washington, DC, https://doi.org/10.1596/1813-9450-9799.
17. CHIȚIMIEA A., MINCIU M., MANTA A.-M., CIOCOIU C.N., VEITH C., 2021, The drivers of green investment: A bibliometric and systematic review, *Sustainability*, 13(6): 3507, https://doi.org/10.3390/su13063507.
18. DAFNOMILIS I., CHEN H.-H., DEN ELZEN M., FRAGKOS P., CHEWPREECHA U., VAN SOEST H., FRAGKIADAKIS K., KARKATSOULIS P., PAROUSSOS L., DE BOER H.-S., DAIOGLOU V., EDELENBOSCH O., KISS-DOBRONYI B., VAN VUUREN D.P., 2022, Targeted green recovery measures in a post-COVID-19 world enable the energy transition, *Frontiers in Climate*, 4: 840933, https://doi.org/10.3389/fclim.2022.840933.
19. DAS C., JHARKHARIA S., 2019, Effects of low carbon supply chain practices on environmental sustainability: An empirical study on Indian manufacturing firms, *South Asian Journal of Business Studies*, 8(1): 2–25, https://doi.org/10.1108/SAJBS-04-2018-0037.
20. DONG C., WU H., ZHOU J., LIN H., CHANG L., 2023, Role of renewable energy investment and geopolitical risk in green finance development: Empirical evidence from BRICS countries, *Renewable Energy*, 207: 234–241, https://doi.org/10.1016/j.renene.2023.02.115.
21. DWARKASING C., 2023, Inequality determined social outcomes of low-carbon transition policies: A conceptual meta-review of justice impacts, *Energy Research & Social Science*, 97: 102974, https://doi.org/10.1016/j.erss.2023.102974.
22. EMISHYAN A., GULIEV I., 2025, BRICS sustainable energy: Challenges and opportunities, *E3S Web of Conferences*, 624: 04003, https://doi.org/10.1051/e3sconf/202562404003.
23. FILIPOVIĆ S., LIOR N., RADOVANOVIĆ M., 2022, The green deal–just transition and sustainable development goals nexus, *Renewable and Sustainable Energy Reviews*, 168: 112759, https://doi.org/10.1016/j.rser.2022.112759.
24. FRAGKOS P., LAURA VAN SOEST H., SCHAEFFER R., REEDMAN L., KÖBERLE A.C., MACALUSO N., EVANGELOPOULOU S., DE VITA A., SHA F., QIMIN C., KEJUN J., MATHUR R., SHEKHAR S., DEWI R.G., DIEGO S.H., OSHIRO K., FUJIMORI S., PARK C., SAFONOV G., IYER G., 2021a, Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States, *Energy*, 216: 119385, https://doi.org/10.1016/j.energy.2020.119385.
25. FRAGKOS P., LAURA VAN SOEST H., SCHAEFFER R., REEDMAN L., KÖBERLE A.C., MACALUSO N., EVANGELOPOULOU S., DE VITA A., SHA F., QIMIN C., KEJUN J., MATHUR R., SHEKHAR S., DEWI R.G., DIEGO S.H., OSHIRO K., FUJIMORI S., PARK C., SAFONOV G., IYER G., 2021b, Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States, *Energy*, 216: 119385, https://doi.org/10.1016/j.energy.2020.119385.
26. GAO K., YUAN Y., LIU T., 2026, Digital transformation and value co-creation in state-owned manufacturing enterprises: A hypernetwork perspective, *Business Process Management Journal*, 1–25, https://doi.org/10.1108/BPMJ-10-2025-1659.
27. GAO Z., ZENG H., ZHANG X., WU H., ZHANG R., SUN Y., LIU L., 2024, Exploring tourist spatiotemporal behavior differences and tourism infrastructure supply–demand pattern fusing social media and nighttime light remote sensing data, *International Journal of Digital Earth*, 17(1), https://doi.org/10.1080/17538947.2024.2310723.
28. GBADAYAN O.J., MUTHIVHI J., LINGANISO L.Z., DEENADAYALU N., 2024, Decoupling economic growth from carbon emissions: A transition toward low-carbon energy systems, a critical review, *Clean Technologies*, 6(3): 1076–1113, https://doi.org/10.3390/cleantechnol6030054.
29. GEELS F.W., SOVACOOL B.K., SCHWANEN T., SORRELL S., 2017, Sociotechnical transitions for deep decarbonization, *Science*, 357(6357): 1242–1244, https://doi.org/10.1126/science.aao3760.
30. HAILIANG Z., IQBAL W., CHAU K.Y., RAZA SHAH S.A., AHMAD W., HUA H., 2023, Green finance, renewable energy investment, and environmental protection: Empirical evidence from B.R.I.C.S. countries, *Economic Research-Ekonomska Istraživanja*, 36(2): 2125032, https://doi.org/10.1080/1331677X.2022.2125032.
31. HONG Q., JIAO X., QIU X., XU A., 2024, Investigating the impact of time allocation on family well-being in China, *Journal of Business Economics and Management*, 25(5): 981–1005, https://doi.org/10.3846/jbem.2024.22252.
32. HU F., YANG H., WEI S., ZHOU H., CHEN Y., HU H., 2026, Urban green technology transfer networks and green finance development: Evidence from the Yangtze River Delta, China, *Pacific-Basin Finance Journal*, 96: 103055, https://doi.org/10.1016/j.pacfin.2026.103055.
33. HUO J., 2025, Finite-difference solution ansatz approach in least-squares Monte Carlo, *Journal of Computational Finance*, 29: 67–121, https://doi.org/10.21314/JCF.2025.008.
34. IMANDOJEMU K., OSABOHIEN R., SULE A., AL-FARYAN M.A.S., 2026, Quantile analysis of the role of renewable energy technology on carbon neutrality in OECD countries, *International Journal of Energy Sector Management*, 20(1): 303–336, https://doi.org/10.1108/IJESM-10-2024-0046.

35. IMANDOJEMU K., SHOWUNMI O.L., OROLE F., ELUYELA F.D., MUSIBAU H., OSABOHIEN R., 2026b, Probing the energy trilemma pillars: Do innovation pathways deliver cleaner and more equitable energy systems?, *Sustainable Development*, https://doi.org/10.1002/sd.71116.
36. JAAFFAR A.H., RASIAH R., OSABOHIEN R., AMRAN A., 2024, Environmental governance experience and green management practices, *Energy Efficiency*, 17(7): 82, https://doi.org/10.1007/s12053-024-10257-2.
37. JI T., WANG S., WANG J., ZHANG J., 2026, Autonomous driving adoption for new energy vehicles, *Journal of Retailing and Consumer Services*, 88: 104552, https://doi.org/10.1016/j.jretconser.2025.104552.
38. JIANG S., YUAN X., 2026, Does the e-CNY pilot boost consumption upgrading?, *Applied Economics Letters*, 1–5, https://doi.org/10.1080/13504851.2026.2634858
39. JIANG S., ZHENG Z., ZHANG M., CHEN Y., CHEN X., 2026, Low-carbon data center optimisation, *IEEE Transactions on Industry Applications*, https://doi.org/10.1109/TIA.2026.3654490.
40. JIANG T., SUN Q., YAN Q., 2026, Normative misperception and low-carbon travel, *Social Behavior and Personality*, 54(3): 1–17, https://doi.org/10.2224/sbp.14977.
41. JIN H., TSAI F.S., MARTINEZ-VAZQUEZ J., 2025, Optimal expenditure decentralization for sustainable development, *Financial Innovation*, 11: 111, https://doi.org/10.1186/s40854-025-00780-1.
42. JOHNSON O., SHAWOO Z., TALEBIAN S., KEMP-BENEDICT E., LINDBLOM A., 2020, Shaping a sustainable and low-carbon recovery that spurs industry transition.
43. KHOSLA R., KAMAT A.S., NARAYANAMURTI V., 2020, Successful clean energy technology transitions in emerging economies: Learning from India, China, and Brazil, *Progress in Energy*, 2(4): 043002, https://doi.org/10.1088/2516-1083/abb52b.
44. LIU B., LYU Y., 2024, Economic corruption, green recovery, and mineral trade relationships in emerging economies, *Resources Policy*, 90: 104725, https://doi.org/10.1016/j.resourpol.2024.104725.
45. LIZANA J., MANTEIGAS V., CHACARTEGUI R., LAGE J., BECERRA J.A., BLONDEAU P., RATO R., SILVA F., GAMARRA A.R., HERRERA I., GOMES M., FERNANDEZ A., BERTHIER C., GONÇALVES K., ALEXANDRE J.L., ALMEIDA-SILVA M., ALMEIDA S.M., 2021, A methodology to empower citizens towards a low-carbon economy: The potential of schools and sustainability indicators, *Journal of Environmental Management*, 284: 112043, https://doi.org/10.1016/j.jenvman.2021.112043.
46. LIU T., DU Y., TAN S., ZHAO S., 2025, Corporate shadow banking networks, *Global Finance Journal*, 68: 101201, https://doi.org/10.1016/j.gfj.2025.101201.
47. LIU Y., 2026, E-commerce clusters and entrepreneurial performance, *Electronic Commerce Research*, https://doi.org/10.1007/s10660-025-10089-x.
48. LUAN Y., TANG D., ADEREMI T., OSABOHIEN R., 2025, Clean energy adoption and sustainable development, *Energy Strategy Reviews*, 59: 101740, https://doi.org/10.1016/j.esr.2025.101740.
49. MA X., SONG C., ZHAO C., ZHAO Z., DENG B., LIU Z., 2024, The role of BRICS countries in the optimal low-carbon transition path for sustainable development, *Journal of Cleaner Production*, 460: 142583, https://doi.org/10.1016/j.jclepro.2024.142583.
50. MIRASGEDIS S., CABEZA L.F., VÉREZ D., 2024, Contribution of buildings climate change mitigation options to sustainable development, *Sustainable Cities and Society*, 106: 105355, https://doi.org/10.1016/j.scs.2024.105355.
51. MOALLEMI E.A., EKER S., GAO L., HADJIKAKOU M., KWAKKEL J.H., REED P.M., OBERSTEINER M., BRYAN B.A., 2020, Global pathways to sustainable development to 2030 and beyond, *arXiv: General Economics*.
52. MOHAMED E.F., ABDULLAH A., JAAFFAR A.H., OSABOHIEN R., 2024, Renewable energy and EKC hypothesis, *Energy Strategy Reviews*, 53: 101387, https://doi.org/10.1016/j.esr.2024.101387.
53. MUJUMDAR A., SHADRIN A., 2021, Impact investment for BRICS cooperation on sustainable development, *Asia-Pacific Social Science Review*, 21(4), https://doi.org/10.59588/2350-8329.1452.
54. NASREEN F., TASAWAR A., RANI A., TALHA M., 2025, Decoding BRICS green growth in the 2010s: An empirical analysis of policy, technology, and investment, *Journal of Management & Social Science*, 2(2): 347–369, https://doi.org/10.63075/8atgvp97.
55. OFORI E.K., HAYFORD I.S., NYANTAKYI G., TERGU C.T., OPOKU-MENSAH E., 2023, Synerging Sustainable Development Goals: Can clean energy (green) deliver UN-SDG geared towards socio-economic-environment objectives in emerging BRICS?, *Environmental Science and Pollution Research*, 30(43): 98470–98489, https://doi.org/10.1007/s11356-023-29209-x.
56. OSABOHIEN R., AKPA A.F., OLONADE O., JAAFFAR A.H., AL-FARYAN M.A.S., 2026, Advancing environmental management through renewable energy and carbon footprint reduction, *International Journal of Energy Research*, https://doi.org/10.1155/er/8136569.
57. OSABOHIEN R., IMANDOJEMU K., JAAFFAR A.H., 2025, Clean energy, environmental policy and energy justice, *Scientific Reports*, 16: 2926, https://doi.org/10.1038/s41598-025-32759-4.
58. PEÑASCO C., ANADÓN L.D., VERDOLINI E., 2021, Systematic review of the outcomes and trade-offs of ten types of decarbonization policy instruments, *Nature Climate Change*, 11(3): 257–265, https://doi.org/10.1038/s41558-020-00971-x.

59. PENG K., FENG K., CHEN B., SHAN Y., ZHANG N., WANG P., FANG K., BAI Y., ZOU X., WEI W., GENG X., ZHANG Y., LI J., 2023, The global power sector's low-carbon transition may enhance sustainable development goal achievement, *Nature Communications*, 14(1): 3144, https://doi.org/10.1038/s41467-023-38987-4.
60. PIGATO M., BLACK S., DUSSAUX D., MAO Z., MCKENNA M., RAFATY R., TOUBOUL S., 2020, Technology transfer and innovation for low-carbon development, *The World Bank*, https://doi.org/10.1596/978-1-4648-1500-3.
61. PRAVEEN B., RATH B.N., AKRAM V., 2025, A new way of thinking about the nexus between green energy and green economic growth: The mediating role of green finance and green technology, *Journal of Environmental Management*, 390: 126235, https://doi.org/10.1016/j.jenvman.2025.126235.
62. PROSKURYAKOVA L., 2023, The contribution of low-carbon energy technologies to climate resilience, *Climate*, 11(12): 231, https://doi.org/10.3390/cli11120231.
63. QI R., LIU C., ZHANG Q., 2024, Evidence mechanism for promoting natural resources and green recovery through green economy: Sustainable assistance in finance, *Resources Policy*, 91: 104760, https://doi.org/10.1016/j.resourpol.2024.104760.
64. QIU J., ZHAO J., WEN F., ZHAO J., GAO C., ZHOU Y., TAO Y., LAI S., 2024, Challenges and pathways of low-carbon oriented energy transition and power system planning strategy: A review, *IEEE Transactions on Network Science and Engineering*, 11(6): 5396–5416, https://doi.org/10.1109/TNSE.2023.3344729.
65. SAMPENE A., LI C., AGYEMAN F., BRENYA R., 2021, Analysis of the BRICS countries' pathways towards a low-carbon environment, *BRICS Journal of Economics*, 2(4): 77–102, https://doi.org/10.38050/2712-7508-2021-4-4.
66. SEMIENIUK G., CAMPIGLIO E., MERCURE J., VOLZ U., EDWARDS N.R., 2021, Low-carbon transition risks for finance, *WIREs Climate Change*, 12(1): e678, https://doi.org/10.1002/wcc.678.
67. SLABE-ERKER R., PRIMC K., ZABAVNIK D., 2023, New thematic relationships in the green recovery literature, *Environment, Development and Sustainability*, s10668-023-03789-7, https://doi.org/10.1007/s10668-023-03789-7.
68. SLAMERŠAK A., KALLIS G., O'NEILL D.W., 2022, Energy requirements and carbon emissions for a low-carbon energy transition, *Nature Communications*, 13(1): 6932, https://doi.org/10.1038/s41467-022-33976-5.
69. SOHAIL M.T., 2023, Green development in BRICS: Unraveling the effects of environmental technology, R&D spending, and green investment in the context of COP21, *Environmental Science and Pollution Research*, 30(57): 120000–120009, https://doi.org/10.1007/s11356-023-30696-1.
70. TIAN H., WANG Z., ZHANG P., LI J., WANG Q., ZHANG S., 2026, Quantum Stackelberg duopoly model, *Physica A*, 681: 131073, https://doi.org/10.1016/j.physa.2025.131073.
71. UDEAGHA M.C., NGEPAH N., 2023, The drivers of environmental sustainability in BRICS economies: Do green finance and fintech matter?, *World Development Sustainability*, 3: 100096, https://doi.org/10.1016/j.wds.2023.100096.
72. WANG R., LAILA U., NAZIR R., HAO X., 2023, Unleashing the influence of industrialization and trade openness on renewable energy intensity using path model analysis: A roadmap towards sustainable development, *Renewable Energy*, 202: 280–288, https://doi.org/10.1016/j.renene.2022.11.035.
73. WANG S., TUO Y., ZHANG X., TAN Y., LIU M., 2024, Driving toward business sustainability: Empirical evidence from low-carbon practices, *Business Strategy and the Environment*, 33(7): 6417–6432, https://doi.org/10.1002/bse.3830.
74. WERIKHE A., 2022, Towards a green and sustainable recovery from COVID-19, *Current Research in Environmental Sustainability*, 4: 100124, https://doi.org/10.1016/j.crsust.2022.100124.
75. WHILE A., EADSON W., 2022, Zero carbon as economic restructuring: Spatial divisions of labour and just transition, *New Political Economy*, 27(3): 385–402, https://doi.org/10.1080/13563467.2021.1967909.
76. WU B., ZHANG Y., FANG C., 2025, Shareholder activism and innovation, *Entrepreneurship Theory and Practice*, https://doi.org/10.1177/10422587251401182.
77. XIA P., ZHU X., CHEN Z., JIN F., HE Q., 2025, Digital financial inclusion prediction, *Computational Economics*, https://doi.org/10.1007/s10614-025-11133-6.
78. YADAV A., GYAMFI B.A., ASONGU S.A., BEHERA D.K., 2024, The role of green finance and governance effectiveness in the impact of renewable energy investment on CO2 emissions in BRICS economies, *Journal of Environmental Management*, 358: 120906, https://doi.org/10.1016/j.jenvman.2024.120906.
79. YANG B., KAO P.T., BAI W., JIANG T., 2025, Institutional entrepreneurship and MNEs, *European Journal of International Management*, 25(3–4): 645–678, https://doi.org/10.1504/EJIM.2025.144605.
80. YAO S., LI T., LI Y., 2023a, promoting sustainable fossil fuels resources in BRICS countries: Evaluating green policies and driving renewable energy development, *Resources Policy*, 85: 103990, https://doi.org/10.1016/j.resourpol.2023.103990.
81. YAO S., LI T., LI Y., 2023b, promoting sustainable fossil fuels resources in BRICS countries: Evaluating green policies and driving renewable energy development, *Resources Policy*, 85: 103990, https://doi.org/10.1016/j.resourpol.2023.103990.
82. ZACHARIADIS T., GIANNAKIS E., TALIOTIS C., KARMELLOS M., FYLAKTOS N., HOWELLS M., BLYTH W., HALLEGATTE S., 2021, 'Building back better' in practice: A science-policy framework for a green economic recovery after COVID-19, *World Bank*, Washington, DC, https://doi.org/10.1596/1813-9450-9528.
83. ZHANG Y., SHOU S., LI Y., 2024, Do green investments impact corporate green innovation? Empirical evidence from Chinese-listed companies, *Frontiers in Environmental Science*, 12: 1468843, https://doi.org/10.3389/fenvs.2024.1468843.

84. ZHENG J., NIE S., JING H., HE Y., LI M., MA Y., DING Z., 2024, HTS maglev system, *IEEE Transactions on Intelligent Transportation Systems*, 25(10): 13573–13583, https://doi.org/10.1109/TITS.2024.3398148.
85. ZHONGPING S., YONGJUN G., YUNBAO X., QIFENG X., ANDLIB Z., 2023, Green financial investment and its influence on economic and environmental sustainability: Does privatization matter?, *Environmental Science and Pollution Research*, 30(39): 91046–91059, https://doi.org/10.1007/s11356-023-28520-x.
86. ZHOU P., LV Y., WEN W., 2023, The low-carbon transition of energy systems: A bibliometric review from an engineering management perspective, *Engineering*, 29: 147–158, https://doi.org/10.1016/j.eng.2022.11.010.
87. ZHOU Y., 2023, Worldwide carbon neutrality transition? Energy efficiency, renewable, carbon trading and advanced energy policies, *Energy Reviews*, 2(2): 100026, https://doi.org/10.1016/j.enrev.2023.100026.